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Critical state characteristics of lateritic soils treated with rice husk ash as subgrade soil

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HIGHLIGHTS

- This study examined critical state characteristics of two lateritic soils treated with rice husk ash as subgrade soils.
- Lateritic soils and rice husk ash were characterized.
- California bearing ratio and drained triaxial tests were done on treated soils to find critical state parameters.
- The critical state parameters were compared with previous values to predict treated soils' behavior during deformation.

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ABSTRACT

The behavior of subgrade materials plays a pivotal role in determining the longevity of transportation infrastructure. More often, interests had been focused on the mechanical behavior of treated soils prior to the failure stage, while the critical state conditions had received very little attention. This study focused on the critical state characteristics of two distinct lateritic soils (Sample 1, non-plastic and Sample 2, plastic) which were treated with rice husk ash (RHA). The chemical composition of the rice husk ash was examined using X-ray fluorescence. The two natural soils were characterized, and the X-ray diffraction technique was used to identify the soil minerals. The lateritic soils were subjected to varying percentages of rice husk ash treatment, which ranged from 0-21% at 3% intervals. The experiments on treated soils were compaction, California bearing ratio (CBR), and shear strength test. For both samples, the maximum dry density was reduced while the optimum moisture content increased with the addition of RHA from 0-21%. The maximum deviator stress attained values of 941.8k N/m^2 and 769.06 kN/m^2 at the application of 9% and 12% RHA for Samples 1 and 2, respectively. The CBR of Sample 1 was reduced by 81% with the addition of 21% RHA, while that of Sample 2 increased by 14.22% with the addition of 6% rice husk ash. The critical state parameter (M) for Sample 1 increased by 5.08% at the addition of 9% RHA, while that of Sample 2 increased by 13.09% at 12% RHA. The values are in the same range with some granular and unsaturated soils.

1. Introduction

Rice is one major staple food worldwide, and its production rate has soared astronomically. The global rice production in 2020 was estimated at 499.31 million metric tonnes. For every 1kg of rice produced, approximately 0.28 kg of rice husk is generated [1]. Consequently, the massive generation of rice husks could pose a potential environmental risk. There should be deliberate efforts to utilize the enormous rice husk for beneficial economic uses to guarantee adequate waste handling mechanisms. However, the importance of rice husk cannot be overemphasized because it has been used from different perspectives that benefit humanity. Rice husk has been a source of fuel for heat [2-4] and electrical energy [5,6]. It has also been used for the absorption and removal of contaminants from wastewater [7,8] and as construction materials in different parts of the world like Asia [9-12] and Africa [13-15]. In most cases, rice husk ash has shown potentially good qualities as a good construction material, such as improving soil's geotechnical and strength characteristics. Rice husk ash is not the only agricultural residue utilized for construction work. There have been some other examples, such as palm husk ash [16], palm bunch ash [17], Bagasse ash [18-20]

In the Tropics, it is common to encounter lateritic soils or use them as fill material during construction. Lateritic soils are locally available and relatively cheaper than most construction materials. Moreover, lateritic soils are very suitable as construction materials for civil engineering projects because they are almost non-swelling. However, they can be very problematic in some cases, especially when active clay minerals are present. In such circumstances, removing the problematic

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soil and replacing it with another lateritic soil from another deposit as fill material might be the best option. Lateritic soils in the treated form had been used as subgrade soils [21-23], road pavements [24-26], earth embankments for dams [27,28] or waste containment [29-31], foundation soils [32-34] and cement blocks [35-37].

A soil's critical state is the soil's condition under stress beyond failure. It is imperative to understand any soil's critical state condition. This will enable the Geotechnical Engineer to predict the soil behavior when the maximum stress the soil can bear is exceeded. Critical state conditions of soils were commonly useful in studying saturated and unsaturated soils. The behavior of drained and undrained conditions of some soils had been effectively evaluated and predicted using critical state parameters of the soils by [38]. Discoveries have also shown that the critical state characteristics could play a significant role in the suction of overconsolidated soil [39], unsaturated soils [40-42] and soil under coupling stress [43]. Additionally, it was found by the critical state concept that soil moisture content and density could influence the mode of failure [44]. Critical state soil mechanics have helped describe the deformation of various feeble rocks like chalk, bonded mudrocks, carbonates, sandstones, and sands [45,46]. Most efforts in studying critical state characteristics of soils had been commonly concentrated on untreated soils. In the case of treated soils, the interests of most researchers are limited to the maximum stress the soil can withstand before failure. The critical state characteristics of treated soils have received very little attention. However, few attempts have been made to study the critical state conditions of treated soils using a palm kernel shell ash and rubber mixture [47] and [48] respectively.

The critical state characteristics of soils treated with rice husk ash have never been examined. Therefore, this study focused on determining the critical state parameters of lateritic soils (a measure of critical state characteristics) treated with rice husk ash as subgrade soil to compare their characteristics with other soils.

