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Original article

Understanding the impacts of binary additives on the mechanical and morphological response of ameliorated soil for road infrastructures

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ABSTRACT

In an attempt to promote a cleaner environment, the deployment of waste materials in soil amendment protocols have been a major concern for civil engineers. Recent discoveries in the study of soil mechanics have revealed the pozzolanic tendencies demonstrated by these waste materials, which are beneficial in the development of road infrastructure. This has necessitated the need for this research to document the impacts of exploring the usage of combined solid waste derivatives in ameliorating the geotechnical parameters of deficient soil. The current stabilization exercise was geared towards the improvement of the mechanical properties of soil and surpassing the detrimental tendencies especially caused by seasonal variations. Moving forward, the microstructural response of the unaltered and additive ameliorated soil was investigated via qualitative means such as scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy. The additives including cement kiln dust (CKD) and rice husk ash (RHA), were added by air-dried weight of the soil and compacted based on the standards of British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). With regard to the compaction exercise, incorporation of these additive materials into the soil facilitated a gradual increase in the maximum dry density (MDDs) followed by a decrease in the optimum moisture contents (OMCs). In view of these research findings, soil treatment studies facilitated a substantial upsurge in the strength (California bearing ratio (CBR) and unconfined compressive strength (UCS)) values of the ameliorated soil, in agreement with the requirements of Nigeria general specification for all compactive efforts. Finally, the usefulness and efficacy of combining these wastes in deficient soil treatment were validated qualitatively via the SEM and FTIR strategies. The results of the SEM analysis revealed some disparities between the unaltered and altered soil specimens, providing insights into the direction of calcite formation in the additive-treated soil.

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1. Introduction

Lateritic soil has been among the leading infrastructural construction materials utilised in the practice of civil engineering for the purpose of engineering infrastructure delivery. The utilization of this lateritic soil as a road foundation material has a long history due to its prevalence in Nigeria and some other parts of the world such as those in South America, Asia and Australia (Gidigasu, 1976). Some lateritic soils in its natural form possess a substantial amount fine content and as well as layers of clay minerals, which inhibit the potency of the soils in terms of strength and stability in withstanding incoming traffic load. Due to this fact, it is almost impossible or difficult to assess suitable construction materials for engineering infrastructures. Consequently, the manifestation of soil materials with unsuitable engineering behaviour in preferred sites are mostly encountered and it is necessary to determine the

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geotechnical indices of these soils so as to render them adequate for construction commitments and attain the minimum benchmark of engineering standards as well. By doing so, the occurrence of persistent pavement failure in road construction, which is frequently caused by the use of poor-quality lateritic soil, can be curbed. An in-depth examination of this deficient soil indicates that it has low bearing capacity, poor workability and high compressibility (Rahman, 1986). This detrimental behaviour is the result of the ingress of moisture, which affects the subgrade material overtime. In order to ameliorate the detrimental effect of these marginal soils on road pavements, several approaches in soil re-engineering are put into place. The first approach is to excavate the deficient soil and substitute it with an imported material of better geotechnical engineering behaviour, while the other approaches are soil treatment protocols involving the amelioration of the mechanical parameters of the deficient soils (Dang et al., 2016).

Interestingly, soil materials could be enhanced and made suitable for specific construction projects via soil stabilization or modification practices (Etim et al., 2018a). These practices enhance both the physical and chemical properties of the soil (Oluwatuyi and Ojuri, 2017). Before now, Portland cement and lime are the primary additives frequently used in enhancing the mechanical properties of the marginal soils. The industrial generation of these additives coupled with the release of carbon dioxide (CO_2) and methane (CH_4) otherwise identified as the greenhouse gases are some of the numerous threats posed by them. Increase in urbanization, massive infrastructural development and rapid progression in populace, there have been a rise in solid waste generation. These waste materials occupy vast hectares of land that would have been used for either construction or agricultural purposes and they are also known to constitute nuisance to the surroundings, thereby posing great health and environmental risks. Similarly, disposing and managing this waste is capital intensive, and as such, its reutilization in soil amendment will be of great benefit to civil engineers and promote a cleaner environment. Interestingly, the continual increase in the prices of cement (being a primary binding agent) coupled with the depletion of ozone layers during production has steered geo-environmental engineers into utilizing these waste materials as either partial or total replacement of these natural binders. The use of these surrogate binding materials is the trending strategy, leading to a massive decline in greenhouse gas generation and a decrease in the soaring price tag of construction projects (Lee et al., 2018; Kajaste and Hurme, 2016). Oyster shell ash (OSA), periwinkle shell ash (PSA), sugarcane straw ash, groundnut shell ash, rice husk ash (RHA), cement kiln dust (CKD), metakaolin, waste wood ash (WWA), bone ash (BA), yam peel ash (YPA), palm bunch ash (PBA), quarry dust (QD), etc. are typical examples of solid waste end products applied by different scholars experimentally in soil treatment studies and in concrete works (Etim et al., 2018b; Etim et al., 2020; Attah et al., 2019a; Attah et al., 2021b; Etim et al., 2018a; Etim et al., 2019; Sujatha et al., 2015; Attah et al., 2020; Akinyele et al., 2015; Mosa et al., 2017; Kiran et al., 2014; Attah et al., 2019b; Oluremi et al., 2017; Adetayo et al., 2019; Ramonu et al., 2018; Alaneme et al., 2021a; Alaneme et al., 2021b; Alaneme et al., 2021c; Attah et al., 2018; Moses et al., 2018, 2019; Onyelowe and Duc, 2018; Onyelowe et al., 2020; Onyelowe et al., 2021; Siddika et al., 2021; Al-Mistarehi et al., 2021). These additives are fast gaining popularity, which can be attributed to their relatively low cost.

