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Effects of Cement and Rice Husk Ash on the Geotechnical Properties of E-Waste Contaminated Soil

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Abstract

E-waste contamination deteriorates the engineering quality of soils, limiting their suitability for construction. This study evaluated the geotechnical properties of e-waste-contaminated soil (CO1) and the effectiveness of cement and rice husk ash (RHA) as stabilizing agents. The untreated soil showed weak characteristics, including low maximum dry density (1.75 g/cm³), high optimum moisture content (17.80%), low California Bearing Ratio (11.46%), and unconfined compressive strength (115.54 kPa). Stabilization with cement alone enhanced strength, with UCS reaching 179.05 kPa at 6% cement content. Further improvement was achieved by incorporating RHA, with the optimum mix of 6% cement and 6% RHA producing the highest UCS of 222.84 kPa representing a 93% increase over untreated soil and 24% over cement-only stabilization. CBR values also improved, confirming enhanced load-bearing capacity. The results highlight that combining cement with RHA effectively stabilizes e-waste-contaminated soils. Moreover, the partial replacement of cement with RHA offers a sustainable, low-cost approach by utilizing an agricultural byproduct, reducing cement demand, and promoting eco-friendly waste management in geotechnical engineering.

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Introduction

The increasing generation of electrical and electronic waste (e-waste) and the traditional method of disposal used in Nigeria have resulted to these heavy metals and toxic chemicals leaching into the soil over time and have caused severe degradation of its environment and potential negative impacts on the soil's engineering properties. This has become a very pressing environmental concern all over the world.

E-waste contaminated soils, such as those found in electronic and electrical waste dump sites generally possess poor engineering properties that make them unsuitable for construction purposes in their natural state. These soils often exhibit low strength, high plasticity, poor compaction characteristics, and contaminant loadings that negatively affect their geotechnical behaviour (Sabat, 2012; Dauda *et al,* 2018). The leaching of heavy metals and the presence of non-degradable particles from e-waste further compromise their load-bearing capacity and pose environmental hazards (Wen *et al*., 2019).

This has necessitated for stabilization of the contaminated soil using cement, which is well known for soil stabilisation properties and agricultural by-product of rice milling such as Rice Husk Ash (RHA), offers a sustainable alternative that can improve soil properties for road construction and civil engineering works when used in combination with cement. According to Bello *et al*.,(2022), soil stabilization is the treatment of soils to enable their strength and durability to be improved upon in such a way that they become adequately suitable for construction beyond their original capability.

One potential solution to mitigate these hazards is the stabilization/solidification of e-waste using cement and Rice Husk Ash (RHA), a by-product of rice milling. This method not only reduces the leachability of harmful substances but also enhances the mechanical properties of the treated soil. Cement plays a critical role in stabilizing e-waste soils by binding heavy metals and hazardous materials into a stable matrix. The hydration process of cement produces calcium silicate hydrate (C-S-H) and calcium hydroxide (Portlandite), which can encapsulate contaminants and reduce their mobility. Cement also increases the pH of the soil, causing the precipitation of certain heavy metals as insoluble hydroxides, further reducing their potential leaching. Several studies have demonstrated the efficacy of cement in stabilizing soils contaminated with heavy metals, including lead, cadmium, and chromium. For instance, Conner and Hoeffner (1998) found that the use of portland cement could significantly reduce the leachability of heavy metals in contaminated soils. In the context of e-waste, cement can effectively bind and immobilize metals found in electronic components, such as lead from CRT monitors, cadmium from batteries, and copper from wiring.

Furthermore, the high cost of cement, which is generally used as a binder, as led to the search for natural materials as alternative. Studies on alternatives or complements to cement has so far centered on the partial replacement of cement with different materials. RHA is a pozzolanic material, rich in amorphous silica, which reacts with calcium hydroxide in the presence of water to form additional C-S-H, enhancing the strength and durability of the cement matrix. When used in combination with cement, RHA not only reduces the amount of cement needed (thus lowering CO_2 emissions) but also contributes to the long-term strength development of the stabilized material.