2. Materials and methods

The lateritic soils used for the investigation in this study were collected with the disturbed sampling method from the Obinze lateritic soil deposit with latitude N5˚22'45.34" and longitude E6˚58'10.45" which was designated as sample 1, while another from Nekede soil deposit on latitude N5˚26'15.20" and longitude E7˚01'47.30" designated as sample 2, both located in Owerri West Local Government Area of Imo State, Nigeria. The soil mineralogy was identified using the X-ray diffraction technique. The tests for characterization of the lateritic soil samples, like the consistency limits, Particle size distributions, and specific gravity, were executed in accordance with [49,50] and [51] respectively. The rice husk was collected from a rice mill in Abakiliki Local Government Area in Ebony State, Nigeria. The rice husk was incinerated to ash under controlled combustion in a furnace at the temperature of 60 ℃ and then sieved through a 0.075mm sieve. The chemical composition of the rice husk ash was determined using the X-ray fluorescence technique. The photograph of the rice husk ash is shown in Plate 1.

Plate 1: Photograph of rice husk ash

The soil samples were treated with rice husk ash (RHA) from 0-21% at 3% intervals by weight of the dry soil. A compaction test was conducted on the treated soil samples to determine the optimum moisture content for each dosage. The British Standard Light was used for the compaction test in which 27 blows were given to each of the 3 layers by a 2.5 kg rammer. The optimum moisture contents obtained were used to prepare the samples for California Bearing Ratio (CBR) and the drained triaxial test by mixing the given dosages of rice husk ash with the lateritic soil and then adding the pre-determined optimum moisture content. The CBR specimens were prepared unsoaked using compaction energy equivalent to the British Standard Light, in which three layers of the soil sample were placed in the mold, and 2.5 kg rammer was used to give 62 blows evenly on each layer. The critical state characteristics of the soil samples were evaluated using a consolidated drained triaxial test to measure the critical state parameters of the soil at different percentages of rice husk ash.

Equations 1 through 3 present the relevant equations for the critical state parameters [52], and the description of the functions in the equations are in the list of notations

$$\rho' = T - U \tag{1}$$

$$v = \Gamma - \lambda \ln\rho' \tag{2}$$

$$q = M\rho' \tag{3}$$

The critical state parameters were computed by plotting the Critical State Line (CSL). The slopes of the curves and the intercept on the Y-axis were obtained as required to represent the critical state parameters.

3. Results and discussion

This section presented the results obtained in this study and also the discussions that supported the results. The results were presented in tables and figures in the following sub-sections.

3.1 Characterization of soil samples

Table 1 presents the index properties, soil classifications, specific gravity, consistency limits, and particle size analysis for both lateritic soils. The specific gravity of samples 1 and 2 were 2.55 and 2.49, respectively. For most soils, the specific gravity falls between 2.65-2.8 [53]. However, the values of specific gravity of the soils slightly fell below the range, which could have resulted from high organic content. The liquid and plastic limits of sample 1 could not be determined because the soil was observed to be non-plastic, making it difficult to roll or mold.The fine portion of the soil is predominantly silty and lacks adequate clay mineral content to enhance soil plasticity.Top of Form Sample 2 has a liquid limit of 33.1% and a plasticity index of 18.3%. The particle size analysis results show that both samples' percentage of passing Sieve Number 4 was approximately 100%. Still, sample 2 has a higher percentage of fines because it is 25.74% finer than sieve Number 200 (0.075mm) compared to sample 1, which is 12.83% finer.

These index properties and particle size distribution were crucial in classifying the soil samples. [54] grouped soil samples 1 and 2 to be among A-3 and A-2-6 soils, respectively. Also, [55] classified sample 1 as silty-sand (SM) while sample 2 was clayey-sand (SC) of low plastic clay. The [54] rated the quality of the soil groups for road construction works according to the soils' consistency indices and particle size distribution. Moving from the left to the right of the [54] indicates a continual reduction in soil quality. Soil samples 1 and 2 are found to be more to the left-hand side of the table. This showed that the two soil samples are suitable for road construction work from the point-of-view of consistency limits and particle size distribution. Figures 1 and 2 show the X-ray diffraction patterns of soil samples 1 and 2. Quartz and orthoclase are commonly occurring non-clay minerals found in Sample 1 up to 83%, and the non-clay minerals are virtually inert to the presence of water. The clay mineral content was just 17% of the overall mineral content, which is not enough to cause the soil to be plastic, confirming the soil's non-plastic nature. On the other hand, Sample 2 contains a higher proportion of clay minerals like kaolinite, muscovite, illite, and vermiculite, up to 42.2%. The clay mineral structures change as the moisture content varies. Clay minerals are somewhat active in the presence of water, though to various degrees. Clay minerals have plate-like structures and can absorb water molecules to expand depending on the type of bonding between their basic units. The films of water encompassing the soil particles and the electrochemical forces interact at the particle-water interface [56]. The plasticity and consistency indices in soil Sample 2 could be attributed to these clay minerals.