The research work of Ali et al. (1992) has experimentally established the usage of only RHA as an additive in the chemical treatment of Malaysian soil. In their study, it was noticeable that using RHA as a standalone binder was inadequate in terms of achieving the engineering benchmark for use as roadwork material. Seenivasan (2016) concluded that increasing the RHA content during soil stabilization protocols led to an insignificant enhancement in the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). In the same vein, in terms of pozzolanic activity, RHA has been considered as a prospective solid waste derivative for soil enhancement (Jauberthie et al., 2000). Recent researchers with specialty in the area of soil geo-engineering have looked into the possibilities of combining two waste materials/ waste material with supplementary cementitious materials (SCM) and the experimented outcomes portrayed positive results such as: lime–iron ore tailings (Etim et al., 2017), CKD–metakaolin (Attah et al., 2021a; Attah et al., 2021c), CKD–RHA (Attah et al., 2021d), CKD–PSA (Ekpo et al., 2020; Ekpo et al., 2021), PSA–cement (Etim et al., 2021a), lime–cement–OSA (Etim et al., 2021b), CKD: locust bean waste ash (Eberemu et al., 2019), cement–pond ash–RHA (Gupta and Kumar, 2019), fly ash–carbide-lime (Consoli et al., 2001), natural pozzolana–lime (Harichane et al., 2011; Al-Swaidani et al., 2016), lime–RHA (Alaneme et al., 2020a; Alaneme et al., 2020b), quarry fine–CKD (Amadi and Osu, 2018), PSA–lime (Etim et al., 2021c), groundnut shell ash (Sani et al., 2019) and so on. The ability of the stabilizers to supply excessive amount of calcium is a crucial factor that must be taken into consideration before the choice of a particular stabilizer (Wang, 2002). In essence, these agricultural wastes (RHA) and industrial wastes (CKD) have the potential to be employed as stabilizing agents, the reason being that they are siliceous and calcareous materials, respectively. The marginal variations in the chemical properties of CKD and RHA is very wide. The CaO content in CKD is high with a low silica and alumina content, whereas the SiO_2 content in RHA is high with a low CaO and alumina content. As a result, when these two materials are combined together as a stabilizing agent, their effects are more pronounced than when used singly. Each of them can supply the required lime or silica necessary to enhance pozzolanic reactions and as such lower the amounts of chemical activators. Furthermore, based on their elemental compositions, they contain similar oxides to that of either cement or lime, which makes them a good surrogate binder material in soil improvement protocols. Hence, CKD being a waste sourced from the cement manufacturing process has been considered potent in soil re-engineering studies (Salahudeen et al., 2014; Okafor and Egbe, 2013), and as such, combining it with RHA will provide additional strength in soil treatment protocols. In addition, the usage of CKD and RHA as standalone stabilizers and the combination of both the additives has been studied in improving clayey soil (Hossain, 2011). In their study, the impact of the studied stabilizer on the mechanical properties via plasticity tests, standard proctor compaction, strength tests, splitting tensile strength and modulus of elasticity on clayey soil was investigated. Interestingly, to the best of the authors' knowledge, considerable uncertainty still exists with regard to the relationship between mechanical tests and microstructural examination of clayey soil materials in the field of soil treatment studies.

Hence, this study attempts to combine the mixture of CKD and RHA in stabilizing lateritic soil. The impacts of these stabilizers on the geotechnical parameters of marginal soil have also been considered as the yardstick for evaluating its performance. The deployment of both qualitative experiments such as Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM) was explored in determining the functional groups and variations in the micro-morphological response of the stabilized soil, respectively.

2. Test materials and methods

2.1. Test materials

In the current investigation, lateritic soil, CKD and RHA are the materials adopted for the research experimentations. The utilized lateritic soil was sampled from a vicinity along East–West road axis in Mkpat Enin L. G. A. Akwa Ibom State as depicted in the GIS plot in Fig. 1. The utilized CKD in this study was sourced from a Cement industry situated at Mfamosing, Calabar, Cross River State. The RHA was obtained through the direct combustion of rice husks found in abundance in a local rice milling factory in Obubra L. G. A. Cross River State, Nigeria. The resultant ash was sieved through the 75 μm aperture size which were further enclosed in a polythene bag and taken to the laboratory for analysis.

2.2. Testing methods

Firstly, the obtained sample soil was sundried for some days and pulverised before usage. Thereafter, materials' characterization and geotechnical tests were performed on the test materials in their unaltered form. These preliminary investigative tests were employed to unravel the behaviour of the sample soil, which also provides the benchmark for soil enhancement protocols. Furthermore, mechanical tests including compaction, CBR, UCS and microstructural examinations such as SEM and Fourier Transformation Infrared (FTIR) spectroscopy were carried out on both the unaltered and the additive-altered soils. The solid waste materials (CKD and RHA) used in the amelioration protocols were applied in requisite quantities in varying percentages of 0–8% at an increasing rate of 2% for CKD and 0–15% for RHA with a step proportion of 3% by the dry weight of soil, respectively. The soil materials were hand mixed with the additives in their right proportions until a homogenous mix was achieved. The compaction response of the soil otherwise known as the maximum dry density (MDD) and optimum moisture contents (OMC) were performed based on the standards documented in BS 1377 and 1924 (1990), respectively. Three compaction standards: Standard Proctor (BSL), West African standard (WAS) and British standard heavy (BSH) were considered for the experiment. The CBR test, being an essential parameter employed for assessing the bearing capacity of soils for subgrades and other pavement materials (Tajdini et al., 2016) was carried out as documented in BS 1377 and 1924 (1990) for both the unaltered and additive-altered soils, respectively. The compacted specimens were wrapped in well-sealed polythene bags and allowed to cure for 6 days since the CBR of the soil treated with CKD and RHA depends on the curing period. Thereafter, the specimens were wholly immersed in waster and allowed to remain for 48 hs prior to CBR testing according to the Nigerian General Specification (1997). The UCS testing of the soil material was carried out using their respective OMCs obtained during compaction, which were later exposed to a curing period of 7 days. In a research work carried out by Choobbasti and Kutanaei (2017), it has been established that the microstructure of clayey soils has a significant influence on their engineering performance. Therefore, the micro-fabric variations of soil materials were assessed via means of non-destructive tests such as SEM and FTIR spectroscopy. The morphologies of the soil materials were understudied using SEM while the molecular vibrations were assessed using the FTIR technique. For us to comprehend the alteration in the micro-level of soil materials due to the incorporation of the CKD-RHA blend, these tests were performed on both the unaltered and the additive-altered soil specimens. In this current article, the sample material required for a proper understanding of the microscopic performance was obtained from soil materials compacted with BSL compaction energy at 7 days of curing. The flow chart showing the methodology of the soil amelioration protocols is shown in Fig. 2.