Studies have shown that RHA improves the mechanical properties and durability of stabilized soils. Ganesan *et al.,* 2008) reported that the inclusion of RHA in cement-stabilized soils increased compressive strength and reduced permeability. Moreover, RHA can mitigate the negative environmental impact of cement production by acting as a partial substitute, which is especially important considering the high carbon footprint of cement manufacturing. The stabilization process of e-waste soils using cement and RHA involves both chemical and physical mechanisms. Chemical Mechanism is the hydration of cement which produces C-S-H and Portlandite, which react with the amorphous silica in RHA to form additional C-S-H. This reaction reduces the porosity of the soil and encapsulates contaminants, preventing them from leaching out, while physical mechanism of Cement and RHA improve the physical structure of the soil by increasing its density and reducing its permeability. This, in turn, limits the movement of contaminants through the soil matrix, further stabilizing the e-waste soil. Several studies have evaluated the performance of cement and RHA in stabilizing soils contaminated with e-waste. Cement and RHA improve the UCS of e-waste soils, indicating an increase in load-bearing capacity. Olufowobi *et al.* (2014) demonstrated that the addition of 10% RHA and 6% cement to e-waste soil improved its UCS significantly over a curing period. CBR values increase with the addition of cement and RHA, indicating better subgrade support for infrastructure. Makusa (2013) reported similar findings, with cement and RHA improving the geotechnical properties of contaminated soils.

Cement production is a major source of CO_2 emissions, so reducing its usage with RHA helps decrease the overall environmental foot prints of the stabilization process. Additionally, RHA is an agricultural waste product, and its utilization in soil stabilization provides a sustainable method for its disposal, reducing environmental pollution from rice milling industries. The stabilization of e-waste soils using cement and RHA presents a viable solution to the environmental challenges posed by e-waste contamination. Cement provides the necessary strength and encapsulation properties, while RHA enhances the pozzolanic reactions and reduces the environmental impact of the process. While challenges remain, the combination of cement and RHA holds great promise for sustainable soil stabilization in regions affected by e-waste pollution.

Geology of the Study Area

Computer Village is situated in Ikeja, the capital of Lagos State, in southwestern Nigeria. Geographically, the area lies approximately between latitude 6°35'N and 6°37'N and longitude 3°20'E and 3°22'E (Google Earth, 2024). It is one of the most urbanized and commercially active zones in Lagos, primarily known for its dense network of electronics related businesses. The area lies within the Dahomey Basin, a marginal sedimentary basin extending from southeastern Ghana through Togo and Benin into the southwestern part of Nigeria. The Dahomey Basin is characterized by a complex assemblage of Cretaceous to Recent sedimentary sequences that unconformable overlie the Precambrian basement complex (Omatsola and Adegoke, 1981; Nton, 2001).

The dominant geological unit underlying the Computer Village area is the **Benin Formation**, which is part of the Tertiary sediments of the Dahomey Basin. The Benin Formation, also referred to as the **Coastal Plain Sands**, is composed mainly of: Unconsolidated **coarse to medium-grained sands, gravels and** Minor lenses of **clay and silt.**

This formation was deposited in a fluvial to deltaic environment during the Miocene to Recent times and is known for its high porosity and permeability (Adepelumi *et al.*, 2009; Omosuyi *et al.*, 2015). The surface and sub-surface soils in Ikeja are typically made up of: Lateritic sandy soils, loamy sands and clayey sands

These soils are the product of intense tropical weathering under alternating wet and dry climatic conditions, leading to leaching and enrichment with iron and aluminum oxides. The presence of ferruginous concretions is common, especially at deeper profiles (Akinlami *et al*., 2018).

The Benin Formation serves as the principal aquifer system in the Ikeja region. Groundwater occurs at shallow to moderate depths and is accessed through wells and boreholes. Due to the high permeability of the sands, the aquifer yields substantial water, though it may be vulnerable to contamination in densely populated or industrialized areas (Adepelumi *et al*., 2009).

