Enhancement of kaolin Clay Soil for Civil Engineering Application Using Rice Husk Ash and Sawdust Ash Geopolymer Cements

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ABSTRACT: These days, good quality road construction materials are scarce and their haulage to the construction site is expensive. When unsuitable materials are encountered during flexible pavement construction, the most technical and economical option is always to improve them to meet design standards. One of these deficient materials mostly encountered in tropical regions is kaolin clay soils. Cement and lime that are traditional deficient soil improvement agents are on high demand therefore have kept the cost of engineering construction financially high. Thus, the use of agricultural wastes such as sawdust and rice husk as alternative construction materials will considerably reduce the cost of construction and as well mitigate the environmental hazards caused by the wastes and cement production. This study investigated and compared the performance of rice husk ash (RHA) and sawdust ash (SDA) geopolymer cements in improving the geotechnical properties of kaolin clay soil used for flexible pavement construction. All laboratory experimental tests were carried out in accordance with British Standard (BS) 1377 and BS 1924 for natural and modified kaolin clay soil samples respectively. Soil samples were mixed with geopolymer cement at stepped concentrations of 0, 4, 8, 12, 16 and 20% by dry weight of soil. Results indicated that the plasticity index value of the natural kaolin clay of 18.52% was reduced to 7.24% at 20% RHA geopolymer cement content. The unconfined compressive strength of the natural soil was improved by 600 and 400 % by RHA and SDA geopolymer cements respectively. It was concluded that the use of up to 20% RHA and SDA geopolymer cements can efficiently and eco-friendly improve kaolin clay for flexible pavement foundation purpose.

KEYWORDS: Weak subgrade, Kaolin clay soil, Sawdust ash, Rice husk ash, Geopolymer cements, Flexible pavements

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I. INTRODUCTION

Soil improvement is usually aimed at treatment of deficient soils to improve their engineering properties and strength characteristics in order to make them permanently become suitable for civil engineering applications and meet design specifications (Salahudeen and Akiije, 2014). In most tropical countries of the world, kaolin clay soils may be so deficient in strength and their stability under working load cannot be guaranteed, especially when in contact with water. In these cases, replacing them with foreign materials will be expensive but rather to improve the in situ soil to meet the desired objective (Osinubi, 1999). However, some kaolin clay soil deposits contain high proportions of kaolinite so much that it is rarely suitable for pavement construction works because of the colloidal conditions (such as plasticity, cohesion, shrinkage, swelling, flocculation and dispersion) conferred upon the kaolinite mineral particles.

In this age of overwhelming vehicular movement, road network are extremely increasing with increase in population which calls for more standard roads and efficient maintenance of the existing ones. In our daily activities, road pavements are important networking means and their construction with standard materials will yield longer service life. In design and construction of flexible pavements, if the subgrade has acceptable bearing capacity, the required materials for the successive layers will be lesser. However, any pavement section built on weak subgrade will be thicker and will require more volume of construction materials for bearing capacity improvement. More so, pavements constructed over weak subgrades are subject to unavoidable pre-mature failures in the like of fatigue and rutting. This problem will be worse in heavy traffic roads (Swamy *et al*., 2021). These days and in most cities, good quality road construction materials are scarce and expensive.

Over the years, deficient flexible pavement foundation soils have been extensively researched on using different means, materials and methods. The two most commonly used stabilizers for active clays are cement and lime (Salahudeen *et al.* 2014). Problem soils improvement with lime is absolutely limited to the warm to moderate climates (Salahudeen and Sadeeq, 2019) but cement may be considered as primary stabilizing agent (Jaritngam *et al*., 2014). However, the high level of usage of industrially manufactured products like lime and cement for deficient soil improvement have made the cost

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of construction projects financially high and unaffordable in some cases (Salahudeen *et al*., 2018a). Thus, the possible use of agricultural wastes such as sawdust and rice husk as alternative construction materials will significantly reduce the cost of construction and as well mitigate the environmental hazards caused by such wastes (Salahudeen and Sadeeq, 2018a; b).