3. Results and discussion

3.1. Materials characterization

In the course of this research, a naturally occurring reddish brown colour lateritic soil obtained along East-West road in Mkpat Enin located in Akwa Ibom State, which is situated within the South-South part of Nigeria was studied. The particle size gradation plot of the unaltered soil is obtainable in Fig. 3, while Table 1 documents the elementary distinctive response of the representative clayey soil. The geochemical constituents of the materials used was verified via X-ray fluorescence (XRF) as presented in Table 2. As shown, the RHA has the highest silica oxide compared with the other materials. The soil under study had more than 35% of the total sample passing sieve No. 200 and its liquid limit and plastic limits are 43.80 and 18.97% which exceeds 41 and 11% respectively, being the minimum requirements for liquid and plastic limits of soils in this category. As per AASHTO characterisation (1986) and Casagrande (1947) procedure, the reference soil is within the category of A-7–6 with group index of 10 and CL referring to the Unified soil classification system (ASTM, 1992). The implication is that soils in this category are generally rated for subgrade use as fair to poor. Table 3 shows the proportions of the soil–additive combinations used in this study.

3.2. Specific gravity

The plot of specific gravity of soil-CKD mixtures with RHA contents is presented in Fig. 4. The specific gravity of the reference soil displayed a dwindling movement with an increase in the CKD-RHA contents. The specific gravity declined from the initial value of 2.60 for the soil material without additives to a lowest value of 2.33 at 8% CKD/15%RHA mixtures. The explanation of this decreasing behaviour was expected going from the perspective of the specific gravities of each additive material. The reference soil sample with a greater specific gravity of 2.60 replaced by the combined additives of 2.53 and 2.10 (CKD and RHA), respectively. Similar results of decreasing trends were observed by Haile et al. (2000) and Qiu and Sego (2001).

3.3. Compaction behaviour

3.3.1. Maximum dry density

The outcomes on the compaction properties of the unaltered and CKD-RHA blend treated soil for the three compaction energies are shown in Fig. 5 (a–c). However, as observed from the compaction results, the outcomes of natural soil samples compacted at BSL, WAS and BSH were 1.83, 1.835 and 1.89 Mg/m^3, respectively. Based on the trends shown in Fig. 5 (a–c), it can be clearly understood that a percentage increase in the concentration of RHA ranging between 3 and 15% resulted in a progressive decline in the compaction energies considered.

Due to the presence of the binding agents (i.e. CKD and RHA blends) in the soil mixtures, the values of MDD decreased from 1.83 to 1.68 Mg/m^3 for BSL, from 1.835 to 1.735 Mg/m^3 for WAS and from 1.89 to 1.745 Mg/m^3 for BSH. More importantly, the gradual reduction in terms of the MDDs of soil mixtures documented during the course of the compaction exercise could not be unconnected with the possible increase in the pH of the matrix as well as the processes of cation exchange taking place within the soil-CKD-RHA structure that ultimately results in the flocculation and agglomeration of the clay constituents (Attah et al., 2021c;

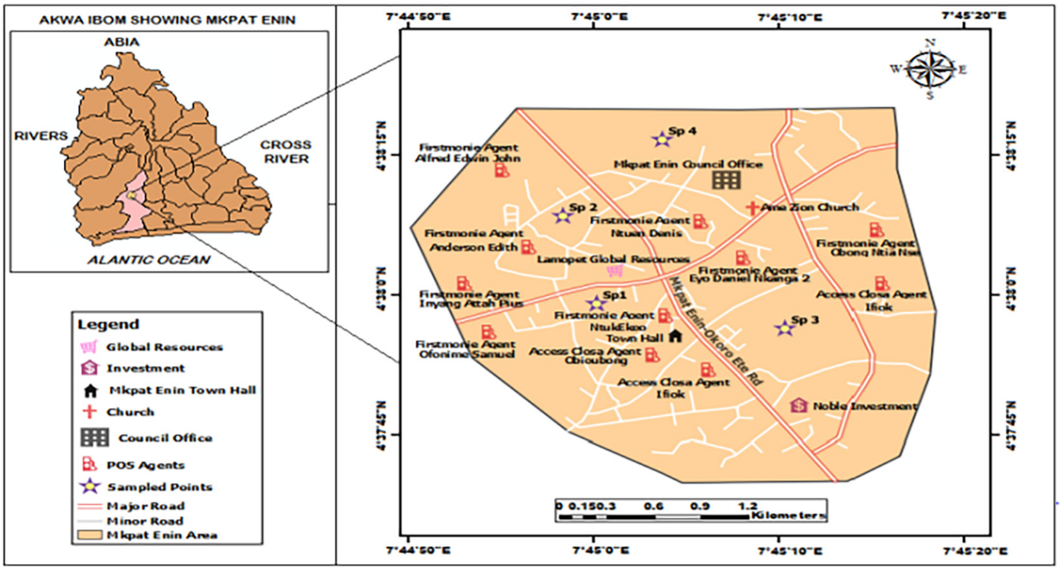

Fig. 1. Location map of unaltered lateritic soil material used in this paper.