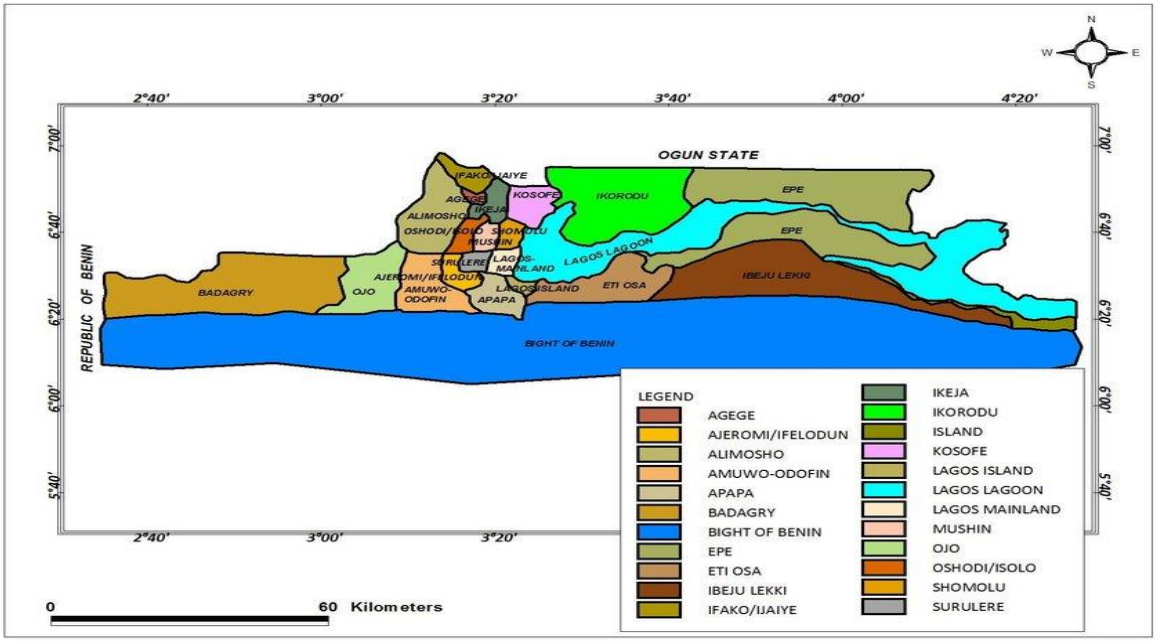

Fig 1: Map of Lagos State showing Ikeja Local Government Area

Materials and Methods

Materials

The primary materials utilized in this study include e-waste contaminated soil, rice husk ash (RHA), Ordinary Portland Cement (OPC), and water.

E-waste Soil Sample

The e-waste soil sample, was collected from an established electrical and electronic waste dumpsite located at Oremeji Street, Computer Village, Ikeja, Lagos State, Nigeria. A sample was taken at a depth of not less than 1 m below ground surface using the disturbed sampling technique. The soil sample was labeled as CO 1 appropriately, noting the soil description, depth of collection, and sampling date before taken to the laboratory. In the laboratory, the sample was air-dried for two weeks to minimize natural moisture content, then sieved through a No. 4 (4.75 mm) sieve to remove coarse materials and debris. Pulverization of soil lumps was performed using a pestle and mortar under controlled pressure to prepare samples for testing.

Rice Husk Ash (RHA): Rice husk fiber was sourced from a rice milling facility in the Agbara area of Lagos State. The husk was initially burned in open air, after which the resulting black ash was calcined in a muffle furnace at temperatures between 650 °C and 750 °C for two hours. This process produced a white ash, rich in amorphous silica, suitable for pozzolanic reactions during soil stabilization.

Ordinary Portland Cement (OPC): The cement used was Ordinary Portland Cement and was procured from a local supplier at Magodo, Lagos State.

Water: Water utilized for all testing activities was sourced from laboratory tap water, which originates from a borehole. Distilled water was not employed in order to better simulate field conditions.

Methods

The collected soil samples were subjected to initial air-drying and pulverization to ensure uniformity. Natural soil properties were determined through standard laboratory tests, including compaction and California Bearing Ratio (CBR) evaluations in accordance with BS 1377.

Subsequently, stabilization procedures involved blending the air-dried soil with varying percentages (0%, 2%, 4%, 6%, 8%, and 10%) of OPC and RHA, individually and in combination. The mixtures were thoroughly homogenized to ensure even distribution of the stabilizing agents.

