Evaluating the Impact of Cement and Rice Husk Ash on E-Waste Soil Strength and Bearing Capacity

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ORIGINAL RESEARCH

Abstract— Electrical and electronic waste (e-waste) refers to discarded electrical and electronic materials such as refrigerators, mobile phones, computers, televisions, and other devices, which significantly deteriorate the engineering properties of soil over time. This study evaluates the effects of varying percentages of cement and rice husk ash (RHA) on the geotechnical properties of e-waste-contaminated soil, focusing on California Bearing Ratio (CBR), triaxial test results, and unconfined compressive strength (UCS). E-waste soil samples stabilized with 0%, 2%, 4%, 6%, 8%, and 10% cement and RHA mixtures. The results revealed a peak CBR value of 59.05%, a maximum deviator stress (σ_3) of 615.05 kN/m², and the highest UCS value of 276.84 kPa, with optimal performance observed at 6% cement-RHA combination. The findings demonstrate that the inclusion of cement and RHA significantly enhances the strength and bearing capacity of e-waste-contaminated soil.

Keywords— Electrical and electronic waste (E-waste), Rice husk ash (RHA), California bearing ratio (CBR), Unconfined compressive strength (UCS), Triaxial test.

1 Introduction

The increasing generation of electrical and electronic waste (e-waste) has become a pressing environmental concern worldwide due to its hazardous nature. E-waste contains heavy metals and toxic chemicals that leach into soil, leading to severe degradation of environmental quality and adversely affecting the engineering properties of soils. In Nigeria, traditional disposal methods have proven inadequate, necessitating the stabilization of contaminated soils. Cement, a widely recognized soil stabilizer, alongside rice husk ash (RHA), a by-product of rice milling, offers a sustainable alternative for improving soil properties for civil engineering applications.

According to Bello et al. [1], soil stabilization involves the treatment of soils to enhance their strength and durability, making them suitable for construction purposes beyond their original capacity. Stabilization and solidification techniques using cement and RHA reduce the leachability of hazardous substances while improving mechanical strength.

Cement contributes by binding heavy metals and hazardous materials into a stable matrix. The hydration of cement produces calcium silicate hydrate (C-S-H) and calcium hydroxide (portlandite), which encapsulate contaminants and reduce their mobility. Additionally, cement raises soil pH, facilitating the precipitation of heavy metals as insoluble hydroxides, thereby reducing potential leaching.

Several studies have confirmed the efficacy of cement in stabilizing heavy-metal-contaminated soils. For example, Conner and Hoeffner [2] found that Portland cement effectively reduces heavy metal leachability. Cement can immobilize metals common in e-waste, such as lead from CRT monitors, cadmium from batteries, and copper from wiring.

The high cost of cement has prompted research into natural materials as partial substitutes. RHA is a pozzolanic material rich in amorphous silica that reacts with calcium hydroxide to form additional C-S-H, enhancing the strength and durability of stabilized soils. Ganesan et al. [3] reported that incorporating RHA into cement-stabilized soils significantly increases compressive strength and reduces permeability. Furthermore, using RHA reduces the demand for cement, thereby lowering carbon dioxide emissions from cement production.

The stabilization mechanism of cement and RHA involves both chemical and physical processes. Chemically, cement hydration products react with RHA to form additional C-S-H, which reduces soil porosity and encapsulates contaminants. Physically, cement and RHA improve soil structure by increasing density and reducing permeability, thus limiting contaminant mobility.

Performance evaluations show that cement and RHA increase the UCS of e-waste soils, indicating improved load-bearing capacity. Olufowobi et al. [4]

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demonstrated that adding 10% RHA and 6% cement significantly enhanced UCS over a curing period. as reported by Makusa [5]. Additionally, Mali et al. [6] showed that cement and RHA combinations significantly reduce heavy metal leachability in contaminated soils.

Environmental benefits include reduced cement usage and effective RHA disposal, thus mitigating pollution from rice milling industries. The combination of cement and RHA presents a promising, sustainable approach for stabilizing e-waste-contaminated soils.

This study investigates the potential of cement and rice husk ash (RHA) as stabilizing agents for e-waste contaminated soils, aiming to enhance both their engineering and environmental properties. The research involves characterizing the physical and geotechnical properties of the soils prior to treatment, determining the optimal proportions of cement and RHA required to improve soil strength and durability, and assessing changes in unconfined compressive strength, California bearing ratio, and compaction characteristics following stabilization. Additionally, the study evaluates the effectiveness of cement RHA treatment in reducing heavy metal leachability, providing insights into environmentally safe and technically viable soil stabilization practices.