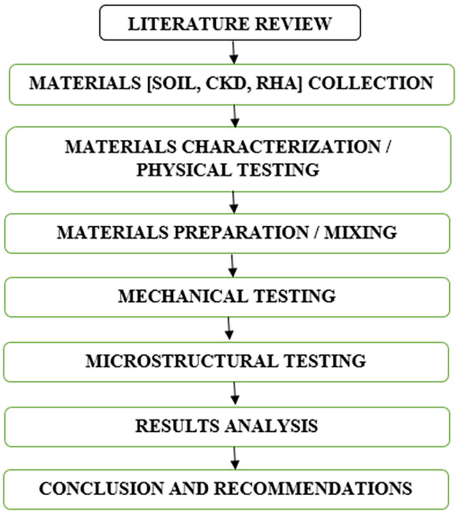

Fig. 2. Flow chart showing the methodology used in this paper.

Amadi et al., 2013; Eberemu et al., 2019). Secondly, this reduction could also be linked with the specific gravities of the binders and soil and also the build-up of the finer ash in the soil matrix. In terms of specific gravity, the surrogate materials (RHA and CKD) having a lower specific gravity of 2.10 and 2.53, respectively, mixes with the soil of a much higher specific gravity (2.60). This could have also been responsible for the downward trend of the MDDs. The documented outcome is in tandem with those of other scholars (Hossain, 2011; Amadi et al., 2013; Eberemu et al., 2019; Sujatha et al., 2015).

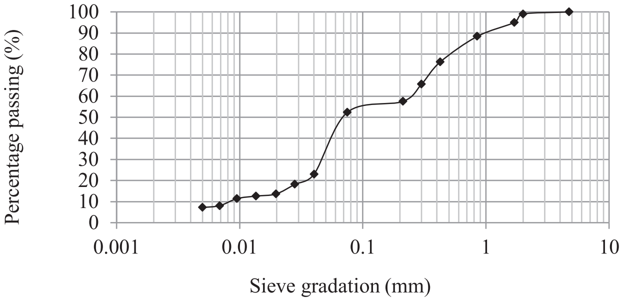

Fig. 3. Particle size gradation plot of unaltered soil.

3.3.2. Optimum moisture content (OMC)

In the same way, the alteration in terms of OMCs of soil CKD-RHA combinations using the three compaction energies are dis-

Table 1
Characterization behaviour of the soil material.

Property of the soil material, %	Quantity
Gravel	0.015
Sand	46.59
Silt	45.2
Clay	7.2
LL	43.80
PL	24.83
PI	18.97
Maximum dry density, Mg/m^3	
BSL	1.830
WAS	1.835
BSH	1.890
OMC, %	
BSL	12.95
WAS	12.50
BSH	12
CBR, % (unsoaked condition)	
BSL	8
WAS	9
BSH	16
CBR, % (soaked condition)	
BSL	5
WAS	7
BSH	9
UCS 7 days, kN/m^2	
BSL	126
WAS	172
BSH	195
Natural Moisture Content, NMC, %	19.80
Gs	2.60
AASHTO classification (Group Index)	A-7-6(10)
USCS classification	CL

Table 2
Geochemical constituents of the materials utilised in this study.

Oxide		CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	Na_2O	TiO_2	SO_3	K_2O	LOI
Mass fraction (%)	Soil	0.45	56.70	6	22.6	0.20	–	0.75	–	–	8.4
	RHA	2.95	75.30	1.98	1.40	2.10	0.98	–	–	5.55	5.61
	CKD	45.75	7.95	5.10	1.98	0.11	–	0.54	–	–	37.25

played in Fig. 5 (a-c). From the plots, the OMCs of the soil mixtures increased with higher CKD contents on one hand and as well marginally increased with increasing RHA content. For the BSL compaction energy, the OMC hit the highest point of 15% at both 8% CKD/12% RHA and 8% CKD/15% RHA while for the WAS compactive effort the maximum OMC of 14.35% was feasible at 8% CKD/15% RHA and for the BSH, the zenith in terms of OMC was 13.9% at 8% CKD/12% RHA. This increasing tendency of OMC could probably be as a result of the non-plastic performance of RHA and increase in fines particles due to the build ups of RHA in soil matrix which would in turn require additional water with the increasing surface area. This finding is consistent with that of previous research (Sani et al., 2020). On the other hand, there is a possible tendency that the increment in the OMC of the soil mixtures could also be facilitated by the pozzolanic response taking place in the soil due to the incorporation of pozzolanic materials. Furthermore, for the compactive efforts utilized in this current research, it is noticeable that the OMCs of the soil mixtures exhibited a dwindling behaviour, which might be attributed to the desiccation process caused by the incorporation of the binding materials into the cavities of the soil (Osinubi et al., 2016). This finding is parallel with the outcome reported by Sani et al. (2017).

3.4. Strength behaviour

3.4.1. California bearing ratio

The outcomes of the soaked CBR tests conducted for each CKD-RHA-soil treatments using BSL, WAS and BSH are plotted in Fig. 6 (a–c). In general, the soaked CBR exhibited a continuous development of strength with an increase in both stabilizers and compaction energies. Fundamentally, the combined impact of CKD-RHA on the deficient soil led to the improvement of the natural soil, and the peak result was achieved at 8% CKD/15% RHA. At this point, it is imperative to note that this trend of enhancement of soaked CBR outcomes could be associated with the formation of pozzolanic cementitious products of calcium silicate hydrate (CSH) and calcium aluminate hydrates (C(A)SH) sourced from the additives, which are required for strength development in the presence of moisture. The documented outcome is in agreement with the findings of other scholars (Attah et al., 2021b; Etim et al., 2019; 2021d). Considering the three compaction energies studied, the topmost soaked CBR values documented are 35, 40 and 58% for BSL, WAS and BSH, respectively. Furthermore, in terms construction materials rating according to the Nigerian General Specification (1997), these peak values documented overlapped both the lower and upper limit of the 20–30% prerequisite for usage as a sub-base material.

