

Research Article

Swelling Potential of Clayey Soil Modified with Rice Husk Ash Activated by Calcination for Pavement Underlay by Plasticity Index Method (PIM)

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Volume change in expansive soils is a problem encountered in earth work around the world. This is prominent with hydraulically bound structures or foundations subjected to prolonged moisture exposure. This behavior of clayey used as subgrade, foundation, landfill, or backfill materials causes undesirable structural functionality and failures. To prevent this happening, clayey soils are studied for possible volume change potential and degree of expansion. Consequently, the problematic soils are stabilized. In this work, the stabilization of clayey highly expansive soil classified as A-7-6 soil and highly plastic with high clay content was conducted under laboratory conditions. The treatment exercise was experimented using quicklime-activated rice husk ash (QARHA), hydrated lime-activated rice husk ash (HARHA), and calcite-activated rice husk ash (CARHA) at the rates of 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10%. Upon treatment with the three calcium compounds to produce three sets of treated experimental specimens, the plasticity index was observed and recorded and swelling potentials were evaluated using the plasticity index method (PIM). The results showed a consistent improvement on the properties of the treated soil with the addition of the different activated admixtures. While the utilization of CARHA and HARHA improved the clayey soil to medium expansive soil, the treated clayey soil substantially improved from highly expansive soil with a potential of 23.35% to less expansive with a final potential of 0.59% upon the addition of 10% QARHA. Finally, QARHA was adjudged as the best binding composite due to the highest rate of reduction recorded with its utilization.

1. Introduction

Soil modification or ground improvement is a popular method widely used in the stabilization of problematic soils utilized for engineering purposes [1–3]. This method is widely used in the geotechnical and geoenvironmental fields due to the substantial improvement recorded in the mechanical, strength, consistency, and gradation properties of expansive soils [3, 4]. Soil stabilization could be mechanical, whereby soil properties are improved by mechanical means to achieve densified mass or chemicals, whereby chemical or organic additives are mixed with representative soils to improve these properties by reactive means [2]. However, to achieve success in a soil stabilization protocol, a chemical stabilization or modification method is accompanied with a mechanical procedure [3, 4]. This is by applying compactive effort on the additive treated soils to achieve the end results, which are strength gain and densification [4]. Various additive binders like cement have been in common use over the decades [3]. This process, although old and conventional, has been observed through environmental impact assessment studies to be associated with environmental hazards [3]. This is because of the greenhouse emissions associated with the production and utilization of cement in construction activities as a binder. Apart from the environmental impact experienced during the use of cement and the associated high cost of construction, cement pastes, cement concretes, and cement treated soils exhibit unacceptable shrink and crack potentials [4, 5]. This makes cement a disadvantaged binding material in construction works. In recent years, the search for more environmentally friendly construction materials that could replace cement partially or totally led to the research on supplementary cementitious materials (SCM) or pozzolanas [6, 7]. These are construction materials occurring in nature and they are not associated with greenhouse effects and high construction costs as they are obtained free of cost [3, 8–10], and in this effort, ash materials have been observed as amorphous and nonbiodegradable, possessing pozzolanic properties with high contents of aluminosilicates that meet the requirements of pozzolanas in accordance with appropriate standards [6, 7]. Further investigation has also led to the establishment that ash derived from the direct combustion of solid waste materials is a good SCM, which upon mixing with soft soils improves the construction properties [7, 8]. To evaluate the sustainability of ash in geoenvironmental endeavors, solid waste materials such as rice husk, sugarcane bagasse, palm bunch, cassava peel, palm kernel, snail shell, periwinkle shell, coconut shell, palm oil fiber, waste tire, egg shell, locust bean shell, and grated coconut meat have been burnt to achieve ash. These ashes, derived from these solid waste materials, have been utilized in the stabilization of various clayey soils' experimental investigations. These were to study the effect of ash on the engineering properties of soft soils utilized as foundation materials, landfill liner and cover materials, and backfills. These investigations have yielded remarkable improvements in soils, which satisfied the basic requirements for construction material's use as a foundation material. In a book "sustainable soil reengineering [8], the authors brought to bear the benefits of utilizing ash as a construction material to improve the properties of expansive soils due to their binding properties [7, 11].