Table 1: Summary of index properties and soil classifications

Sample Number	Specific Gravity	Atterberg Limit			Sieve Analysis							USCS	AASHTO
		LL	PL	PI	D10	D30	D60	CC	CU	% Passing sieve 4	% Passing sieve 200		
		%	%	%	mm	mm	mm						
1	2.55	NP	NP	NP	0.001	0.26	0.43	430.0	157.2	99.86	12.83	SM: Silty Sand	A-3
2	2.49	33.1	14.8	18.3	0.007	0.12	0.14	56.9	4.9	100.0	25.74	SC:Clayey Sand	A-2-6

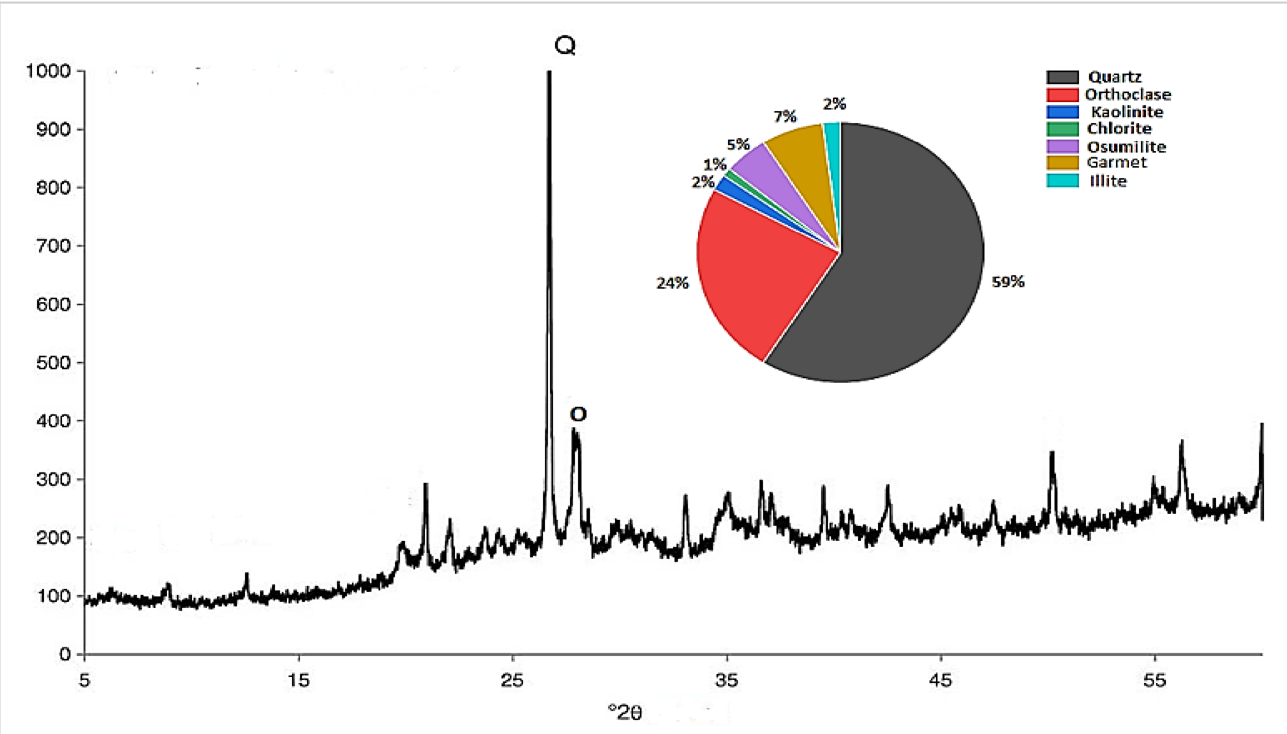

Figure 1: X-Ray diffraction pattern for soil sample 1

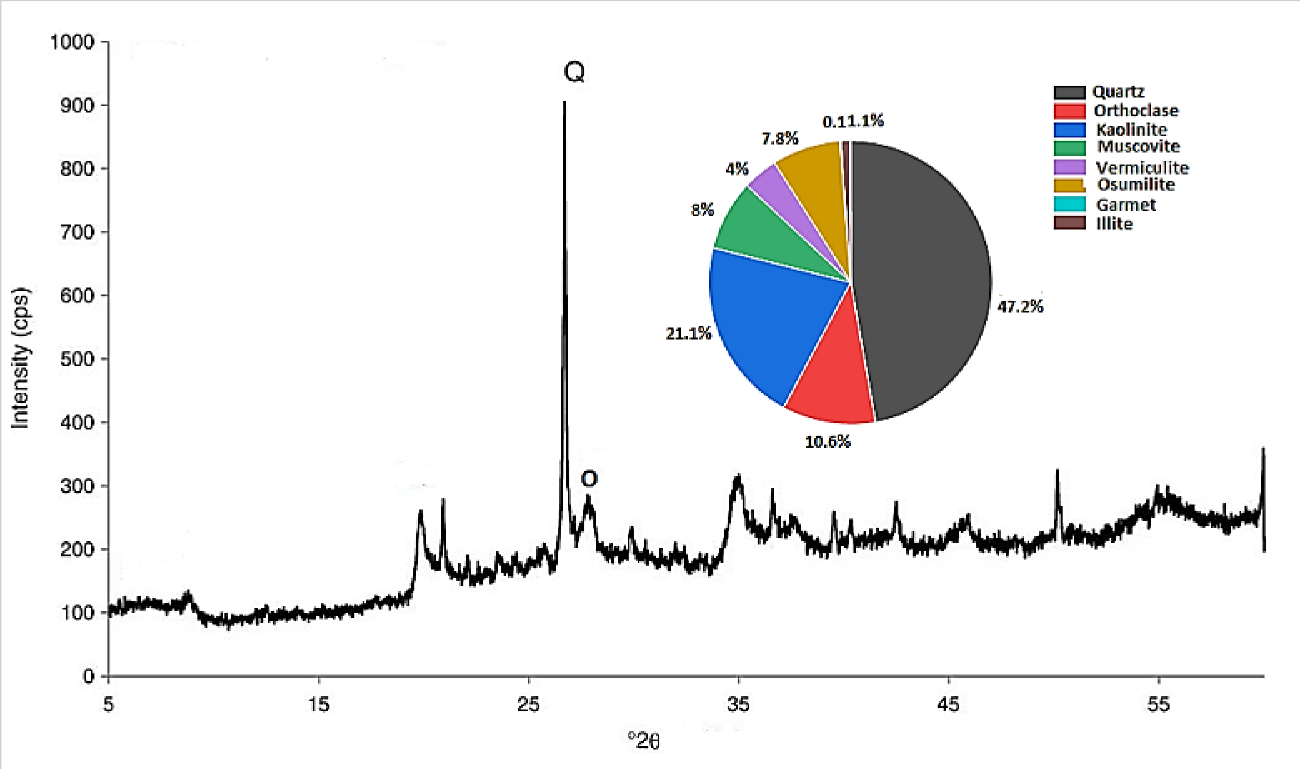

Figure 2: X-Ray diffraction pattern for sample 2 soil

3.2 Characterization of rice husk ash

Figure 3 and Table 2 presented the X-ray fluorescence results for the rice husk ash constituents (RHA). The results show that RHA contains a very high silica content of about 83.64%. The requirements for materials to be regarded as pozzolanic materials have been established by [57], which stipulates that such material must contain a minimum of 70% for SiO_2 + Al_2O_3 + Fe_2O_3 and a maximum value of 4% for SO_3. In the results of the constituents of RHA, SiO_2 + Al_2O_3 + Fe_2O_3 gave a value of 85.65%, while SO_3 had an insignificant value of 0.61%. This confirms that RHA is a good pozzolanic material for civil engineering works.

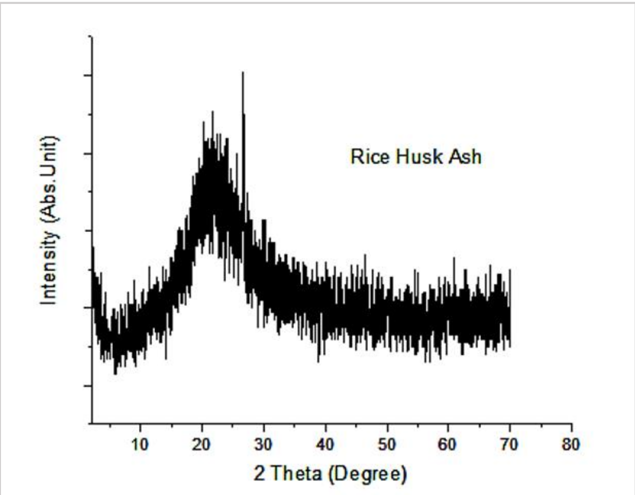

Figure 3: X-Ray fluorescence intensity peaks of rice husk ash

Table 2: Showing the constituent materials of RHA from X-ray fluorescence

S/No	Constituent	Composition (%)
1	SiO_2	83.64
2	V_2O_5	0.002
3	Cr_2O_3	0.01
4	MnO	0.33
5	Fe_2O_3	1.05
6	CO_3O_4	0.003
7	NiO	0.001
8	CUO	-----
9	Mb_2O_3	0.04
10	P_2O_5	5.29
11	SO_3	0.61
12	CaO	2.61