Similarly, the unsoaked CBR (CBR_U) of soil stabilized with the CKD-RHA blend using BSL, WAS and BSH compaction energies is depicted in Fig. 6 (a–c). From these plots, it is noticeable that the strength values of the treated soils showed an impressive CBR value compared with those of the unaltered soil for the three compaction energies. The improved strength could likely be linked with CKD being the major source of calcium and silica from RHA reacting with the soil material in the presence of moisture. Hence, the soil under investigation had been exposed to hydraulically bound conditions with an adequate amount of both calcium and silica made available, which ensured pozzolanic reactions and as well the gradual enhancement of the CBR values (Al-Mukhtar et al., 2012). The behaviour of the studied soil material follows a similar trend to that observed by previous investigators who improved similar soil with calcium chloride (Sani et al., 2018) and periwinkle shall ash (Etim et al., 2019). The existing conditions of the Nigerian General Specification (1997) stipulate that for a soil material to be considered as a base material, it should achieve a least possible CBR_U value of 80% while the benchmark for sub-base rating is 20–30% with both compacted at optimum moisture and at 100% West African Standard compaction (Gidigasu and Dogbey, 1980; Gidigasu, 1982). Based on the abovementioned, the documented peak unsoaked outcomes of CKD-RHA ameliorated soil materials for BSH alone were above the minimum requirement of 80%, while the specimens compacted using BSL and WAS were far below the stipulated minimum values. The soil treated with the CKD-RHA blend peaked at CBR_U values of 44, 59 and 83% using BSL, WAS and BSH compaction energies, respectively. In general, it is noticeable that the soil materials showed an improved strength with higher compaction energies, which is consistent with the report of Osinubi (2006).

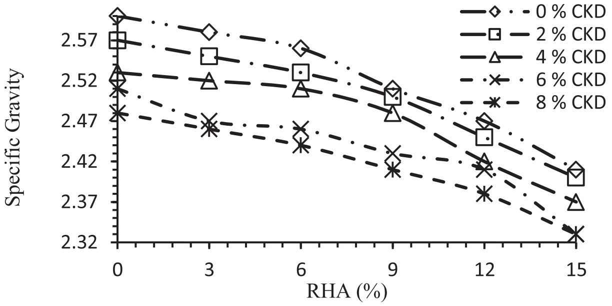

Fig. 4. Plot of specific gravity of soil-CKD-RHA contents.

Table 3
Proportion of soil–additive combinations.

S + 0 % CKD + 0 % RHA	S + 2 % CKD + 0 % RHA	S + 4 % CKD + 0 % RHA	S + 6 % CKD + 0 % RHA	S + 8 % CKD + 0 % RHA
S + 0 % CKD + 3 % RHA	S + 2 % CKD + 3 % RHA	S + 4 % CKD + 3 % RHA	S + 6 % CKD + 3 % RHA	S + 8 % CKD + 3 % RHA
S + 0 % CKD + 6 % RHA	S + 2 % CKD + 6 % RHA	S + 4 % CKD + 6 % RHA	S + 6 % CKD + 6 % RHA	S + 8 % CKD + 6 % RHA
S + 0 % CKD + 9 % RHA	S + 2 % CKD + 9 % RHA	S + 4 % CKD + 9 % RHA	S + 6 % CKD + 9 % RHA	S + 8 % CKD + 9 % RHA
S + 0 % CKD + 12 % RHA	S + 2 % CKD + 12 % RHA	S + 4 % CKD + 12 % RHA	S + 6 % CKD + 12 % RHA	S + 8 % CKD + 12 % RHA
S + 0 % CKD + 15 % RHA	S + 2 % CKD + 15 % RHA	S + 4 % CKD + 15 % RHA	S + 6 % CKD + 15 % RHA	S + 8 % CKD + 15 % RHA