Onyelowe et al. [9, 10, 12], conducted reviews on the recycling and reuse processes of solid waste materials to derive ash for soil stabilization and on the valorization and sequestration of emissions released during the controlled incineration mechanism. In their findings, different relevant literatures were reviewed and cited as supporting the method of ash derivation while maintaining an ecofriendly atmosphere. These ashes have shown successful results because of their aluminosilicate content, which forms calcium aluminate hydrates and calcium silicate hydrates in ionized clayey soil in the presence of moisture. This process is called calcination reaction. This is the process by which ionized clayey soil, at the doubled diffused layer phase, when mixed with moisture, reacts with calcium ions (Ca^{2+}) from the ionized compounds of the additives to form flocs and build strength-gain matrixes responsible for strengthening in expansive soils. Additive compounds of calcium that supply the abundance of calcium for the calcination process in expansive soils during stabilization are calcium oxide (quicklime/burnt lime), calcium hydroxide (hydrated lime/flaked lime), and calcium carbonate (calcite). In the recent past, Rimme and Greenland [13] conducted an experimental work on the swelling behavior of a clayey soil modified with calcite. This is one of the earliest works on soil stabilization by calcination and carbonation processes. This work showed that calcite can serve as a good construction material and as a supplementary binder. In a previous conference paper, Lasledj and Al-Mukhtar [14] worked on the effect of hydrated lime on the engineering properties of highly expansive clay. This work showed that highly expansive clay can be technically strengthened to be used as a foundation soil by stabilizing it with hydrated lime. Soon et al. [15] had investigated the use of bacteria to induce the precipitation of calcite for soil properties improvement for construction purposes. The results of this research also showed that calcite can be utilized to improve the plastic and swelling properties of expansive soil. Hafshejani and Jafari [16] investigated the effect of calcite on some selected properties of soil. The results of this work showed that calcite enhances both calcination and carbonation reactions in soil during the stabilization process. This further helped the soil to form strengthening compounds and agglomeration of particles of the treated soil. In addition, Yazarloo et al. [17] conducted a research on the effect of calcite on the plastic properties of lean clay. The results also proved remarkably that calcite possesses binding properties when ionized in the presence of soil molding moisture. Another work that made a remarkable impact in the geoenvironmental effort was conducted by Amadi and Okeiyi [18] where they considered the effects of both quicklime and hydrated lime on the properties of highly expansive soils. The results of the comparative analysis of the laboratory of this work adjudged quicklime to have shown better engineering properties and better alternative stabilization for clayey soils. In addition, in a work published in "case studies in construction materials," there was a short communication on the calcination of clays to make pozzolan by Almenares et al. [19]. Results of this work showed that reactive pozzolan can be produced in industrial scale with calcite. Lime was also proven to be a good binding material in a research conducted by Baldovino et al. [20] to improve the consistency and strength properties of clayey soil. Haas and Ritter [21] conducted a research on soil

improvement utilizing quicklime and harnessing its long-time effect on soil properties. In the same research, the carbonation effect on the treated soil was also examined. In a work published earlier, Pastor et al. [22] proved the ability of limestone/calcite to improve the swelling potential of clayey soils. Lime was observed to consistently improve the soil properties examined with increased proportion. Peron et al. [23] and Liu et al. [24], respectively, worked on the bioremediation of desiccation of cracking resulting from swelling of clay soil utilizing calcite induced through a biotechnical process. Results showed remarkable improvement in the cracking potential of the clayey soil. These compounds are known to be calcium rich compounds in their ionized state and can serve to enhance the calcination reactions in soil stabilization. However, these materials are also considered caustic and can also serve as caustic activators for ash materials to improve the pozzolanic activities of ash. This ash-calcium compound combination forms geopolymer binders (GPB), and it has been shown by the results of previous studies on the application of geopolymer cement (GPC) in soil modification and stabilization that this blend forms modified soils with high crack shrinkage, high temperature, and sulfate attack resistance. Rivera et al. [1] conducted a research on clayey soil stabilization through the application of cementing materials activated by alkali (i.e., caustically activated). In this work, a mixture of NaOH and Na₂SiO₃ was used to activate supplementary binding materials and the activated blend was used to stabilize soil. The results from this work showed substantial improvement in the compaction, compression, and flexure properties of the treated soil. Right in the same year 2020, Onyelowe et al. [25] conducted a research on the index and compaction properties of clayey soils treated with quarry dust activated with NaOH and Na₂SiO₃. The results also showed remarkable improvement in the dry density at optimum moisture of the soil. In addition, the plasticity of the treated representative soil reduced with increased proportion of the additive.