13	K_2O	3.71
14	Al_2O_3	0.92
15	TiO2	0.14
16	Ag_2O	0.001
17	Cl	1.529
18	ZrO_2	0.002
19	SnO_2	0.08

3.3 Compaction characteristics of lateritic soils treated with RHA

The compaction results for the maximum dry density and optimum moisture content are shown in Figures 4 and 5, respectively. The results revealed important trends as the rice husk ash content increased from 0-21%, the optimum moisture content rose from 8.8-18.7% and 11.5-18.8% for Samples 1 and 2, respectively, while the maximum dry density dropped from 2.04–1.63 g/cm^3 and 1.97-1.66 g/cm^3 for Samples 1 and 2 respectively. The rise in the optimum moisture content with an increase in rice husk ash content could be attributed to the expansion of the surface area by the utterly fine ash particles, which necessitated higher moisture content to cover their surface sufficiently. Conversely, the drop in maximum dry density as ash content increased was likely due to the inherent lower density of the ash material relative to the soil. This is because as RHA content increases, the soil particles are partially replaced by the ash fines in a given volume of treated soil, consequently reducing the density continually. Furthermore, in Figures 4 and 5, it is evident from the graphical presentation that the decrease in maximum dry density was more pronounced in sample 1 compared to sample 2. This disparity can be attributed to the coarser texture of sample 1 and the relative fineness of sample 2. Coarse-grained soils attain higher maximum dry densities than finer soils. The more the ash replaced the coarser soil particles, the quicker the density drops compared to finer soil.