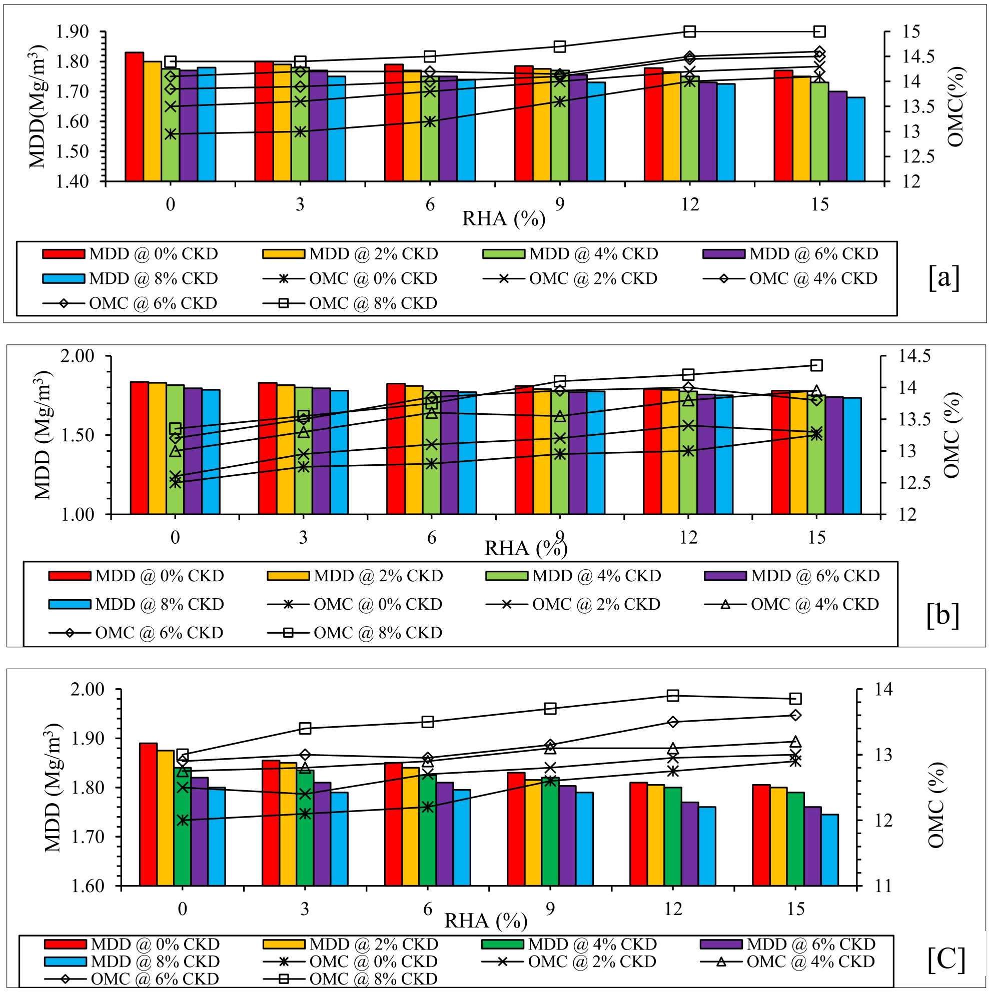

Fig. 5. Behaviour of the MDD and OMC of soil CKD-RHA admixtures for: (a) BSL (b) WAS and (c) BSH compaction energies.

3.4.2. Unconfined compressive strength

During the soil re-engineering process, the unconfined compressive strength (UCS) test gives an understanding of the desired amount of additive. The UCS of CKD against proportion of different RHA treatment cured for 7 days is described in Fig. 7 (a – c) for British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). The incorporation of RHA-CKD into the soil material tends to increase the UCS values of soil for the three compactive efforts.

For the soil specimen compacted with BSL, the UCS values increased from 126 to 691 KN/m^2, for WAS it increased from 172 to 829 KN/m^2 whereas for BSH, it increased from 195 to 1158 KN/m^2. Evidently, comparing the UCS outcomes of the natural soil with the optimally treated soil sample for the three compaction energies, the maximum percentage of increment is about 493%. This significant enhancement in the UCS could be ascribed to the chemical reaction taking place between the soil material and the binders or surrogate materials (CKD and RHA), thereby leading to the formation of a cementitious material. These surrogate (binders) materials do exhibit cementitious behaviour and fill up the voids in the soil mixtures as well, which in turn enhances the strength properties of the stabilized soil material. In addition, the strength improvement of the treated soil samples could also be as a consequence of the solidification of the soil mixtures due to the formation of cementitious compounds (CSH and CASH), which was also confirmed by micro-structural alterations. The current trend of results seems to be consistent the previous findings (Etim et al., (2019; Etim et al., 2020; Ekpo et al., 2020; Ekpo et al., 2021). The outcomes of the UCS exercise of the treated soil samples for the different compaction energies understudied were further down the minimum strength benchmark of 1034 kN/m^2 for acceptable lime stabilization as specified by TRB (1987). Interestingly, the peak values of 691, 829 and 1158 KN/m^2 were within the limits of 687–1373 kN/m^2 for the sub-base material in road infrastructure as detailed by Ingles and Metcalf (1972). On a general note, the increase in the values of CBR and UCS is due to the cementation effect between the liberated lime from the additive materials (CKD and RHA) combined with silica and alumina from the studied soil.

3.5. Microstructural examination

3.5.1. Scanning electron microscopy

The recent discoveries in soil geo-engineering have encouraged researchers to deploy nondestructive experimentation with the aim of unravelling the microscopic morphological variations of soil materials (Sani et al., 2018; Attah and Etim, 2020; Etim et al., 2020; Ekpo et al., 2020). The SEM results of the untreated soil with magnifications of 1000x and 500x are presented in Fig. 8 a-b. The surface of the unaltered soil appear to be rough and closely packed with large aggregations comprising loose porous materials. There is also more than a few intra-granular pore spaces observed within the soil grains. The treated soil mixtures with magnification of 1000x and 500x are shown in Fig. 9 a-b. On addition of the addi-