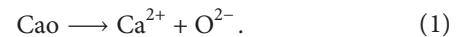
When expansive soils are used as underlay in flexible pavements, they are steadily exposed to moisture attack through capillary/suction action or migration of run-off through the cracks or heaves of failed pavements. As this structural anomaly happens, the clayey soils experience swelling and changes in structure, and as more moisture percolates in the foundation from above or below, it experiences longer exposure and the plasticity potential, which is directly proportional to the swelling potential, is impaired. The pavement structure fails eventually. Conversely, when the pavement underlying expansive clayey material undergoes modification based on the prevailing environmental conditions, with weather-resistant additives, hydraulically bound conditions seem not to be any problem. This is the gap this research promises to close, by utilizing calcium compound and activated ash materials in the modification of expansive soil to improve the plasticity condition and swelling potential. Chen [26] had reported the relationship between swelling potential as a dependent variable and plasticity index and clay activity as independent variables; hence, the analytical method of estimating swelling potential from the Atterberg limit experiment or plasticity index method (PIM) is applied in this work. It will suffice to note

that the emphasis in this research work is to investigate the application of novel material combinations in the stabilization of soft soils for pavement foundation purposes. Chen [26] also suggested a swelling potential limit of 0% to 12.6%, which corresponds to low-medium swelling potential consistency for soils to be considered for use as pavement compacted subgrade.

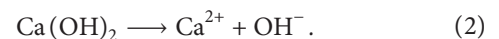
2. Materials and Methods

2.1. Materials

2.1.1. Quicklime (CaO). Quicklime is a whitish water-soluble caustic material with a melting point of 2613°C, boiling point of 2850°C, density of 3.34 g/cm³, and pH of 12.4. It has a cubic halite structure and crystalline solid at room temperature. It is obtained from the burning of limestone, so it is referred to as burnt lime [27]. It dissociates into ions of calcium and oxygen as presented in equation (1). For this reason, it has an abundant supply of calcium for calcination and pozzolanic reaction with clayey soil dipole minerals. In aqueous solution, it becomes hydrated with lime and this is the reason that its pH is hardly determinate. It possesses binding properties that meet the requirements of the appropriate standards [6, 7]. This crystalline solid was obtained in the market and stored securely for use.



2.1.2. Hydrated Lime (Ca(OH)₂). Hydrated lime is the quicklime chemically combined in water with 46–48% CaO, 33–34% magnesium oxide (MgO), and 15–17% chemically combined with water. It is a crystal, nonflammable, odorless inorganic powder, which is soluble in water at ambient temperature. It has a melting point of 580°C, boiling point of 2850°C, and density of 2.21 g/cm³. Its density is less than that of quicklime (3.34 g/cm³) due to its more aqueous condition that creates pores in the structure of the solid [27]. It is caustic with a pH of 12.8 and possesses pozzolanic characteristics, which makes it a good supplementary or alternative binder in civil engineering and earth work. It dissociates into ions of calcium and hydroxyl as presented in equation (2) and this property enhances its ability to calcinate the dipole minerals of clayey soils in a stabilization procedure by pozzolanic reaction. It was obtained from the chemical store and kept under room temperature for use in this research work. It meets the standard conditions stipulated in the appropriate design codes [6, 7].



2.1.3. Calcite (CaCO₃). Calcite is a crystalline whitish limestone with a melting point of 1339°C, decomposing at boiling point and with a density of 2.71 g/cm³. It is denser than hydrated lime (2.21 g/cm³) and less dense than quicklime (3.34 g/cm³). It is caustic, soluble in water, and has a pH of 9.91 [27]. It dissociates into ions of calcium and

carbonate as presented in equation (3). It exists in various forms such as chalk, limestone, and China clay. It is a primary component of Portland cement production. This inorganic compound has been found to be a good construction material with binding properties useful in soil stabilization. This compound contributes to calcination and carbonation in a clayey soil stabilization used in earth work. Calcite has been a subject of research in geoenvironmental engineering field profession, especially in earth work and clayey soil stabilization. It has impacted so much in the field that experts have gone further to induce its precipitation with bacteria species for the purposes of avoiding the carbon footprint because of its utilization in its inorganic form. It was obtained from the chemical stores and stored for use in the present research work.