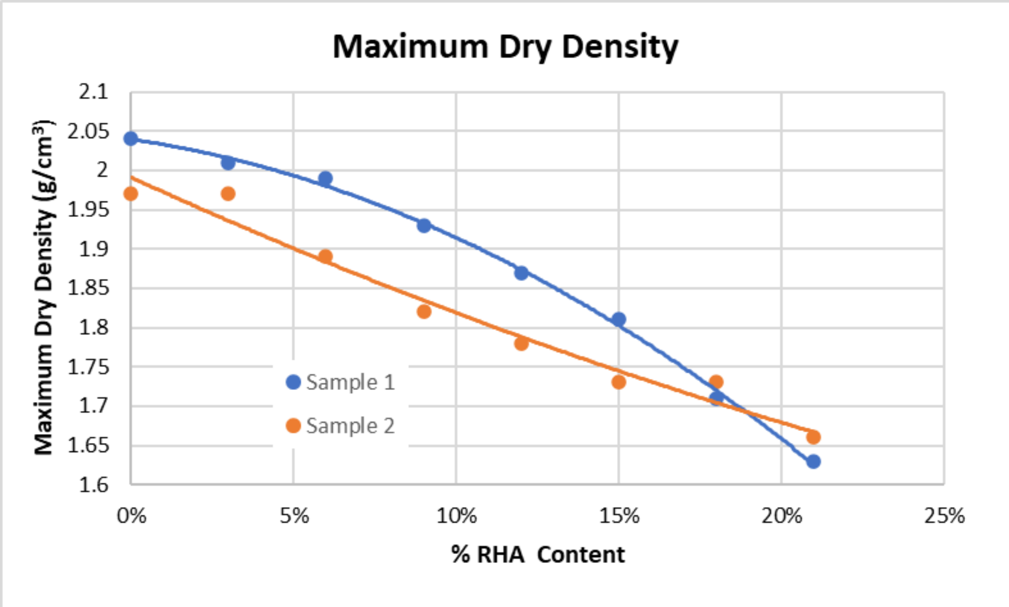

Figure 4: Variations of maximum dry density with percentage RHA content

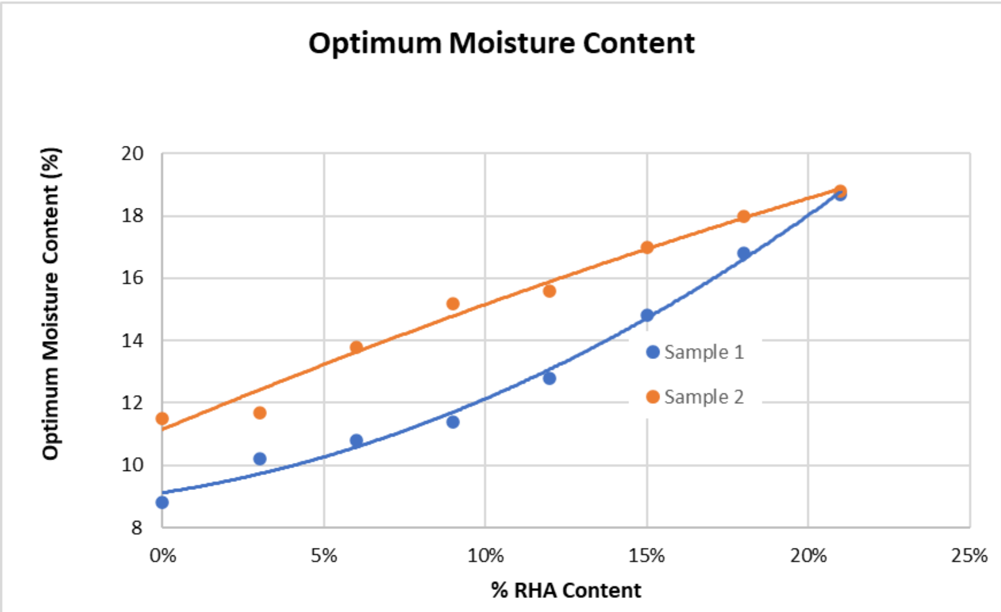

Figure 5: Variations of optimum moisture content with percentage RHA content

3.4 Strength characteristics of lateritic soils treated with RHA

3.4.1 California bearing ratio test (CBR)

The relationships of CBR of soil Samples 1 and 2 and RHA contents are presented in Figure 6.The test results for CBR reveal distinct patterns for the two samples. Sample 1 showed a decrease in CBR from 49.3-9.37% as the RHA content increased from 0-21%, which is contrary to the usual trend [13-15], although best results achieved were when used as admixtures to binders. This reduction trend in CBR could result from the inert nature of soil because of the lack of clay minerals, which could have supplied the compounds required for a pozzolanic reaction to produce cementitious compounds. Rather, the rice husk ash caused a dilution effect, in which the added RHA to lateritic soil reduced the concentration of soil particles and, consequently, the lesser the load-bearing particles in terms of resistance to penetration within the soil-ash mixture. Additionally, the alteration in the distribution of particle sizes may occur due to the addition of RHA, in which the finer RHA particles potentially fill the voids between soil particles, diminishing the interlocking effect and consequently producing a lower CBR value.In contrast, Sample 2 initially experienced a slight increment in CBR from 21.44-24.49% as RHA content increased from 0-6%, which was also followed by a gradual decrease in CBR from 23.02-18.43% as RHA content increased from 9-21%. The initial rise in CBR value was likely because of the high silica content (83.64%), as shown in Table 2, which reacts with calcium compounds in the soil to form more hydrated calcium silicate compounds. These hydrated calcium silicate compounds are cementitious, improving the soil particles' binding and leading to a higher CBR value. The reduction in CBR for both samples can be attributed to the excessive content of RHA. During sample testing, it was also observed that the soil exhibited a low resistant effect to penetration at very high RHA content, which may contribute to the lower CBR observed at high ash content in Sample 2. Notably, the optimum RHA content for Sample 2 appears to be 6%, as CBR values declined below this threshold.