In recent times, researchers in engineering fields have worked towards environmental friendly, efficient and more sustainable systems to protect our planet earth from the degradation of global warming. Cement production contributes to global carbon emissions and hence climate change in several ways and forms. Favier *et al.* (2018) reported that a ton of cement emits 600–900 kg of CO2 as a result of decomposition of calcium carbonate to calcium oxide and due to other processes like energy demand and materials processing. More so, cement production has been accused of accounting for 5–8% of the total global anthropogenic carbon dioxide emissions (Mareike *et al*., 2020). In an attempt to reduce the negative environmental impact of cement in the construction industry, researchers have used ash from agricultural and industrial wastes to partially replace cement.

Globally, approximately 1.3 billion tons of solid waste were generated in 2010, and it is estimated to increase to around 2.2 billion tons a year by 2025 (Araya-letelier *et al*., 2017). The most efficient and eco-friendly solution to this surplus of rice husk and sawdust may be achievable in the building industry's urgent need for alternative construction materials, most of which are composites of the conventional building materials and agro-industrial by-products. The building industry (e.g. structures and highways) has the capacity of making use of rice husk and sawdust in large quantities.

Since soil is suitable for admixing inert agro-industrial wastes, many researchers (Onyelowe *et al*., 2020; 2021; Sadeeq *et al*., 2015a; 2015b; Salahudeen and Sadeeq, 2019; Salahudeen *et al*. 2022) have studied the benefits of adding numerous types of agro-industrial wastes to deficient soils as stabilizing agents.

Rice husk is an agricultural solid waste of the lignocellulosic biomass discharged from the milling of rice paddy (see Figure 1). It is normally disposed on landfills and this practice constitute pollution of the environment. Conversely, Rice husk ash (RHA) is derived from the direct combustion of the rice husk biomass released from rice production. Rice husk is an agro-industrial by-product that is rich in silica. When properly incinerated under controlled burning process, rice husk becomes pozzolanic that is capable of been used to replace lime or cement at various percentages of treatment. Incorporating rice husk ash in cement concrete and mortar mix has been reported to yield high compressive strength results (Mboya *et al*., 2017).

During the milling process of paddy, about 78% of the total weight represents rice, broken rice and bran while the remaining 22% by weight is the rice husk (Khan *et al.*, 2014). Koteswara-Rao *et al.* (2012) discovered that 80-85% of silica is contained in rice husk ash. Rukzon and Chindaprasirt (2008) reported that the properties and reactivity of the amorphous or crystalline silica in RHA depends majorly on the temperature, burning duration and grinding.

The second material used in this research is sawdust. Sawdust is a waste from the wood and timber industry (see Figure 2). Sawdust is the residue generated by saw-teeth when wood is cut into lumber. The main chemical composition of sawdust are carbon (60.8%), oxygen (33.8%), hydrogen (5.2%), and nitrogen (0.9%) (Phonphuak and Chindaprasirt, 2015).

Figure 1: Rice husk in various forms (A) Whole husk (B) Grinded husk during milling (C) Burnt husk (D) Grinded husk at dumb site

Figure 2: Sawdust in various forms depending on saw-teeth

Because of its firing property, sawdust is to generate heat in a process that results in ash residue, one most difficult waste to dispose. Safe disposal of sawdust is unarguably a problem of major concern to our environment in general and to the wood industry in particular. Sawdust can create wildfires during periods of intense heat, (Zepeda-Cepeda *et al.*, 2021).

Wood is one of the oldest fuel sources known to man. Ohunakin (2010) reported that about 80 million cubic metres of fuel wood is being consumed in Nigeria yearly for cooking and other household heating purposes. Onochie *et al.* (2018) reported that the amount of wood waste generated annually in the saw mills is estimated at about 2 million m^3 out of which 20% is sawdust and that Nigerian saw mills skyrocketed from around 500 in 1975 to 1200 in 1981. The current statistics is not well documented but from the trend, it will be in multiple folds in 2022. Since the bulk density of sawdust could be as low as 150 - 200 kg/m^3 (Rominiyi *et al.*, 2017), the 20% it is highly combustible. One of the environmental problems facing cities and towns today is the improper disposal of the wastes being generated daily by the ever-increasing activities of sawmills (Oluoti *et al*., 2014). Abandonment of sawdust causes aesthetic problems and air pollution which could in turn cause respiratory problem in humans.