The Standard Proctor Compaction Test was conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of each soil-cement-RHA blend. CBR testing followed the general specification of the Federal Ministry of Works and Housing (1997)., where specimens were compacted, cured for six days under unsoaked conditions.

All laboratory procedures adhered strictly to BS 1377 standards for natural soil and BS 1924 standards for stabilized materials.

Results and Discussion

Table I: Engineering Properties of CO1 e-waste soil before treatment

Properties	E-waste soil samples (control) CO1
Maximum Dry Density (g/cm^3) Optimum	1.75
Optimum Moisture Content (%)	17.80
California Bearing Ratio (%)	11.46
Unconfined compressive strength (kPa)	115.54
Cohesion (kPa)	19
Angle of internal friction Θ^0	18
Soil Classification	A-2-6
Colour	Light Brown
Soil Type	Silty-Clayey Sand

Table II: Summary of all test result for e-waste soil samples CO1 treated with cement

				CBR	Triaxial Test			UCS
E-waste Soil sample	Cement content	Max. Dry Density (MDD) (g/cm^3)	Optimum Moisture Content (OMC) %	Unsoaked (%)	Deviation Stress σ^3 (KN/m^2)	Cohension (KN/m^2)	Angle of Friction $(\Theta)^0$	Uncured (kPa)
CO1	0%	1.75	17.80	11.46	233.35	19	18	115.54
	2%	1.85	16.70	22.45	352.45	17	21	152.34
	4%	1.92	16.55	24.96	438.06	12	21	158.65
	6%	2.11	16.14	30.09	522.56	07	25	179.05
	8%	1.87	15.85	28.95	513.75	13	20	157.80
	10%	1.82	15.94	26.05	495.20	16	20	149.05

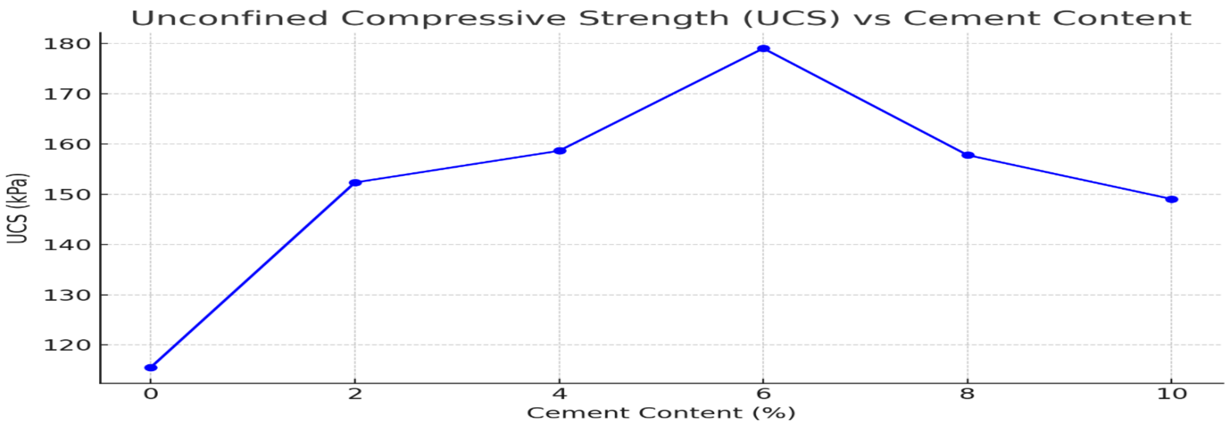

Fig 2: Graph of UCS vs. cement content

Table III: Summary of all test result for e-waste soil samples CO1 treated with cement and RHA