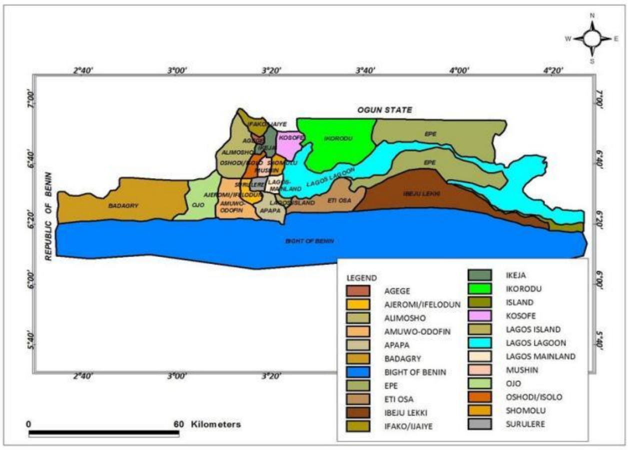

Fig 1: Map of Lagos State showing Ojo Local Government Area

1.1 Geology of Study Area

Lagos State, situated in the southwestern part of Nigeria, exhibits a distinctive geological setting influenced largely by its coastal proximity to the Gulf of Guinea. The region is predominantly characterized by sedimentary formations, coastal plains, lagoons, and an intricate network of creeks. Ojo Alaba, the specific study location, is positioned near the Lagos Lagoon along the Badagry Expressway, approximately 20 km from Lagos city center. It spans several neighborhoods, including Alaba Rago, Alaba Onilu, Alaba Isale Oko, and Alaba Suru. The site lies within the geographic coordinates of latitude 6.4500° N and longitude 3.2000° E.

The area experiences a tropical wet climate, marked by high temperatures and humidity levels throughout most of the year, and two distinct rainy seasons. Given its low-lying topography and proximity to the lagoon, Similarly, CBR values increased with the inclusion of cement and RHA,

Ojo Alaba is highly susceptible to seasonal flooding, exacerbated by insufficient drainage infrastructure. The region is widely recognized as a major hub for international trade, hosting the Alaba International Market, the largest electronics market in Africa—as well as the Lagos International Trade Fair Complex. The area attracts significant commercial activities, particularly in the trade of electrical and electronic equipment, contributing to high volumes of e-waste generation.

2 METHODOLOGY

2.1 MATERIALS

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

2.1.1 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.

2.1.2 Ordinary Portland Cement (OPC)

The cement used was Ordinary Portland Cement (Grade 42.5R), procured from a local supplier at Magodo, Lagos State.

2.1.3 Water

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

2.2 Materials Preparation and Treatment

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 [1].

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

2.3 Experimental Investigations

E-waste contaminated soil was treated with 0–10% cement and tested for compaction, CBR, UCS, and triaxial shear strength following ASTM standards. The results provide a quick assessment of how cement improves the soil's engineering properties.

2.3.1 Compaction Test

The compaction behaviour of the untreated and

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cement-treated soils was evaluated using the Standard Proctor procedure in accordance with ASTM D698. For each cement content, soil–cement blends were compacted in a standard mould at different moisture contents. The dry density–moisture relationship was established by plotting measured dry densities against moisture contents, and the maximum dry density (MDD) and optimum moisture content (OMC) were obtained from the peak of the compaction curve.

2.3.2 CALIFORNIA BEARING RATIO (CBR)

The unsoaked California Bearing Ratio test was conducted following ASTM D1883. Soil–cement mixtures were compacted in CBR moulds at their respective MDD and OMC. After 24 hours of conditioning, the penetration test was performed at a loading rate of 1.25 mm/min. Load–penetration data were used to compute CBR values at 2.5 mm and 5.0 mm penetrations. The higher of the two values was recorded as the unsoaked CBR for each mixture.

2.3.3 UNCONFINED COMPRESSIVE STRENGTH (UCS)

Unconfined compressive strength was determined in accordance with ASTM D2166. Cylindrical specimens (38 mm × 76 mm) were prepared by static compaction at the respective MDD and OMC for each cement content. Specimens were loaded axially at a constant strain rate of approximately 1%/min until failure. The UCS was calculated as the peak axial stress prior to specimen collapse. All UCS values represent uncured strengths.