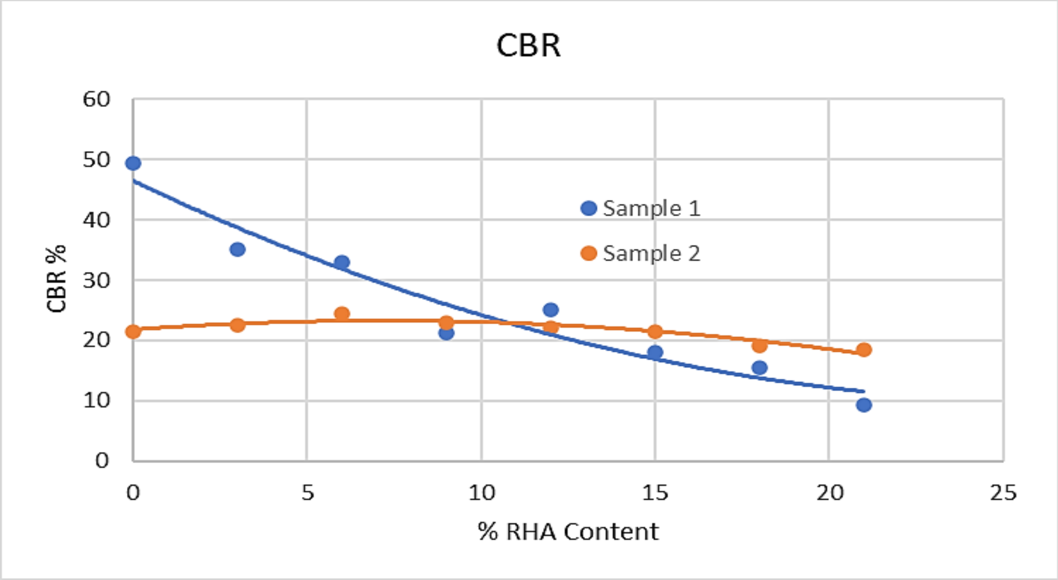

Figure 6: Variations of CBR with increase in RHA contents

3.4.1 Shear strength test

The results of the shear strength characteristics, like maximum deviator stress and residual deviator stress, are presented in Figures 7 and 8, respectively. From Figures 7 and 8, the maximum deviator stress increased to a peak value of 941.8 kN/m^2 as the RHA content increased to about 9% for sample 1 and 769.06 kN/m^2 at 12% RHA content for sample 2. Then, it reduced to 577.2 KN/m^2 at 21% RHA content for sample 1 and 634.26 kN/m^2 at 21% for sample 2. Sample 1 showed a higher initial value of 857.20 kN/m^2 at 0% RHA content, and sample 2 gave a 601.42 kN/m^2 at 0% RHA content. This could be attributed to the higher internal shear resistance of the particles in sample 1 than in sample 2, but the rate of reduction in strength when the percentage of RHA was increased was higher in sample 1 than in sample 2. The results for residual deviator stress showed a similar trend. The improvement in the deviator strength of the soil could also be attributed to the pozzolanic reactions between RHA and the soil's components, which increased the binding effect, as mentioned earlier. This caused the cohesion and, ultimately, the shear strength of the treated soil to increase.