E-waste Soil sample	cement	Rice husk ash (RHA)	Max. Dry Density (MDD) (g/cm^3)	Optimum Moisture Content (OMC) (%)	CBR Unsoaked (%)	Triaxial Test Deviatior Stress σ^3 (KN/m^2)	Cohension (KN/m^2)	Angle of Friction (Θ)^0	UCS Uncured (kPa)
CO1	0%	0%	1.75	17.80	11.46	233.35	19	18	115.54
		2%	1.86	17.81	12.56	257.40	20	20	123.65
		4%	1.97	17.85	12.60	275.45	20	22	125.95
		6%	2.23	17.90	13.05	285.05	14	25	145.84
		8%	2.12	17.95	12.05	150.30	19	24	139.05
		10%	2.06	18.25	11.45	138.45	15	22	121.92
	2%	0%	1.85	16.70	22.45	352.45	17	21	152.34
		2%	1.96	16.80	27.45	354.75	19	22	157.52
		4%	2.11	16.90	32.05	375.20	20	24	165.05
		6%	2.24	17.35	39.50	485.20	12	28	168.85
		8%	2.12	16.40	23.89	338.45	15	26	152.48
		10%	2.03	16.35	22.54	332.40	14	25	150.85
	4%	0%	1.92	16.55	24.96	438.06	12	21	158.65
		2%	2.12	16.60	31.45	455.62	12	23	166.84
		4%	2.20	16.75	38.25	475.50	19	24	168.95
		6%	2.59	16.85	40.45	483.50	11	28	172.48
		8%	2.15	17.01	30.56	327.40	15	26	166.48
		10%	2.08	17.45	27.60	315.45	12	24	160.65
	6%	0%	2.11	16.14	16.14	522.56	07	25	179.05
		2%	2.15	16.21	16.21	587.40	15	26	180.65
		4%	2.22	16.25	16.25	595.45	10	26	191.95
		6%	2.45	16.40	16.40	675.05	05	29	222.84
		8%	2.25	16.75	16.75	510.30	19	24	199.05
		10%	2.21	16.65	16.65	508.45	13	22	181.92
	8%	0%	1.87	15.85	15.85	513.75	13	20	157.80
		2%	1.95	15.90	15.90	514.75	15	22	177.52
		4%	2.25	16.20	16.20	515.20	17	23	185.05
		6%	2.84	16.35	16.35	585.20	11	26	198.85
		8%	2.35	16.40	16.40	538.45	15	24	182.48
		10%	2.30	16.45	16.45	532.40	14	21	180.85
	10%	0%	1.82	15.94	15.94	495.20	16	20	149.05
		2%	1.85	16.10	16.10	525.62	17	21	156.84
		4%	1.87	16.15	16.15	545.50	18	23	158.95
		6%	1.89	16.25	16.25	583.50	11	26	162.48
		8%	1.85	16.31	16.31	567.40	15	24	152.48
		10%	1.82	16.85	16.85	545.45	13	22	140.65