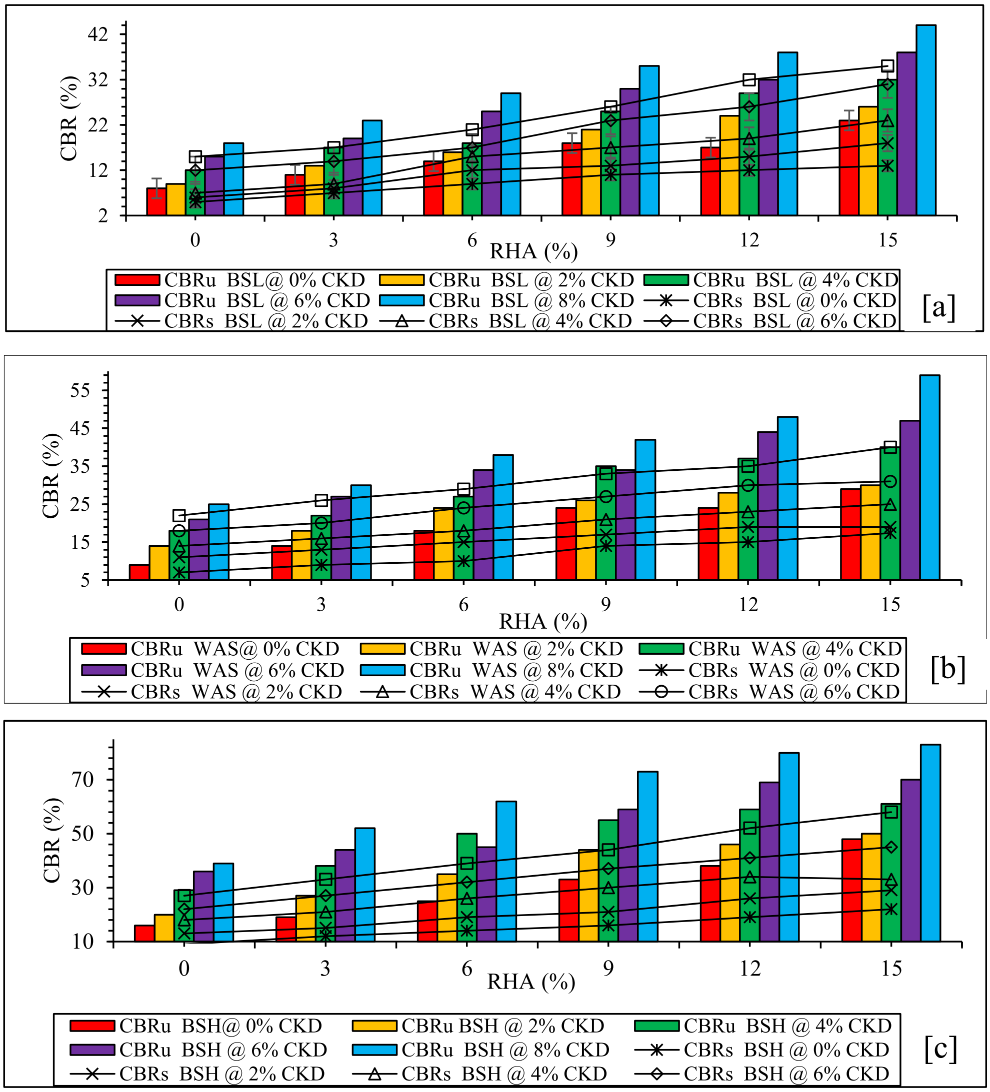

Fig. 6. Plots of soaked and unsoaked CBR of soil CKD-RHA admixtures for: (a) BSL (b) WAS and (c) BSH compaction energies.

tives, varying sizes of pores detected in the untreated soil lessened/closed up due to the establishment of flocs in the treated soil specimen. The morphologies of the treated soil parades a smooth-like finishing with few noticeable inter-granular linkages. The manifestation of white lumps on the surface of the additive-blended soil confirms the formation of cementitious hydration products of CSH and C(A)SH. Similar results were reported in previous studies (Mirzababaei et al., 2009; Sani et al., 2018; Oluwatuyi et al., 2019; Etim et al., 2021a, 2021b).

3.5.2. Fourier transform infrared (FTIR)

The FTIR band of the untreated soil as presented in Fig. 10 shows that the IR peak at 678.4 cm^{-1} is associated with the meandering of Si-O-Si, the peak at 749.2 cm^{-1} can be ascribed to the stretching of quartz Si-O, while the peak at 790.2 cm^{-1} can be attributed to the distortion of OH, which has connection with that of Mg^{2+} and Al^{3+} (Saikia and Parthasarathy, 2010; Eisazadeh et al., 2010). The IR peak at 909.5 cm^{-1} may perhaps be attributed to the OH assemblage, which is associated with the double aluminium ion, $2Al^{3+}$ deformation, whereas the wave numbers at 1028.7 cm^{-1} and 998.9 cm^{-1} correspond to the stretching of Si-O (Saikia and Parthasarathy, 2010; Eisazadeh et al., 2010). The IR peaks at 3652.8 cm^{-1} and 3693.8 cm^{-1} could be linked to the inner-surface hydroxyl groups. The peak at 3623 cm^{-1} confirms the broadening of the OH of the crystalline hydroxyl of the soil (Madejova and Komadel, 2001; Bhuvaneshwari et al., 2010). The IR peak at 1636.6 cm^{-1} may perhaps be ascribed to the H-O-H distortion of water (Saikia and Parthasarathy, 2010). However, the FTIR spectrum of the additive-blended soil (see Fig. 11) exhibited some dissimilarities in terms of wavelengths compared with the spectrum of the unaltered soil. Interestingly, the few variations of wavelengths may perhaps not be unconnected with the pozzolanic chemistry between the additives and the soil. The additive-blended soil exhibited two remarkable peaks at 872.2 and 1416 cm^{-1}. The occurrence of the FTIR bands could be attributed to the establishment of cementitious compounds, which is an indicator of strength development in the treated soil.

4. Conclusion

In this experimental study, reutilization of both industrial and agricultural wastes as surrogate materials in the amelioration process of clayey soil for pavement foundations was investigated. The foremost deductions made based on this exercise can be detailed as follows:

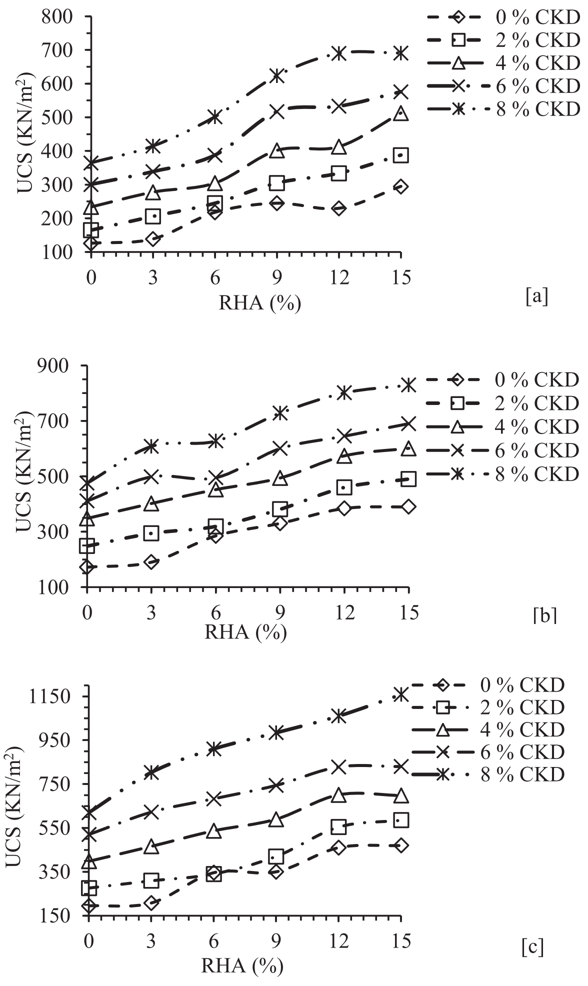

Fig. 7. Plots of 7-day curing the UCS of the soil CKD-RHA admixtures for: (a) BSL (b) WAS and (c) BSH compaction energies.