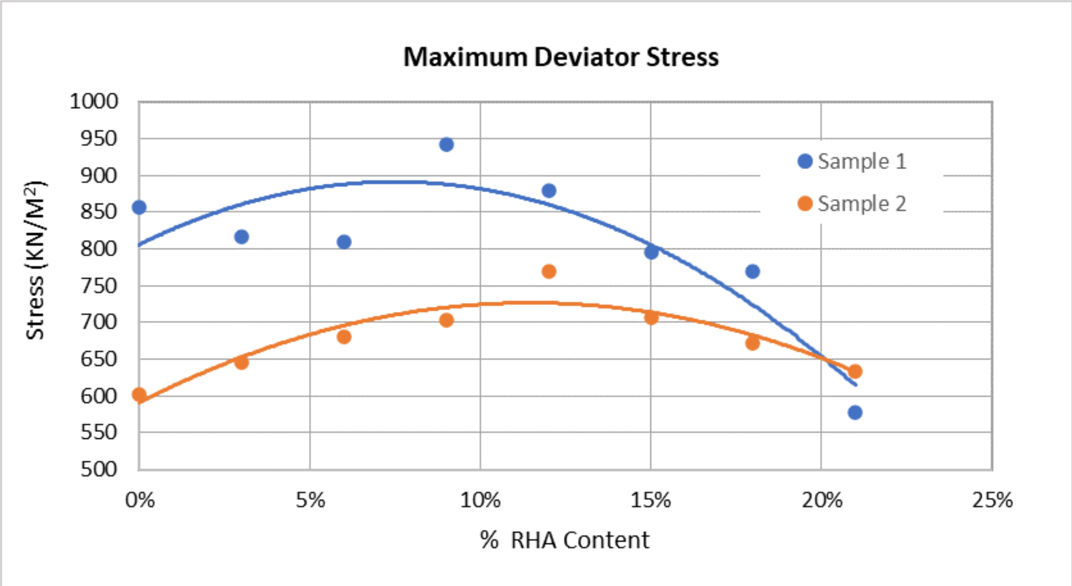

Figure 7: Graphs of maximum deviator stress against % RHA content

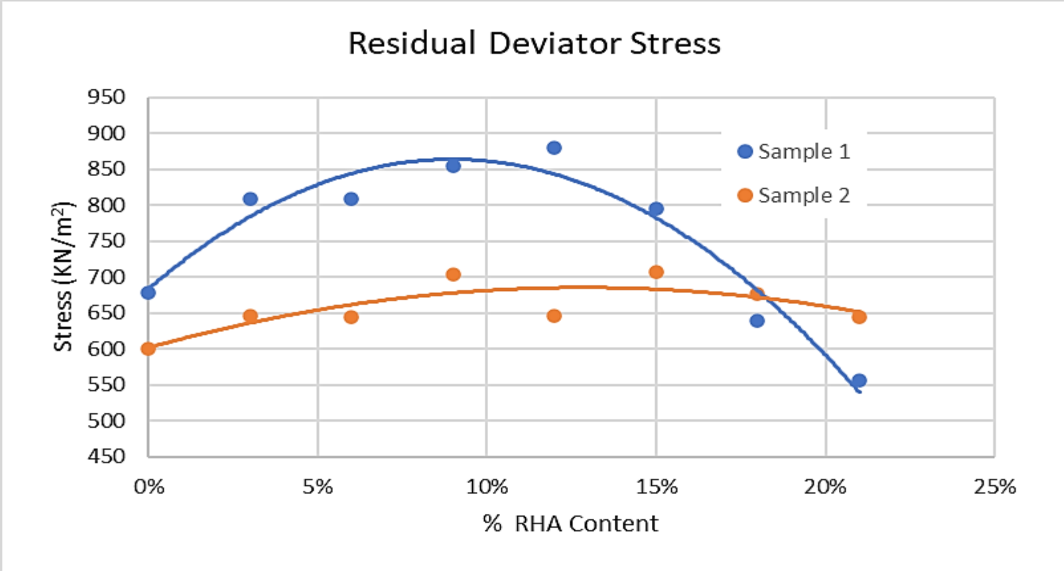

Figure 8: Graphs of residual deviator stress against % RHA content

3.5 Critical state parameters of untreated and treated soils

The plots for the critical state lines of the two soils are shown in supplementary file 1-32, and the summary of the critical state parameters is also presented in Table 3. From the results, the values of the critical state parameter "M" which is the slope of the shear stress-effective stress plots at the critical state of sample 1, increased from1.7427-1.8313 when the RHA content increased from 0-9% and then decreased to 1.471 with increased in rice husk ash content up to 21%. Also, the value of 'M' for sample 2 increased from 1.5228-1.7222 with an increase in rice husk ash content from 0-12% and then decreased to 1.6179 with an increase in rice husk ash content up to 21%. The trend of the results for the 'M' value for both soils had a similar trend with a slight difference, though it was found that sample 1 had higher values of 'M,' which ranged from 1.831 to 1.471 compared to sample 2, which ranged from 1.72 – 1.522. This difference may be attributed to the texture of the two samples. Sample 1 has a lesser content of fines, which will give room for the RHA to fill up the void spaces and have more reaction with the soil particles, and this reaction causes a binding effect on the soil particle through its pozzolanic characteristics. Meanwhile, Sample 2, with its higher fine content, gives less space for the interaction of the RHA with the soil, yielding a lower value of "M."

Table 3: Summary of values critical state parameters of treated soils

	λ		Γ		M	
% RHA Content	**Sample 1**	**Sample 2**	**Sample 1**	**Sample 2**	**Sample 1**	**Sample 2**
0	0.001	0.0151	1.2434	1.3097	1.7427	1,528
3	0.0034	0.0109	1.1999	1.3004	1.6981	1.5912
6	0.0053	0.0086	1.2621	1.3203	1.7034	1.6217
9	0.0038	0.0192	1.289	1.4235	1.8313	1.6975
12	0.0045	0.0134	1.3163	1.4082	1.7484	1.7222
15	0.0065	0.0222	1.3643	1.4883	1.7097	1.6765
18	0.0118	0.0191	1.4555	1.4524	1.6963	1.6819
21	0.0236	0.0152	1.5835	1.481	1.471	1.6179

Comparing the values of the critical state parameters (M) to the values obtained from the previous studies, [42] got M between 0.178 and 0.82 for lateritic soil treated with palm kernel husk ash; [58] obtained values around 1.1 for porous sandstones; [59] got values between 0.42 and 0.7 for tire-soil mixture; [60] found values around 1.2 for consolidated soil and [61] got values between 0.813 and 0.885 for untreated lateritic soil. In view of the preceding, it can be deduced that the values of "M" obtained for the two lateritic soils in this study are somewhat higher. However, the "M" values are still in conformity with some previous studies like [62] which obtained an "M" value of 2.0 for granular soils that underwent dilation, and [63] that got values of up to 2.01 for unsaturated soil. These higher values of "M" indicated that the soil becomes stiffer and less compressible due to the effects of RHA, including pozzolanic reactions and improved cohesion. [63] suggested that a steeper "M" slope indicates that the soil can withstand higher stresses with less volume change.