Geopolymer cement, which is an alkali-activated aluminosilicate binder, is formed by reacting well ground ash that is rich in silica and alumina with a solution of alkali or alkali salts (Aziz and Mukri 2016). Geopolymer is also known as geocement, alkali-activated cement, alkali-bonded ceramic and inorganic polymer concrete. The mixture of silica and alumina materials results in a combination of gels and crystalline compounds that form a new matrix when hardened (Feng *et al.* 2004; Rios *et al.* 2016). Researchers have confirmed that geopolymer cements have yielded appreciable results that indicate improvement in strength, bonding of fine particles and durability characteristics of modified deficient soils compared to cement (Torgal *et al*. 2012). Geopolymer cement performance assessment has yielded high compressive strength, low plasticity and shrinkage and significant resistance to fire and acid and acidic environments. Geopolymerization is the process of geopolymer reaction which determines the strength of bonding. Geopolymerization process is influenced by several factors such as the alkali concentration, Al_2O_3/SiO_2 ratio, curing temperature and time, moisture/solid ratio, heat energy and pH value (Zhang *et al*,. 2013; Sukmak *et al.*, 2013a; b; Abarikwu *et al.*, 2013; Nath and Sarker, 2014; Abdullah *et al.*, 2015).

Geopolymer cements have been successfully used in a steamed or dry heat-cured concretes, a very different environment from geotechnical ground improvement where heat control is practically impossible. As a result, studies on deficient soil improvement with geopolymer cements have always and can only be investigated at ambient temperature (Cristelo *et al.,* 2013; Zhang *et al.*, 2015). Although low temperature do delay the process of geopolymerisation and cause decrease in strength gain in modified soils. To improve the applicability of geopolymer cements in deficient soil modification at ambient temperature and ensure their superiority over cement, lower moisture/binder ratio and higher alkaline activator content should be maintained to reduce the setting time and expedite strength gain (Bernal and Provis, 2014; Abdullah *et al.*, 2015). The two commonly used geopolymer cement of biomass origin are rice husk and sawdust ash geopolymer cements. Reported researches in the literature have been confusing as per which of these waste ashes performs better in geopolymerisation since the usages are with soils of different origins. This study investigated and compared the performance of the two biomass ashes in geopolymerisation process with the same soil type and source. The study aimed at using rice husk and sawdust ash geopolymer cements as alternative binders and efficient and eco-friendly alternative construction material to stabilize kaolin clay soil.

II. MATERIALS AND METHODS

A. Materials

Soil: The kaolin clay soil used for this study was obtained from a borrow pit as disturbed samples at a location within Latitude 9. 988267^0 N and longitude 8.899075^0 E. The location map of the site where the soil was fetched is presented in Figure 3.