2.3.4 TRIAXIAL COMPRESSION TEST

Shear strength parameters were obtained from consolidated drained triaxial tests conducted following ASTM D4767. Cylindrical specimens were prepared at MDD and OMC and enclosed in a rubber membrane before being placed in the triaxial chamber. Each specimen was isotropically consolidated under selected confining pressures and subsequently sheared at a constant strain rate such that pore pressure dissipation was ensured throughout loading. From the deviator stresses at failure, Mohr circles were constructed and a linear Mohr–Coulomb failure envelope was fitted to derive cohesion (c) and internal friction angle (φ) for each cement content.

2.3.5 Soil Classification and Physical Description

Particle size distribution and Atterberg limits were determined in accordance with ASTM D422 and ASTM D4318, respectively. Classification followed the AASHTO system. Colour and general soil type were documented through visual inspection. The untreated AL1 soil was classified as A-2-6 and described as a light-brown silty-clayey sand.

2.3.5 DATA QUALITY ASSURANCE

All laboratory tests were performed in triplicate, and the mean values are reported. Testing procedures adhered strictly to relevant ASTM standards. Any deviations from standard requirements were minimized to ensure reproducibility and reliability of results.

3 RESULTS AND DISCUSSION

The findings from the study, as well as the discussions of the results, will be discussed in this section.

3.1 ENGINEERING PROPERTIES OF AL1 E-WASTE SOIL BEFORE TREATMENT

The engineering properties of the AL1 e-waste-contaminated soil prior to any stabilization treatment are summarized in Table I.

Table I: Engineering Properties of AL1 e-waste soil before treatment

PROPERTIES	E-WASTE SOIL SAMPLES (CONTROL)
	AL1
Maximum Dry Density (g/cm^3) Optimum	1.73
Optimum Moisture Content (%)	16.75
California Bearing Ratio (%)	10.78
Unconfined compressive strength (kPa)	127.45
Cohesion (kPa)	20
Angle of internal friction Ө^0	24
Soil Classification	A-2-6
Colour	Light Brown
Soil Type	Silty-Clayey Sand

The findings in Table I presents the properties of the AL1 e-waste soil sample (control), highlighting key characteristics typical of silty-clayey sand, a soil type commonly found in areas with a mixture of fine and coarse particles. The Maximum Dry Density (MDD) is 1.73 g/cm^3 with an Optimum Moisture Content (OMC) of 16.75%, indicating a relatively moderate density and moisture content. This balance between compaction and water content is characteristic of silty-clayey soils, which generally require higher moisture content to achieve maximum compaction [1]. The California Bearing Ratio (CBR) value of 10.78% suggests a poor load-bearing capacity in the natural state, primarily due to the presence of fine particles (clay and silt) that reduce strength under loading [2]. The Unconfined Compressive Strength (UCS) of 127.45 kPa falls within the typical range for silty-clayey soils, attributed to the moderate strength provided by fine particles and moisture retention [3]. The soil exhibits a cohesion of 20 kPa and an internal friction angle (Ɵ) of 24°, indicating reasonable shear strength. This behavior is consistent with clayey soils, where particle interlocking and cohesion contribute significantly to stability [4]. According to the AASHTO soil classification system, the AL1 sample is classified as A-2-6, indicating a silty or clayey sand with fair to poor engineering properties [3]. Additionally, the light brown color suggests the presence of organic content and a fine-grained nature.

3.2 TEST RESULTS FOR E-WASTE SOIL SAMPLES

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AL1 TREATED WITH CEMENT

The engineering properties of AL1 e-waste-contaminated soil after stabilization with varying percentages of cement are summarized in Table II, showing the effects of cement content on compaction, strength, and shear parameters.

The findings in Table II present the results of cement stabilization on e-waste soil and evaluate its suitability for construction purposes. The Maximum Dry Density (MDD) increased from 1.73 g/cm³ for untreated soil to 2.10 g/cm³ at 6% cement content. The observed increase in MDD is attributed to cement particles filling the soil voids, resulting in improved compaction and dry density, consistent with findings by Amadi [1]. Beyond 6% cement content, a decrease in MDD is observed, likely due to the formation of cementitious products leading to particle flocculation and reduced compaction efficiency.