2.1.4. Rice Husk Ash (RHA). The RHA was derived from the direct combustion of rice husk collected from rice mills in Abakaliki, Nigeria. The ash according to the studies satisfies the requirements of a pozzolanic material in accordance with British Standard International BS 8615-1 (2019) [6] and American Standard for Testing and Materials ASTM C618 [7] due to the presence of Al_2O_3 , SiO_2 , and Fe_2O_3 in its chemical oxides' composition. The release of silica and alumina from the activated rice husk ash triggers a pozzolanic reaction in the clayey soil-adsorbed complex interface through hydration and calcination, the stabilization points of which are presented in Figures 1 and 2.

2.1.5. Clayey Soil. The clayey soil used as a representative soil for this experimental work was collected from a depth of 1 meter from a borrow pit located at Ndoro Oboro, Abia State. The representative (natural) soil was prepared in accordance with British Standard International BS1377 [28] and stored for laboratory work at room temperature, and the treated soil was prepared in accordance with British Standard International BS1924 [29]. The soil was tapped with a rubber pestle to remove lumps and sundried for 48 hours. After that, 300 g of the sundried natural soil was collected and mixed with varying proportions of admixture to prepare the experimental specimens.

2.2. Methods. Basic laboratory experiments were conducted in accordance with the conditions of the British Standard International [28] as follows: particle size analysis of soil and rice husk ash, Atterberg limits test (the liquid limit was determined by spreading the sample in the cup of brass of the Cassagrande apparatus and applying the grooving tool to divide it. The moisture content when the groove closed for 1.27 cm after 25 blows of the cup was recorded as the liquid limit. Three samples were tested and the average was calculated), compaction test, specific gravity of soil test, and California bearing ratio test to enable the characterization of the representative soil and rice husk ash. The chemical oxide composition of the test soil and rice husk ash was conducted

using X-ray diffraction method by testing three specimens and the average was calculated. The set-up was applied for the identification and characterization of compounds based on their oxide composition by weight. This was done by obtaining the dual wave/particle nature of X-rays to obtain information about the compounds of crystalline materials. These basic tests were conducted under laboratory conditions in accordance with the British Standard International BS1377 [28]. The rice husk ash was activated using three compounds of calcium in accordance with the requirements of Davidovits [30]. The three sets of activated rice husk ash activated with caustic binders, CaO , $\text{Ca}(\text{OH})_2$, and CaCO_3 , were achieved by mixing 5% by weight of rice husk ash of each of the activating compounds to achieve quicklime-activated rice husk ash (QARHA), hydrated lime-activated rice husk ash (HARHA), and calcite-activated rice husk ash (CARHA), respectively. These composites of activated rice husk ash (QARHA, HARHA, and CARHA) were utilized in the proportions of 0% (reference test), 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10% by weight of dry soil to modify the clayey soil in the stabilization process. Atterberg limits (liquid limit (w_L) and plastic limit (w_P)) behaviors of the calcined RHA modified clayey soil were observed by experimentation after curing for 24 hours using the Cassagrande apparatus in accordance with the design standard [31, 32]. From the observed test results, the plasticity index (I_P) was computed from equation (4) and swelling potential (w_S) was equally computed from equation (5) [33–35].

$$I_P = w_L - w_P, \quad (4)$$

$$w_S = 0.00216 * I_P^{2.44}, \quad (5)$$

where I_P is the plasticity index, w_L is the liquid limit, w_P is the plastic limit, and w_S is the swelling potential.

3. Results and Discussion

3.1. Materials Characterization. The basic characteristic features of the representative clayey soil are presented in Tables 1 and 2 and Figure 3. From the basic test results, it can be deduced that the soil has 45% of its particles passing the sieve size 0.075 mm, liquid limit of 66%, and with a natural moisture content of 14%. The abovementioned properties show that the soil is an A-7-6 soil group according to AASHTO classification [36, 37] and poorly graded with high clay content (CH) according to USC system. Further, the plasticity index of the soil of 45% shows that the soil is highly plastic and breaks upon the application of load. The representative clayey soil also has a swelling potential, which is a function of plasticity of 23.35% and this means that the soil is highly expansive [38]. The MDD of the soil was observed to be 1.25 g/cm^3 at an OMC of 16%. This shows that the soil is very porous, agreeing with its swelling potential and expansive condition. Also, the soil was observed to have a specific gravity of 1.43 indicating that a high organic material is present in the soil. These properties have characterized the soil as a problematic and high expansive soil very unsuitable for earth work.