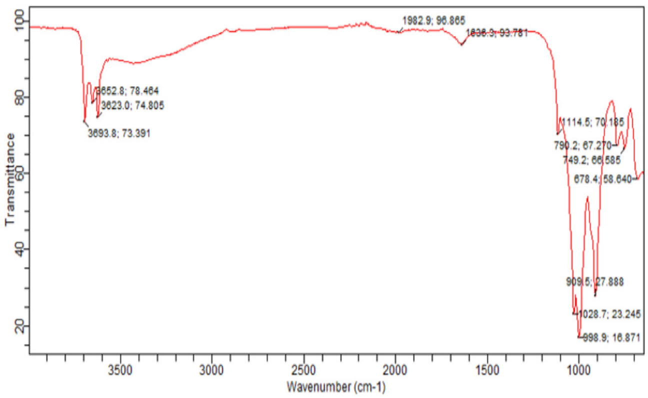

Fig. 10. FTIR band of virgin soil.

- For the various admixture blends, the MDD increased with increased compaction energy, while the OMC decreased with increased compaction energy, which is conventional for soil compaction protocols.
- The UCS of the stabilized soil for the 7-day curing period was found to increase progressively as the binder content increases for all the compactive efforts considered. Also, the CBR (soaked and unsoaked) is enhanced significantly with an increase in the CKD-RHA contents for all the compactive efforts. Interestingly, the optimum combination of CKD and RHA for an efficient stabilization protocol of the marginal soil was established at 8% CKD/15%RHA.
- The microstructural study using SEM reveals the building up of cementitious products of CSH and C(A)SH, which is believed to have resulted in the strength improvement of the altered soil. Furthermore, the outcome of the FTIR experimentation clearly 0.0.that for both the treated and untreated soils, there are visible manifestations of OH connections, H-O–H distortion of water, Si-O quartz and Si-O-Si.

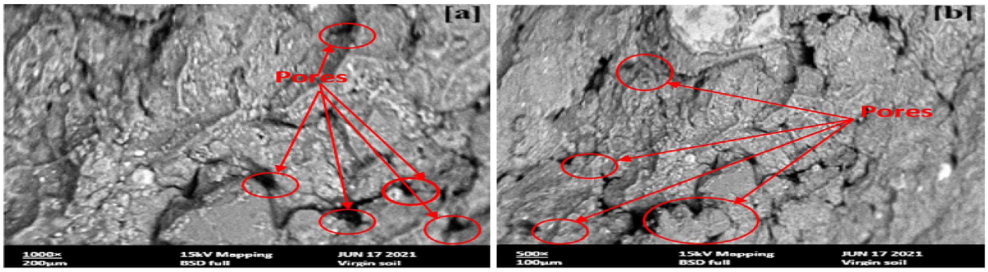

Fig. 8. SEM micrographs of virgin soil at (a) 1000x magnification and (b) 500x magnification.

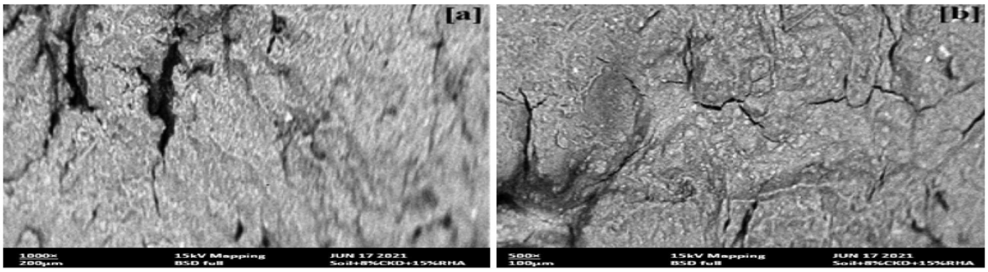

Fig. 9. SEM micrographs of soil treated with blended additives at (a) 1000x magnification and (b) 500x magnification.

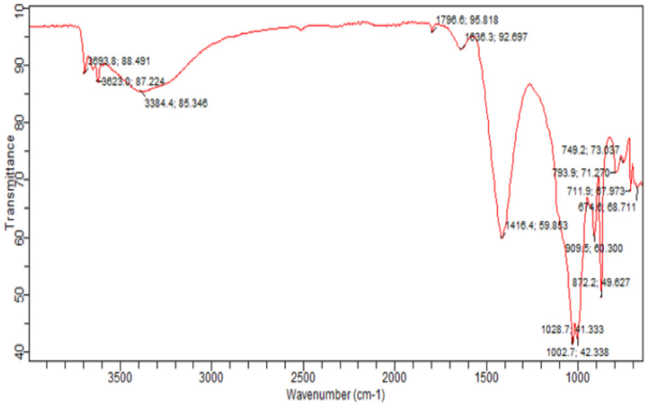

Fig. 11. FTIR band of soil treated with blended additives.

- The results of this study clearly show that mixing CKD and RHA has a positive impact on the reference soil, which makes it viable enough for enhancing the behaviour of marginal soils. Considering the sustainability of cleaner environment and incessant surge in cost of natural stabilizing agents such as those of cement and lime, the application of CKD/RHA could represent an alternative source of stabilization as well as curbing the environmental menace caused by these traditional stabilizers during their production.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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