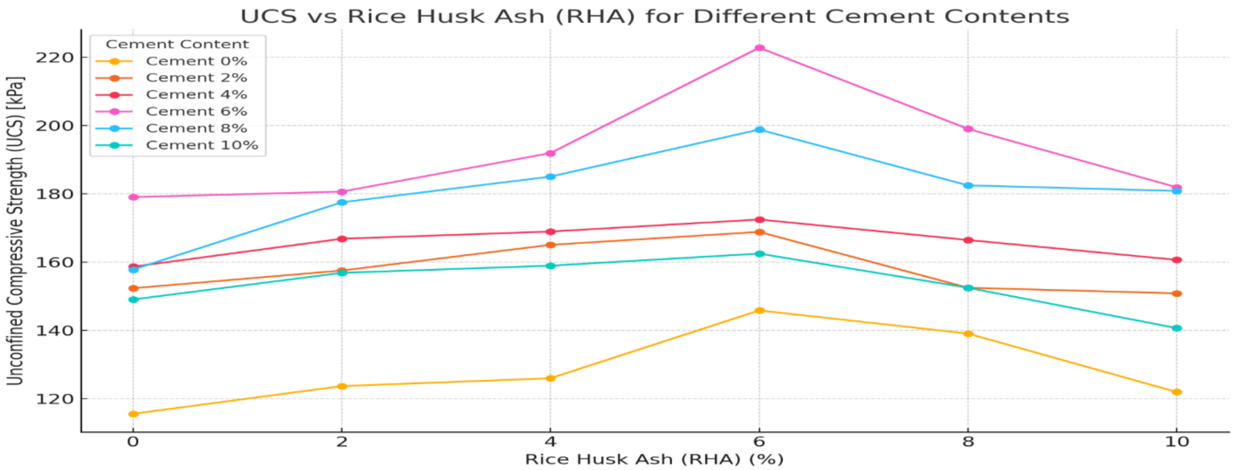

Fig 3: Graph of UCS vs. cement content and RHA

Table I shows an untreated e-waste soil sample, classified as CO1, it exhibits several fundamental geotechnical properties that are essential in understanding its behaviour under loading and its suitability for construction. The maximum dry density (MDD) is a measure of how compact a soil can become when optimal moisture is present. At 1.75 g/cm³, the e-waste soil demonstrates moderate compaction characteristics typical of granular soils with silt-clay fines. This value indicates that although the soil can achieve reasonable compaction, its density is not high enough for heavy structural applications without stabilization.

This MDD value aligns with findings from studies by Amu *et al*. (2011), where untreated silty-sandy lateritic soils in Nigeria recorded MDD values between 1.60 and 1.85 g/cm³, indicating that the presence of metallic particles from e-waste might be marginally influencing compaction behavior.

The OMC is the moisture level at which the soil achieves maximum compaction. An OMC of 17.80% suggests relatively high water absorption, possibly due to the presence **of** fine-grained materials such as clay and silt, which tend to retain moisture. High OMC in e-waste affected soil has been similarly reported by Dauda *et al*. (2018), suggesting that toxic oxides like PbO and CuO contribute to finer soil fractions, increasing water retention while the CBR value of 11.46% falls within the range of moderate subgrade strength**,** suitable for light traffic roads. According to Ola (1983)**,** CBR values less than 15% typically require stabilization for improved load-bearing capacity. The relatively low CBR also reflects the weak bonding and internal structure of the soil, likely exacerbated **by** e-waste contamination, which disrupts natural cohesion and particle orientation.

The UCS which is a measure of the soil's ability to withstand axial loading without lateral support. A UCS value of 115.54 kPa indicates low strength, which is below the 200–300 kPa threshold recommended for stabilized subgrade materials (Amadi, 2010). The presence of toxic heavy metals from e-waste could alter soil particle interaction and lead to early failure under stress. The cohesion of 19 kPa reflects the soil's resistance due to interparticle attraction, which is moderate for silty-clayey materials. Contaminants like Pb and Cu oxides may bond weakly with silicate minerals, reducing true cohesion. Sabat (2012) noted that untreated lateritic soils often show cohesion values between 15 and 30 kPa while an internal friction angle of 18° is considered low, indicating poor granular interlocking and high fines content. This limits shear strength, especially in saturated conditions. According to Head (2006), soils with high clay content and metal oxides exhibit lower friction angles, often below 25°.

The A-2-6 classification suggests a silty or clayey sand, with fair to poor subgrade quality. Soils in this group often require modification or stabilization to enhance strength and durability. The AASHTO system considers both particle size distribution and Atterberg limits in assigning this group **and the** light brown colour is characteristic of iron-stained sandy soils but may also reflect contamination by decomposed organic and inorganic components of **e-waste**, including plastics, foams, and metallic dusts.

The combination of silt and clay within a sandy matrix explains the observed engineering behaviors: moderate density, high moisture content, and low shear strength. These mixtures typically exhibit poor performance under load unless chemically or mechanically treated. The engineering behavior of the-waste soil sample (CO1) indicates sub optimal performance for construction use in its untreated state. The low CBR, UCS, and internal friction angle, combined with moderate MDD and high OMC, call for stabilization, preferably with cement or pozzolanic materials so as to improve its mechanical performance.

Table II shows the geotechnical response of e-waste (CO1) contaminated soil to incremental cement stabilization from 0 to 10%. The key parameters measured include Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), Triaxial Strength parameters (Deviator Stress, Cohesion, and Friction Angle), and Unconfined Compressive Strength (UCS). These values offer insights into the mechanical behaviour as well as the engineering suitability of the treated soils for construction applications.