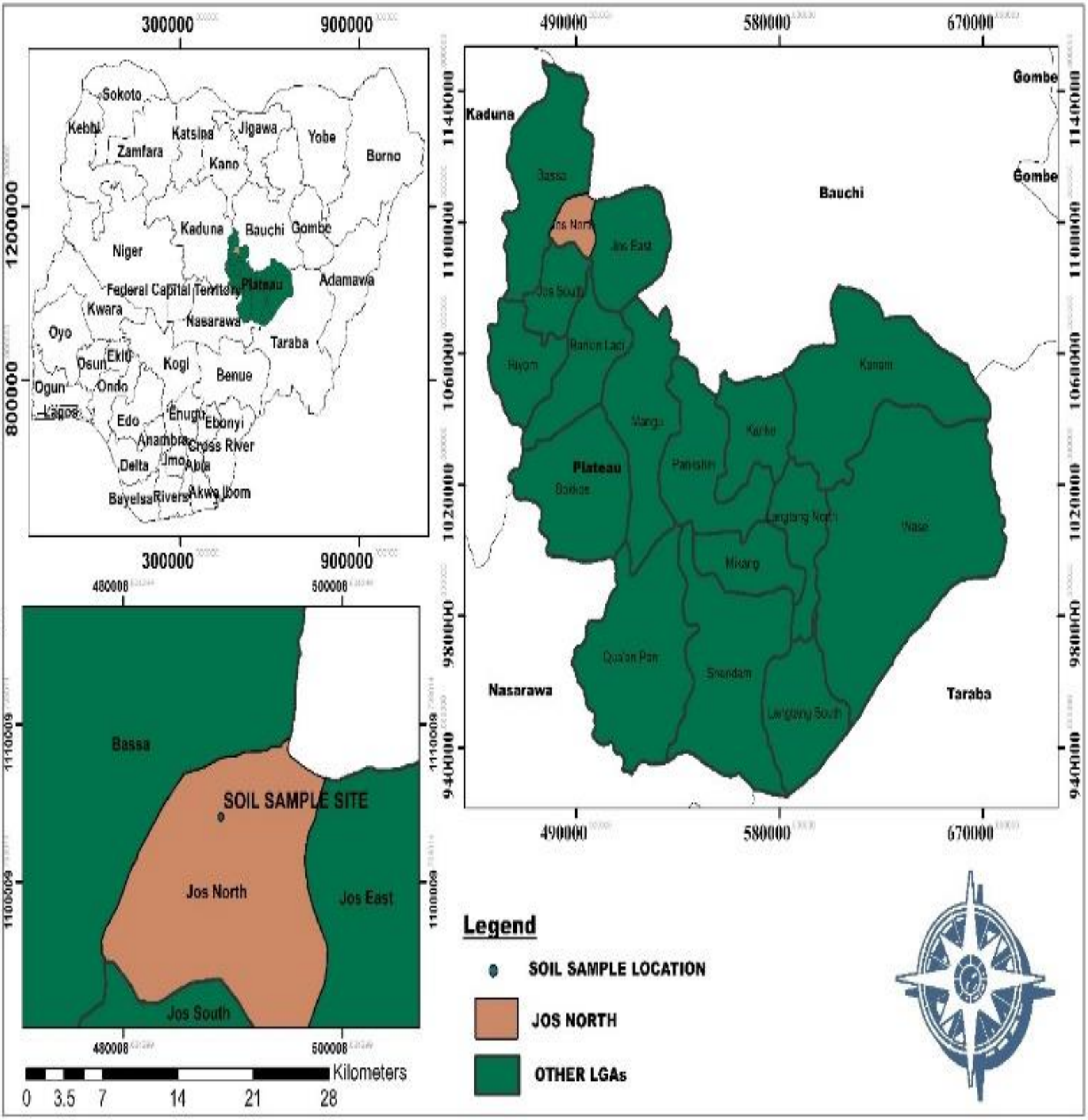

Figure 3: Soil site location map

Rice husk ash (RHA): The rice husk used was locally obtained from a rice mill factory. RHA was produced by burning the dried rice husks in an open air which is the most commonly used approach. The burning process continued in an open air temperature for about 2 weeks. When the rice husk burnt to ash and cooled, the ash was sieved through sieve No. 200 (75µm opening) to obtain the ash.

Sawdust ash: Bulk packages of sawdust was obtained from a timber-processing yard, the same process used on rice husk ash was also followed on sawdust ash.

Alkaline activator: The alkaline activator used for this study is a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

B. *Methods*

General procedures: All laboratory experimental tests were carried out in accordance with BS 1377(1990) and BS 1924 (1990) for natural and modified kaolin clay soil samples respectively. Soil samples were mixed with geopolymer cement (mixture of rice husk ash/sawdust ash and alkaline activator) at stepped concentrations of 0, 4, 8, 12, 16 and 20% by dry weight of soil. The experimental tests conducted include the particle size distribution, Atterberg limits, compaction characteristics, California bearing ratio and unconfined compressive strength tests.

Compaction test: The moisture-density test was performed on the natural and geopolymer cement treated kaolin clay soils using the British Standard light compactive effort as recommended in BS 1377(1990).

Strength tests: The strength tests performed in this study are the unconfined compressive strength (UCS) and California bearing ratio (CBR) tests. They were carried out on both the natural and geopolymer cement treated soil samples. The curing periods considered for the UCS samples were 7, 14 and 28 days before the specimens were tested. The CBR sample preparation and testing were carried out in accordance with the BS procedures and then based on the Nigerian General Specifications (1997) which specifies that specimens be cured in the open air for six days and then soaked for 24 hours before testing.