Table II: Summary of all test results for e-waste soil samples AL1 treated with cement

E-waste Soil sample	Cement content	Max. Dry Density (MDD) (g/cm³)	Optimum Moisture Content (OMC) %	CBR Unsoaked (%)	Triaxial Test Deviator Stress σ³ (KN/m²)	Cohesion (KN/m²)	Angle of Friction (Θ)⁰	UCS Uncured (kPa)
AL1	0%	1.73	16.75	10.78	294.89	20	24	127.45
	2%	1.80	16.70	20.42	342.75	16	25	136.34
	4%	1.90	16.20	27.96	408.06	14	25	176.65
	6%	2.10	16.15	30.09	552.56	09	27	210.05
	8%	1.95	15.87	29.95	533.75	12	19	186.80
	10%	1.82	15.39	28.05	515.20	14	18	186.05

The Optimum Moisture Content (OMC) showed a slight decrease with increasing cement content, reducing from 16.75% for untreated soil to 15.39% at 10% cement content. This reduction is attributed to the absorption of moisture by cement during hydration, thereby decreasing the water needed for compaction [1]. The cement also acts as a binder, limiting the soil's water retention capacity.

California Bearing Ratio (CBR) values increased significantly from 10.78% for untreated soil to 30.09% at 6% cement content, indicating enhanced load-bearing capacity. This improvement is due to pozzolanic reactions between cement and soil, forming calcium silicate hydrate (C-S-H) compounds [3]. However, beyond 6% cement content, a slight decline in CBR values was noted, possibly due to disruption of optimal particle arrangement.

The deviator stress (σ_3) and cohesion (c) exhibited notable trends with cement addition. The deviator stress increased from 294.89 kN/m² at 0% cement to 552.56 kN/m² at 6%, indicating improved shear strength. Conversely, cohesion decreased from 20 kN/m² to 9 kN/m² at 6% cement, which could be due to reduced soil plasticity and ductility following cement treatment. This behavior aligns with the findings of Akinmusuru and Akinola, (1999).

The angle of internal friction (Θ) increased from 24° to 27° at 6% cement content, reflecting enhanced interparticle friction. Beyond 6% cement, the angle decreased slightly, possibly due to excessive cement content disrupting the soil matrix.

Unconfined Compressive Strength (UCS) values showed a steady increase with cement addition, rising from 127.45 kPa to 210.05 kPa at 6% cement content. This increase is attributed to the formation of cementitious compounds such as C-S-H and calcium hydroxide. Beyond 6% cement, the UCS plateaued, suggesting that further cement addition did not significantly enhance soil strength.

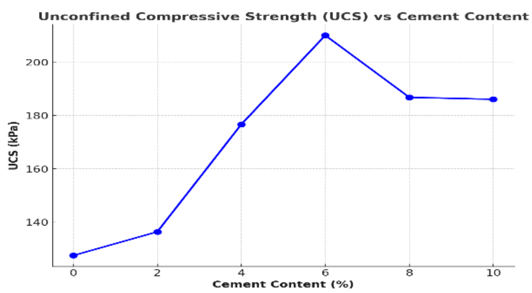

Fig 2: Graph of UCS vs. cement content

The findings in Figure 2 illustrate the variation of UCS with different cement contents in e-waste soil. UCS increased sharply from 0% to 6% cement content, peaking at approximately 210 kPa. 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.

3.3 TEST RESULTS FOR E-WASTE SOIL SAMPLES AL1 TREATED WITH CEMENT AND RHA

The effects of combined cement and rice husk ash (RHA) stabilization on the engineering properties of AL1 e-waste-contaminated soil are summarized in Table III, showing variations in strength, compaction, and shear parameters with different stabilizer proportions.

Table III: Summary of all test results for e-waste soil samples AL1 treated with cement and RHA