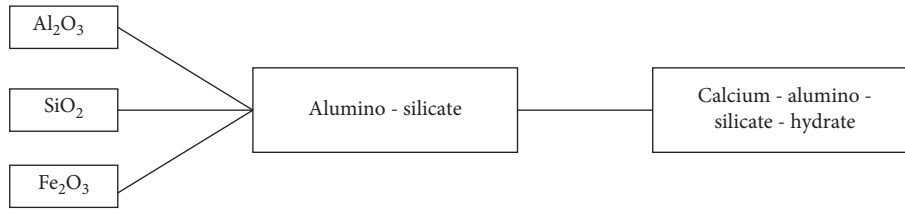


FIGURE 1: Pozzolanic composition of rice husk ash and stabilized soil.

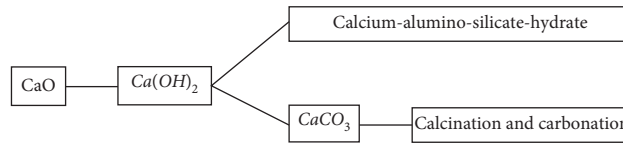


FIGURE 2: Quicklime hydration path, carbonation of hydrated lime, and formation of aluminate-silicate-hydrates of calcium in calcined soil.

TABLE 1: Characterization properties of clayey soil.

Property description of clayey soil and units	Value
% passing sieve, no. 200 (0.075 mm) [28]	45
w_N (%)	14
w_L (%)	66
w_P (%)	21
I_p (%) = $w_L - w_P$	45
w_s (%) = $0.00216 * I_p^{2.44}$ [33]	23.35
Degree of expansion [33]	High
G_s (specific gravity)	1.43
AASHTO classification [36]	A-7-6
Unified soil classification system	CH
δ_{max} (g/cm ³) (MDD)	1.25
ω (%) (OMC)	16
CBR (%)	8
Color	Reddish

TABLE 2: Particle size distribution (PSD) of test materials.

Materials	% passing sieve (mm)										
	19	6.35	4.75	2.36	1.18	0.6	0.425	0.3	0.15	0.075	Pan
Clay soil	100	100	94	88	82	76	70	58	51	45	0
Rice husk ash	100	97	89	75	62	55	42	35	22	14	0

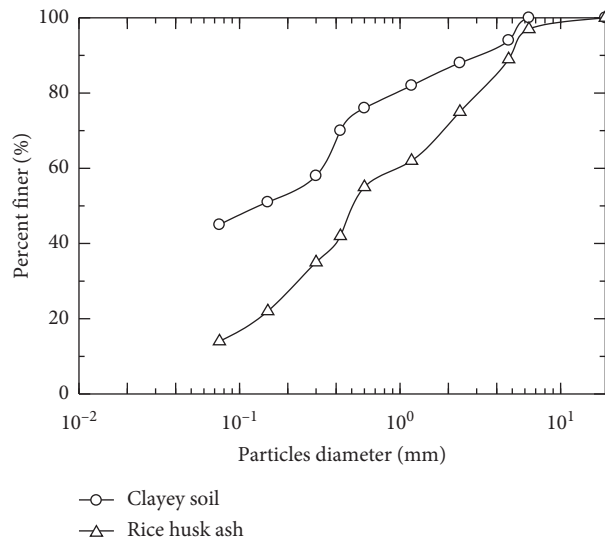


FIGURE 3: Particle size distribution curve of the clayey soil and rice husk ash.

Table 3 presents the chemical oxide composition of the representative soil and rice husk ash. The results show that the soil has Na_2O with the high oxide composition by weight of the soil. This oxide contributes to the expansive condition of the soil. The ferrite composition is rich in the red color of the clayey soil and contributes to the pozzolanic reaction during stabilization work [7]. This property supports the high swelling potential of the clayey soil. Conversely, the rice husk ash has a high of aluminosilicates, which fulfills the minimum requirements of pozzolana in accordance with appropriate design standards [7].