The MDD increased from 1.75g/cm³ at 0% to a peak of 2.11g/cm³ at 6% cement, before dropping slightly at higher cement contents. This shows an improved particle bonding and densification due to cement hydration products like Calcium Silicate Hydrate (C-S-H**)** and Ettringite, which fill voids and bind soil particles tightly (Osinubi *et al*., 2009) while the decline in MDD **at** 8 to 10% **may indicate** flocculation and agglomeration of cementitious compounds, which increase void ratios (Sabat, 2012).

OMC decreased from 17.80% to 15.85% with increasing cement content, this is expected because cement absorbs part of the soil moisture for hydration, thereby reducing the water available for compaction (Amadi, 2010), while a slight rise in OMC at **10% cement** (15.94%) may be attributed to excess unreacted cement requiring more water for mixing, as also reported by Ghosh and Subbarao (2007).

The CBR increased steadily from 11.46% at 0% to a maximum of **30.09% at 6% cement**, indicating significant improvement in **bearing capacity** and **resistance to penetration** while the drop at 8% and 10% suggests that after a certain threshold, further cement does not proportionally enhance load-bearing, possibly due to **brittle behavior** or over stiffening**,** leading to cracking under load (Dauda *et al*., 2018). A CBR of above **20%** is suitable for **sub-base** and base layers**,** making 4% to 6% cement treatments viable for road construction (Ola, 1983).

The Deviator **Stress (σ3)** increased with cement content from 233.35 kN/m² at 0% **to** 522.56 kN/m² at 6%**,** indicating enhanced load-carrying capacity under confining stress, this reinforces the pozzolanic reaction theory**,** where cement reacts with soil silicates and aluminates to form strong interparticle bonds (Osinubi *et al*., 2009). Cohesion **d**ecreased from 19 kN/m² at 0% to a minimum of **7** kN/m² at 6%**,** then increased again to 16 kN/m² at **10%**, this counterintuitive behavior could be explained by **the** transition from cohesion dominated to friction dominated shear strength which is a common outcome in cement treated soils where particle friction governs strength more than clay cohesion (Sabat and Pati, 2009). The Angle of Internal Friction **(ϴ)** increased from **18° to a** peak of 25° at 6%**,** indicating **a** shift toward granular behaviour d**ue** to cementitious stiffening and interlocking and this corroborates findings by (*Amu et al.,*2011), who observed similar increases in treated lateritic soils, enhancing slope and embankment stability.

UCS rose from 115.54 kPa at 0% **to** 179.05 kPa at 6%**,** before declining at higher cement contents. The strength gained is due to the formation of cementitious gels (C-S-H and C-A-H) that bind soil particles (Ghosh *et al*., 2020) while the drop at 8% and 10% may result from excess cement leading to brittleness**,** shrinkage cracks, or **poor dispersion** in the soil matrix (Osinubi *et al*., 2009). The peak strength at 6% confirms the optimum cement content for stabilization of CO1 soil, beyond which economic and mechanical returns diminish.

The stabilization of e-waste-contaminated soil (CO1) with cement shows clear improvements in geotechnical properties up to 6% cement content, after which performance declines slightly. This indicates that 6% cement is the optimum level for achieving desirable strength and durability without unnecessary material use or negative mechanical trade-offs. This result is consistent with earlier studies on contaminated and lateritic soils treated with cement or similar binders.

Table III presents the results of laboratory tests performed on the e-waste conntaminated soil sample CO1, stabilized with varying combinations of cement from 0% to 10% and rice husk ash (RHA), from 0% to 10% . The tests include measurements of Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), Triaxial test results (deviator stress, cohesion, angle of friction) and Unconfined Compressive Strength (UCS).

The MDD values **generally** increase with cement and RHA content, peaking at combinations of **6% cement + 6%** RHA (2.45 g/cm³) **and** 8% cement + 6% RHA (2.84 g/cm³)**, this is due to the** filler effect **and** pozzolanic **reactions** of RHA, which enhance particle packing and cementitious bonding, consistent with findings by **Ghosh and Subbarao (2007)** and **Osinubi *et al.* (2009)** while the OMC values remain relatively stable (around 16–18%), with minor fluctuations. The addition of RHA tends to slightly **increase OMC**, possibly due to its **high surface area**

and absorptive silica content, requiring more water during compaction and curing (Sabat, 2012).