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E-waste Soil sample	cement	Rice husk ash (RHA)	Max. Dry Density (MDD) (g/cm³)	Optimum Moisture Content (OMC) (%)	CBR Unsoaked (%)	Deviatior Stress σ³ (KN/m²)	Triaxial Test Cohension (KN/m²)	Angle of Friction (θ)⁰	UCS Uncu (kPa
		0%	1.73	16.75	10.78	583.50	20	24	127.4
		2%	1.75	17.01	14.56	587.40	16	26	132.3
	0%	4%	1.87	17.45	15.60	595.45	14	26	135.4
		6%	2.10	17.60	29.05	625.05	10	28	154.2
		8%	2.05	17.85	22.05	550.30	15	24	129.6
		10%	1.97	18.23	19.45	508.45	13	23	121.3
		0%	1.80	16.70	20.42	342.75	16	25	136.3
		2%	1.87	16.80	27.45	365.75	14	28	127.5
		4%	1.92	16.90	32.05	405.20	11	27	145.0
	2%	6%	2.20	17.25	39.50	485.20	09	29	168.8
		8%	2.12	17.65	33.89	338.45	15	26	152.4
		10%	1.98	17.75	32.54	312.40	14	25	140.8
		0%	1.90	16.20	27.96	408.06	14	25	176.6
		2%	2.18	16.60	31.45	425.62	12	26	186.8
		4%	2.28	16.75	48.25	515.50	11	27	191.9
	4%	6%	2.89	17.05	60.45	583.50	09	29	198.4
AL1		8%	2.15	17.21	50.56	567.40	15	26	182.4
		10%	2.00	17.85	42.60	525.45	10	24	180.6
		0%	2.10	16.15	30.09	552.56	09	27	210.0
		2%	2.15	16.25	30.56	547.40	13	26	211.6
	6%	4%	2.22	16.45	40.60	575.45	15	26	221.9
		6%	2.75	16.70	59.05	615.05	07	28	276.8
		8%	2.05	16.85	42.05	540.30	16	24	256.0
		10%	1.98	17.15	35.45	518.45	13	22	231.9
		0%	1.95	15.87	29.95	533.75	12	19	186.8
		2%	2.05	15.90	37.45	544.75	14	20	187.5
	8%	4%	2.13	16.20	42.05	575.20	18	22	194.0
		6%	2.64	16.35	49.50	595.20	11	26	218.8
		8%	2.30	16.40	33.89	538.45	15	24	182.4
		10%	2.13	16.45	32.54	532.40	14	22	180.8
		0%	1.82	15.39	28.05	515.20	14	18	186.0
		2%	1.87	15.60	31.45	525.62	16	22	196.8
	10%	4%	1.97	15.75	38.25	535.50	19	24	198.9
		6%	2.13	16.05	40.45	583.50	11	28	232.4
		8%	2.04	16.21	30.56	567.40	15	24	211.4
		10%	1.94	16.85	22.60	555.45	13	21	190.6

The findings in Table III illustrate the geotechnical properties of the e-waste soil (AL1) treated with various combinations of cement and rice husk ash (RHA). MDD exhibited a general increase with increasing cement and RHA contents, peaking at 2.75 g/cm³ at 6% cement and 6% RHA. This improvement is attributed to the pozzolanic reaction between cement, RHA, and soil, forming binding compounds like C-S-H and calcium aluminate hydrates (C-A-H) [1]. At 10% RHA, a slight reduction in MDD was observed, likely due to particle flocculation reducing compaction efficiency.

The OMC increased slightly with rising RHA content, reaching 18.23% at 10% RHA and 0% cement, due to the high-water absorption capacity of RHA. Although cement also absorbs water during hydration, the combined stabilization effect minimizing overall water demand at lower RHA contents.

CBR values improved significantly with combined cement and RHA treatment, peaking at 60.45% at 6% cement and 6% RHA. This enhancement is linked to the formation of strong cementitious compounds that resist deformation under load. At higher RHA contents, CBR values slightly decreased, indicating reduced soil compaction efficiency.

Deviator stress (σ_3) also increased with stabilization, reaching 615.05 kN/m² at 6% cement and 6% RHA. The increased shear resistance is due to the improved particle interlocking from cementitious bond formation [6]. However, higher RHA contents (8% and above) led to a decrease in deviator stress, likely due to brittleness induced by over-stabilization.

Cohesion (c) decreased with cement addition but stabilized with RHA inclusion, with the lowest value of 7 kN/m² recorded at 6% cement and 6% RHA. The decrease is associated with a reduction in plasticity and increased soil stiffness resulting from cement and RHA reactions.

The angle of friction (θ) reached a maximum of 29° at 6% cement and 6% RHA, suggesting improved interparticle friction. Beyond this point, a slight decrease was observed, potentially due to excessive stabilizer content disrupting soil structure.