3.2. Consistency Index and Swelling Potential of Clayey Soil Modified with Calcined Rice Husk Ash. On a general guiding note, Figure 4 shows specific reaction paths for hydration, calcination, carbonation, and pozzolanic reactions of soil treatment and stabilization. The plasticity/consistency limits of the clayey soil with the addition of rice husk ash activated with CaO (quicklime-activated rice husk ash; QARHA) are presented in Figure 5. It can be observed that the increase in the proportion of the additive (CaO-activated rice husk ash) brought about a substantial reduction in the plasticity of the clayey soil. For instance, on the addition of 1% QARHA by weight of solid, the plasticity of the treated soil reduced by 11.1% compared with the reference test at 0% QARHA. Further on this treatment, at the addition of 5% QARHA, the plasticity was reduced by 20.8% compared to the addition of 4% QARHA and 57.8% reduction in plasticity when compared with the reference test at 0% QARHA. This decrease in plasticity with increased QARHA was maintained until the last proportion of 10% QARHA, which recorded a reduction of 77.8% compared to the reference test at 0% QARHA. This behavior was due to the increased pozzolanic effect of the additive on the soil, which must have increased hydration reaction and eventual reduction of liquid limits at the nucleating surface of the adsorbed moisture clay surface. It is also important to note that the swelling potential of the treated soil is reduced at the same rate as the plasticity because they respond in direct proportionality. This shows also that the swelling potential reduced with the increased proportion of QARHA. Above all, it is important to note that the treated soil reduced from highly plastic ($\approx 17\%$) to medium plastic (7–17%) at 6% QARHA addition and maintained this consistency until the addition of 10% QARHA addition and this agrees with previous findings [33, 37]. Similarly, the swelling potential improved from highly expansive 23.35% at the reference test to low expansive 0.59% at the 10% addition of QARHA [33]. These substantial improvements on the plasticity and swelling potential of the treated expansive clayey soil with the addition of QARHA were due to the activated reactions of aluminosilicate compounds released from RHA by using the calcination action of quicklime. The cation exchange reaction between the dipole negative ions of the treated clayey soil and calcium cations from the activated admixture improved hydration along the stabilization path. This further improved the formation of clogs and flocs in the treated soil, which eventually reduced both the plasticity condition and

swelling potential of the treated soil consistently. The combination of quicklime and RHA formed nucleating strengthening points and surface areas within the double diffused layer of the dipole clay mineral, thereby producing Ca-Al-Si-H, which can be observed in the previous research [4]. This compound is responsible for the flocculation of clayey minerals. This behavior was also possible due to the prolonged hydration of the quicklime for its long-term hydration footprint. As a result, the percentage reduction with higher proportions of quicklime kept increasing as shown in the reduction index recorded above. This further improved the swelling potential presented in Figure 6. This result conforms to the results of previous research works that used quicklime as a binder in clay soil stabilization. Another reason for this achievement in the improvement of both swelling potential and plasticity of the treated soil with the addition of QARHA was that the density of the treated soil was improved with a more dense admixture, which was from the combination of quicklime (density of 3.34 g/cm^3) and RHA (density of 2.13 g/cm^3). Finally, the cementitious properties of the individual additives contributed to the improved volume change and load-bearing properties recorded in the treated clayey soil. This observation agrees with earlier works [38].

The addition of rice husk ash activated with $\text{Ca}(\text{OH})_2$ (hydrated lime-activated rice husk ash (HARHA)) was also studied and there was a consistent reduction in the plasticity and swelling potential of the treated clayey soil with the increased addition of HARHA, as presented in Figures 5 and 6. The percentage reduction in plasticity of the treated was 6.7% at the addition of 1% HARHA compared to the reference test at 0% HARHA. At 5% addition of HARHA, the percentage reduction in plasticity was 8.1% compared to 4% addition and 24.4% reduction compared to the reference test at 0% HARHA, and finally, at 10% addition of HARHA, the percentage reduction in plasticity was 53.3% compared to the reference test at 0% HARHA. Note also that the plasticity of the treated clayey soil maintained a highly plastic consistency but consistently reduced from 45% in the reference test to 21% at the addition of 10% HARHA. Similarly, the swelling potential of the HARHA treated soil reduced consistently and substantially through the entire procedure. This behavior was due to the binding effect of hydrated lime and aluminosilicates from the blended rice husk ash. Calcination reaction and subsequently pozzolanic reaction due to ion exchange and hydration reactions made this improvement in the plasticity of the HARHA treated soil possible. Comparatively, while the percentage reduction with the 1% addition of HARHA was 6.7% compared to the reference test, the 1% addition of QARHA was 11.1%. In addition, at 10% HARHA addition, it recorded a percentage reduction of 53.3% while QARHA recorded 77.8% compared to the reference test. This behavior with the addition of HARHA was due to improved hydration reaction, which utilizes moisture to form flocs during the stabilization protocol. But this later blend recorded a value below that of QARHA addition because QARHA being a hybrid composite of quicklime that requires more moisture than hydrated lime based composites, its rate of hydration in the soil

TABLE 3: Chemical oxide composition of the additive materials.