CBR values increases with cement and RHA, peaking **at** 6% cement + 6% RHA (16.40%) indicating improved bearing capacity, Beyond the optimum, excess RHA can lead to reduced CBR due to unreacted ash and weak matrix formation (Dauda *et al*., 2018). The **deviator Stress** and Friction Angle (Ɵ) increase significantly with higher cement–RHA content, with peak values of **675.05 kN/m²** and **29°** at 6% cement + 6% RHA while **cohesion** shows a non-linear trend: at low cement levels, it increases with RHA; at high cement levels, it initially drops due to **cement** replacing the cohesive clay structure, then increases again as hydration products form (Amadi, 2010; Sabat and Pati, 2009).

The UCS values improved from 115.54 kPa (untreated) **to** 222.84 kPa (6% cement + 6% RHA) and 198.85 kPa (8% cement + 6% RHA)**,** this confirms that partial substitution of cement with RHA can enhance strength due to pozzolanic reactions forming additional C-S-H and C-A-H gels**,** as also observed by Ghosh *et al*. (2020) and Amu ***et*** *al*. 011) while At higher RHA percentages (>6%), strength begins to plateau or decline, likely due to **i**nsufficient lime for full pozzolanic reaction (Sabat, 2012).

The laboratory results confirms that at 6% cement + 6% RHA blend provides optimal improvement in strength, compaction, and load bearing capacity of e-waste-contaminated soil. RHA effectively supplements cement by enhancing pozzolanic activity, reducing cement use, and improving sustainability.

Figure 2 illustrates the variation of UCS with different cement contents in e-waste soil. UCS increased sharply from 0% to 6% cement content, peaking at approximately 180kPa. This improvement is attributed to the formation of cementitious bonds that strengthen the soil matrix. Beyond 6% cement content, UCS declined slightly and stabilized between 8% and 10%, likely due to over-stabilization, reduced compaction, and increased brittleness.

Figure 3 presents the UCS behavior of e-waste soil treated with varying cement and RHA percentages. Across all RHA contents, UCS values increased with cement content up to 6%, then declined slightly beyond 6%. RHA enhanced UCS performance, with 6% RHA producing the highest UCS across all cement contents. This improvement is attributed to the secondary C-S-H gel formation, contributing to additional strength. However, excessive RHA beyond 6% contributed to a slight decline in UCS, again attributed to the formation of brittle soil structures.

Conclusion

The control sample CO1, characterized as silty-clayey sand with moderate compaction and strength properties, necessitates stabilization to enhance its suitability for engineering applications. Baseline California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and shear strength values suggest that the soil, in its natural state, may not meet the requirements for construction projects demanding higher load - bearing capacities and durability. Consequently, stabilization using cement and RHA is recommended to improve its geotechnical properties.

Cement stabilization significantly improves the engineering properties of the e-waste soil sample CO1, particularly its Maximum Dry Density (MDD), CBR, deviator stress, and UCS. The optimal cement content is identified at 6%, at which the soil achieves peak values in compaction, load-bearing capacity, shear strength, and compressive strength, making it suitable for supporting infrastructure without the need for costly excavation and soil replacement. Beyond 6% cement content, a slight decline in performance is observed, indicating that over stabilization may adversely affect the soil's mechanical behaviour. Therefore, at 6% cement content is recommended for achieving the best balance between strength and durability for the studied e-waste soil.

Furthermore, stabilization with a combination of cement and RHA markedly improves the engineering properties of the soil. Optimal results are achieved at 6% cement and 6% RHA, where the soil exhibits maximum MDD, CBR, deviator stress, and UCS, along with a favourable balance between cohesion and angle of internal friction. These enhancements render the stabilized soil more suitable for applications such as road and embankment construction, offering improved load bearing capacity, shear strength, and compressive strength. However, increases in stabilizer content beyond 6% result in a reduction of these properties, suggesting the existence of an optimal stabilization range. Additionally, the increased cohesion and angle of internal friction provide improved stability and erosion resistance, which is vital for embankments subjected to dynamic loads and varying environmental conditions. The rise in CBR values is particularly critical for road construction, as higher CBR indicates better load distribution and improved resistance to deformation under traffic loads, leading to more durable road structures.

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