UCS values showed a significant increase with cement and RHA content, reaching 276.84 kPa at 6% cement and 6% RHA. This result reflects the beneficial effects of combined pozzolanic activity and matrix strengthening [6]. However, at RHA contents above 6%, UCS values declined slightly, likely due to over-stabilization effects leading to brittleness.

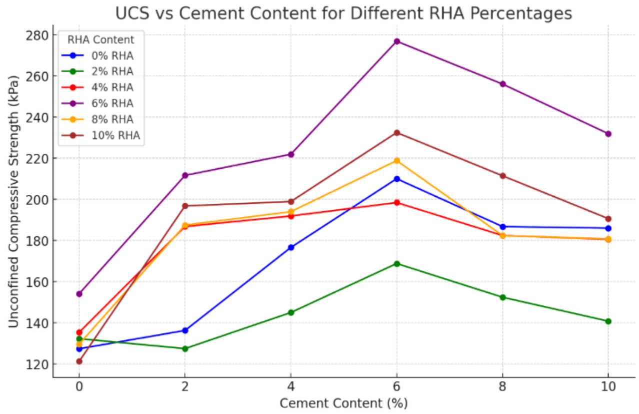

Fig 3: Graph of UCS vs. cement content and RHA

The findings in Figure 3 present 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 [8]. However, excessive RHA beyond 6% contributed to a slight decline in UCS, again attributed to the formation of brittle soil structures.

4 ENVIRONMENTAL IMPACT

The stabilization of e-waste contaminated soils enhances the mechanical properties of the soil, making it more suitable for construction applications while reducing the need for excavation and disposal of contaminated soils, thereby mitigating environmental degradation [1]. The treatment of soils with cement and rice husk ash (RHA) helps immobilize heavy metals and other toxic substances present in e-waste, consequently minimizing the leachability of contaminants and reducing the risk of groundwater and soil pollution [2]. Additionally, RHA, a byproduct of rice milling, is often discarded as waste; its use in soil stabilization promotes sustainable waste management practices by recycling agricultural residues and reducing the environmental impact associated with waste disposal [3]. Considering that cement production is highly energy-intensive and a significant contributor to CO_2 emissions, incorporating RHA into cement-based stabilization treatments helps reduce the overall carbon footprint by partially replacing cement

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with RHA.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions were made from experimental research work.

1. The control soil sample AL1, classified as silty–clayey sand, exhibits moderate compaction and strength characteristics which, in its natural state, are inadequate for engineering applications requiring high load-bearing capacity and durability.
2. Baseline California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and shear strength values indicate that stabilization is necessary to improve the soil's engineering performance.
3. Cement stabilization significantly enhances the geotechnical properties of the soil, including Maximum Dry Density (MDD), CBR, deviator stress, and UCS.
4. An optimal cement content of 6% was identified, at which peak compaction, load-bearing capacity, shear strength, and compressive strength were achieved.
5. Cement contents exceeding 6% resulted in a marginal reduction in mechanical performance, indicating that excessive cement addition may negatively affect soil behavior.
6. Combined stabilization using cement and rice husk ash (RHA) further improves the engineering properties of the soil compared to cement-only stabilization.
7. The optimum combined stabilization was achieved at 6% cement and 6% RHA, producing maximum values of MDD, CBR, deviator stress, and UCS, along with a favorable balance between cohesion and angle of internal friction.
8. Increased stabilizer contents beyond the optimal range led to a decline in geotechnical performance, confirming the existence of an optimal stabilization threshold.
9. The improved cohesion and internal friction angle contribute to enhanced stability and erosion resistance, particularly under dynamic loading and variable environmental conditions.

5.2 RECOMMENDATIONS

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

1. The untreated AL1 soil should not be used directly for load-bearing engineering applications without prior stabilization.
2. Cement stabilization at an optimum content of 6% is recommended for improving the strength and durability of the soil where single-stabilizer treatment is preferred.
3. For enhanced performance, combined stabilization using 6% cement and 6% rice husk ash (RHA) is recommended, particularly for road subgrade and embankment applications.
4. Stabilizer contents exceeding the identified optimum levels should be avoided, as over-stabilization may reduce mechanical efficiency and increase material costs.
5. The stabilized soil is suitable for applications requiring improved load distribution, reduced deformation under traffic loads, and increased resistance to shear and erosion.
6. Future studies should evaluate long-term durability, moisture susceptibility, and field-scale performance of cement–RHA stabilized soils under varying environmental and loading conditions.

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