Materials	Oxides composition (content by weight, %)												
	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	TiO ₂	LOI	P ₂ O ₅	SO ₃	IR	Free CaO
Clay soil	22.45	28.09	2.30	10.66	4.89	12.10	14.33	0.07	—	5.11	—	—	—
Rice husk ash	56.48	22.72	5.56	3.77	4.65	2.76	0.01	3.17	0.88	—	—	—	—

IR is the insoluble residue; LOI is the loss on ignition.

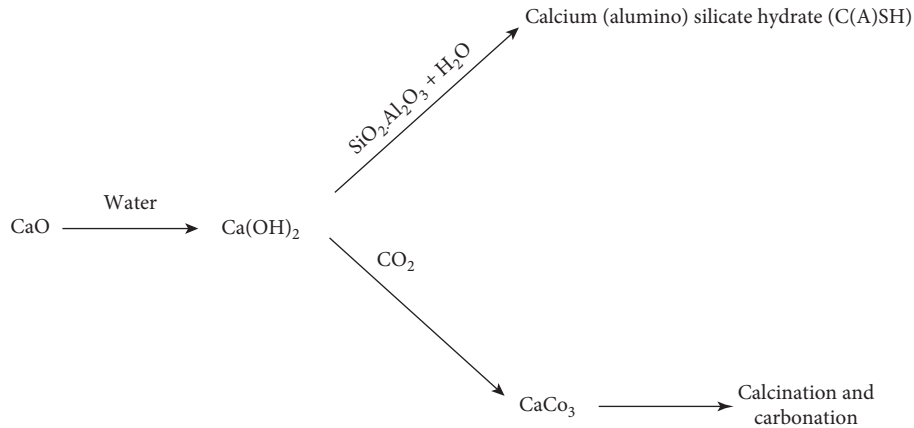


FIGURE 4: Specific reaction paths for hydration, calcination, carbonation, and pozzolanic reactions of soil treatment.

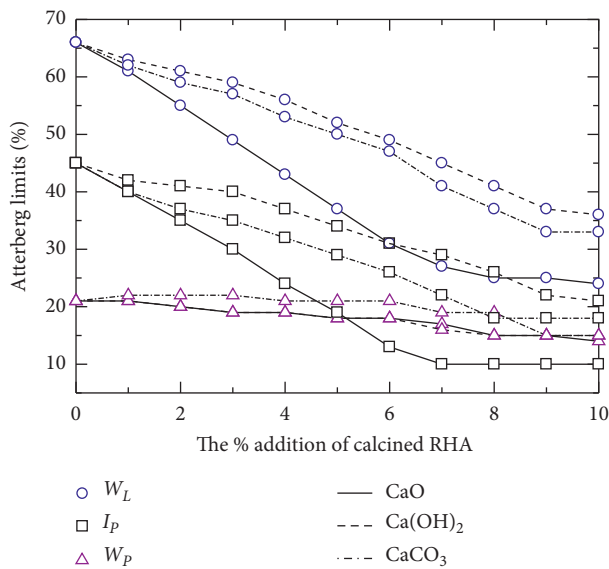


FIGURE 5: Atterberg limits behavior of quicklime (CaO), hydrated lime (Ca (OH)₂), and calcite- (CaCO₃-) activated rice husk ash (QARHA, HARHA, and CARHA) treated clayey soils.

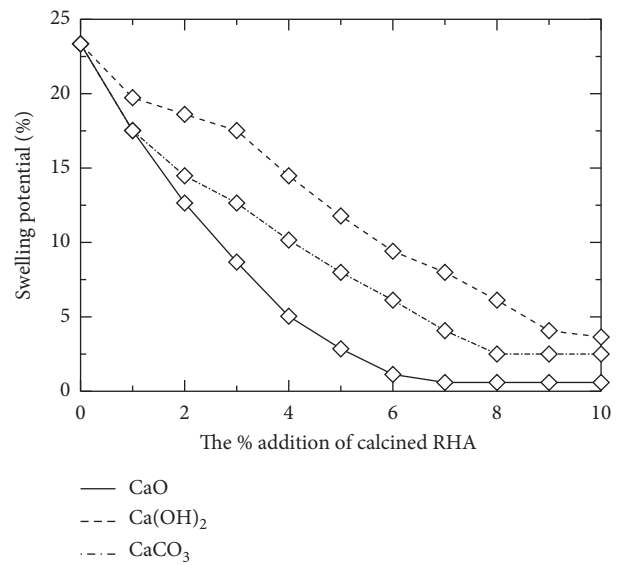


FIGURE 6: Swelling potential behavior of quicklime (CaO), hydrated lime (Ca (OH)₂), and calcite- (CaCO₃-) activated rice husk ash (QARHA, HARHA, and CARHA) treated clayey soils.