The critical state parameters "λ" and "Γ" are the slopes and intercepts of the critical state lines of the specific volume-effective stress plots, respectively. The critical state parameter "λ" for sample 1 increased from 0.001-0.026, whereas sample 2 fluctuated from 0.0151-0.0152 as the rice husk ash content increased from 0-21%. The critical state parameter "Γ" for sample 1 increased from 1.2434-1.5835, and that of sample 2 increased from 1.3097-1.481 with the increase in rice husk ash content from 0-21%. The increments in the values could result from the pozzolanic reactions between the rice husk ash and soil components, which enhanced the shear strength and reduced compressibility. Comparing the two samples, the values of λ and Γ increased as the amount of fines (RHA content) increased, and their initial values of the critical state parameters corresponded to the same range as that of sand. The trend conforms with [64], where the critical state parameters (λ and Γ) of sand matrix soil increased with the fine content, which ranged from 0 .062 – 0.160 for λ and 1.732 to 2.431 for Γ. Other studies like [52],[65,66] all had values in the same range with the values of "λ" and "Γ" for sand and sand fine matrix. Therefore, the deformation pattern of the lateritic soils treated with rice husk ash under wheel load when used as a subgrade soil would be like that of sand or sand fine matrix.

Never mind that the rice husk ash did not show much significant improvement on some of the strength properties like California bearing ratio, and even though there is a decrease in soil sample 1, the slight application of rice husk ash (optimum content level) to the two soils especially for subgrade purposes is a good discovery. The California bearing ratio requirement for subgrade soils is usually any value above 10-15%. For soil sample 1, the California bearing ratio was more than 49%, while for soil sample 2, it was about 21% and increased slightly at the application of a small dosage of rice husk ash. Therefore, the addition of a small content of rice husk ash would be beneficial to the two soils because the study showed that the presence of rice husk ash improved their critical state characteristics and, therefore, would help the soils to resist deformation in case the critical state of the soil is attained under wheel loads to avoid quick development of potholes on the road pavements.

4. Conclusion

In conclusion, the study of the critical state of two lateritic soils treated with rice husk ash (RHA) as a subgrade material has provided valuable insights into these soils' engineering properties and performance. The key findings and conclusions of this study can be summarized as follows:

1) The lateritic soils 1 and 2 were rated silty sand (SM) and Clayey sand (SC) in the Unified Soil Classification System, while the AASHTO rating system referred to them as A-3 and A-2-6 respectively.
2) Sample 1 mainly contains non-clay minerals (quartz and orthoclase) with slight clay minerals like kaolinite, chlorite, osumilite, garnet, and illite. In contrast, Sample 2 contains substantial amounts of non-clay minerals (quartz and orthoclase) and substantial quantities of clay minerals like kaolinite, muscovite, vermiculite, osumilite, garnet, and illite.
3) Rice husk ash was also confirmed as a good pozzolanic material.
4) For samples 1 and 2, the maximum dry density was reduced while the optimum moisture content increased with the addition of rice husk ash from 0-21%.
5) For sample 1, the California bearing ratio was reduced by 81% at the addition of 21% rice husk ash, while sample 2 increased by 14.22% at the addition of 6% rice husk ash.
6) The maximum deviator stress attained maximum values of 941.8 kN/m^2 and 769.06 kN/m^2 when applying 9% and 12% rice husk ash for Samples 1 and 2, respectively.
7) The critical state parameter (M) for Sample 1 increased by 5.08% at the addition of 9% rice husk ash, while that of Sample 2 increased by 13.09% at 12% rice husk ash, and the values were of the same range with some granular soils and unsaturated soils.
8) The critical state parameter (λ) for Sample 1 increased by 96.15%, while that of Sample 2 did not show any significant change with the addition of 21% rice husk ash. Also, the critical state parameter (Γ) increased by 27.35% and 13.08% with the addition of 21% rice husk ash for Samples 1 and 2, respectively. These values were in the same range as some sand and fine sand matrices.
9) This study confirms that the critical state conditions of treated soils are also measurable, like the untreated soils, and aids in making informed decisions about subgrade stabilization in road construction projects, leading to more efficient and sustainable transportation networks.

List of Notations

ρ' = Effective stress at a critical state
T = Total stress at critical state (The sum of the confining pressure and the deviator stress)
U = Pore water pressure at a critical state
v = Specific volume at a critical state
q = Shear stress at a critical state
λ, Γ, and M = Constants (Critical state parameters)

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Author contributions

Conceptualization, Chibundu Enyinnia and Ugochukwu Okonkwo; data curation, Chibundu Enyinnia.; formal analysis, Chibundu Enyinnia.; investigation, Chibundu Enyinnia.; methodology, Chibundu Enyinnia.; project administration, Chibundu Enyinnia, resources, Chibundu Enyinnia.; software, Chibundu Enyinnia.; supervision, Ugochukwu Okonkwo.; validation, Chibundu Enyinnia, Ugochukwu Okonkwo and Chidobere Nwa-David.; visualization, Ugochukwu Okonkwo.; writing—original draft preparation, Chibundu Enyinnia.; writing—review and editing, Ugochukwu Okonkwo and Chidobere Nwa-David. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data for this study will be made available on request.

Conflicts of interest

The authors declare that there is no conflict of interest.

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