stabilization procedure is always higher. This result places QARHA as a better construction binding material for the stabilization of clayey soils. This was due to the fact that QARHA had longer term hydration due to the presence of quicklime than HARHA which had hydrated lime in its composition. The rate of activation between CaO and RHA in the formation of QARHA was higher than that between Ca (OH)₂ and RHA in the formation of HARHA due to a more prolonged hydration resulting from the quicklime present in QARHA. QARHA also had a higher density

composition due to the density of CaO in its composition and hence produced better results in the improvement of plasticity and swelling potential of the treated clayey soil from highly expansive 23.35% with medium expansive 3.64% at 10% HARHA. This is in agreement with the previous work and observations [21].

In Figures 5 and 6, the plasticity and swelling potential of treated clayey soil with the increased addition of calcite-activated rice husk ash (CARHA) is presented. With the addition of 1% additive, the plasticity reduced to a

percentage of 6.7% compared to the reference result (0% additive), equal to the result observed with the use of HARHA. Further with the addition of the additive, the percentage reduction in plasticity was 7.5% at 4% by weight addition of CARHA compared to 3% CARHA record, and around 7% and 8% by weight addition CARHA, the improvement in the plasticity of the treated soil moved to around 10.3% percentage reduction. In addition to this behavior, the improvement in the plasticity of the treated soil was consistent until the addition of 10% by weight of the additive. In the case of swelling potential behavior with CARHA treatment, the clayey soil improved from highly expansive with a potential of 23.35% to medium expansive with a potential of 2.50% in agreement with the findings in previous researches [33, 34]. For comparative reasons, at 5% CARHA addition, the percentage reduction in plasticity compared to the reference test of 0% CARHA was 35.6%. In addition, at 10% CARHA treatment, the percentage plasticity reduction was 60.0%. Generally, the percentage reduction in the plasticity of the HARHA, CARHA, and QARHA treated clayey soil at 1%, 5%, and 10% proportions is 6.7%, 24.4%, and 53.3, 6.7%, 35.6%, and 60.0%, and 11.1%, 57.8%, and 77.8%, respectively. These were achieved through the calcination and pozzolanic reaction path for soil stabilization as presented in Figure 4. The results also show that the swelling potential was influenced more by the QARHA composite formulation which consistently reduced the swelling potential of highly expansive soil of 23.35% (15–25%) to less expansive soil of 0.59% (0–1.5%) in agreement with the findings in previous researches [33, 39–42].

4. Conclusion

The effect of calcination and pozzolanic reaction on the plasticity and swelling potential of clayey highly expansive soil was investigated and the following are concluded:

- (i) The representative soil was observed through laboratory study to be highly expansive, highly plastic, and classified as an A-7-6 soil with high clay content.
- (ii) The rice husk ash was activated with three calcium compounds to form QARHA, HARHA, and CARHA composites.
- (iii) These composites were utilized to treat the expansive soil in varying proportions and results observed.
- (iv) The effect of the treatments on the swelling and plasticity behavior of the treated was observed.
- (v) The three composite additives influenced the soil in a similar pattern reducing the swelling potential and plasticity condition of the soil.
- (vi) While all three additives improved the properties of the clayey soil in a substantial pattern, QARHA was adjudged to be the best binding construction material compared to the effects of HARHA and CARHA on the treated soil.

- (vii) Generally, all three combinations, QARHA, HARHA, and CARHA, were able to improve the swelling potential of the treated expansive soil by substantially reducing the values below and within the permissible standard limits, which are between 0% and 12.6% proposed for a compacted soil material to be used as pavement foundation (subgrade) material. This proves the potential of activated rice husk ash to be used as a sustainable construction material in the foundation of pavements.

Data Availability

The data supporting the results have been included in the paper being considered for publication and in case there is further information needed with regard to this paper, Dr. Kennedy Onyelowe should be contacted at the Kamapala International University, Uganda, or via e-mail: kenedy-chibuzor@kiu.ac.ug.

Conflicts of Interest

The authors declare that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

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