Oxide compositional analysis: The oxide compositional analysis of rice husk ash (RHA) and sawdust ash (SDA) were carried out using X-ray fluorescence spectrometer (see Table 1). The combined content of calcium oxide and silicon oxide for RHA and SDA are 67.94 and 65.4% respectively. It has been reported by Onyelowe et al. (2020; 2021) and Salahudeen et al. (2022) that one of the compounds that are responsible for strength gain in stabilised soils is calcium silicate hydrates (CSH) derived from calcium oxide and silicon oxide contents of the ash that formed the geopolymer cement. With the relatively high contents of these two oxides in the ashes used for this study, it is hopeful that geopolymer cements made of them will yield impressive results. However, the higher the loss on ignition content of an ash, the lesser will be its strength improvement potential due to its high content of volatile organic content.

Table 1: Oxide composition of rice husk ash a sawdust ash (Concentration in %)

Oxide	Rice Husk Ash	Sawdust Ash
SiO_2	64.2	48.7
SO_3	0.91	0.91
K_2O	4.68	9.1
CaO	3.74	16.7
Fe_2O_3	6.42	5.6
MgO	4.8	0.82
P_2O_5	3.6	-
Loss On Ignition (LOI)	4.65	18.85
MnO	0.43	0.69
ZnO	0.2	2.52
PbO	0.06	9.1
TiO_2	0.64	0.40
NaO	-	0.6
MnO_2	0.35	-

Alkaline activator preparation: The sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) mixture was prepared in ratio of 1:1 which together formed 44% of the geopolymer cement. The sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solution was prepared by mixing water with NaOH and Na_2SiO_3 in a metal container. The geopolymer cement was made up of 56% ash and 44% alkaline activator. The rice husk ash geopolymer cement was prepared separately and used independently from sawdust ash geopolymer cement.

The geopolymer cement was added to the soil in steps of 0,4,8,12,16 and 20% of the dry weight of the natural kaolin clay soil. For every test conducted, a total of eleven (11) specimens of natural kaolin clay soil, rice husk ash geopolymer cement (RHA-GPC) and sawdust ash geopolymer cement (SDA-GPC) treated soil samples were prepared for the experimental investigations. The batching schedule for each investigation is presented in Table 2.

Table 2: Batching Schedule for samples

Sample 1 **Natural kaolin clay soil**	
Sample 2	Sample 7
Kaolin clay soil + 4% RHA-GPC	Kaolin clay soil + 4% SDA-GPC
Sample 3	Sample 8
Kaolin clay soil + 8% RHA-GPC	Kaolin clay soil + 4% SDA-GPC
Sample 4	Sample 9
Kaolin clay soil + 12% RHA-GPC	Kaolin clay soil + 4% SDA-GPC
Sample 5	Sample 10
Kaolin clay soil + 16% RHA-GPC	Kaolin clay soil + 4% SDA-GPC
Sample 6	Sample 11
Kaolin clay soil + 20% RHA-GPC	Kaolin clay soil + 4% SDA-GPC

III. RESULTS AND ANALYSES

A. *Material Properties of the Kaolin Clay*

The kaolin clay used in this study was classified as A-6 and low plasticity clay (CL) soil according to AASHTO classification system (AASHTO, 1986) and the Unified Soil Classification System (ASTM, 1992) respectively. Summary of the soil's properties are presented in Table 3. The presented test results in Table 3 show that the soil is not suitable for flexible pavement construction in its natural state. A subgrade soil with plasticity index of 18.52% and California bearing ratio of 5.45% is in need of improvement by every design standard.

Table 3: Properties of Natural kaolin clay Soil

S/No	Property	Value
1	Colour	Red
2	Percentage passing #200 sieve	56.28
3	Liquid limit (%)	44.93
4	Plastic limits (%)	26.41
5	Plasticity index (%)	18.52
6	Specific gravity	2.37
7	ASHTO Classification	A-6
8	USCS	CL
9	Natural moisture content (%)	18.21
10	Maximum dry density (Mg/m^3)	1.82
11	Optimum moisture content (%)	12.01
12	Carlifonia bearing ratio (%)	5.45
13	Unconfined compressive strength (kN/m^2)	178.65

B. *Improvement in Particle Size Distribution*

The particle size distribution curves of the natural kaolin and geopolymer cement treated soil samples are presented in Figure 4. It can be observed that with increase in admixture (RHA and SDA geopolymer cements content), the curves shifted rightward indicating a decrease in fines content which is an appreciable improvement in the properties of the soil.

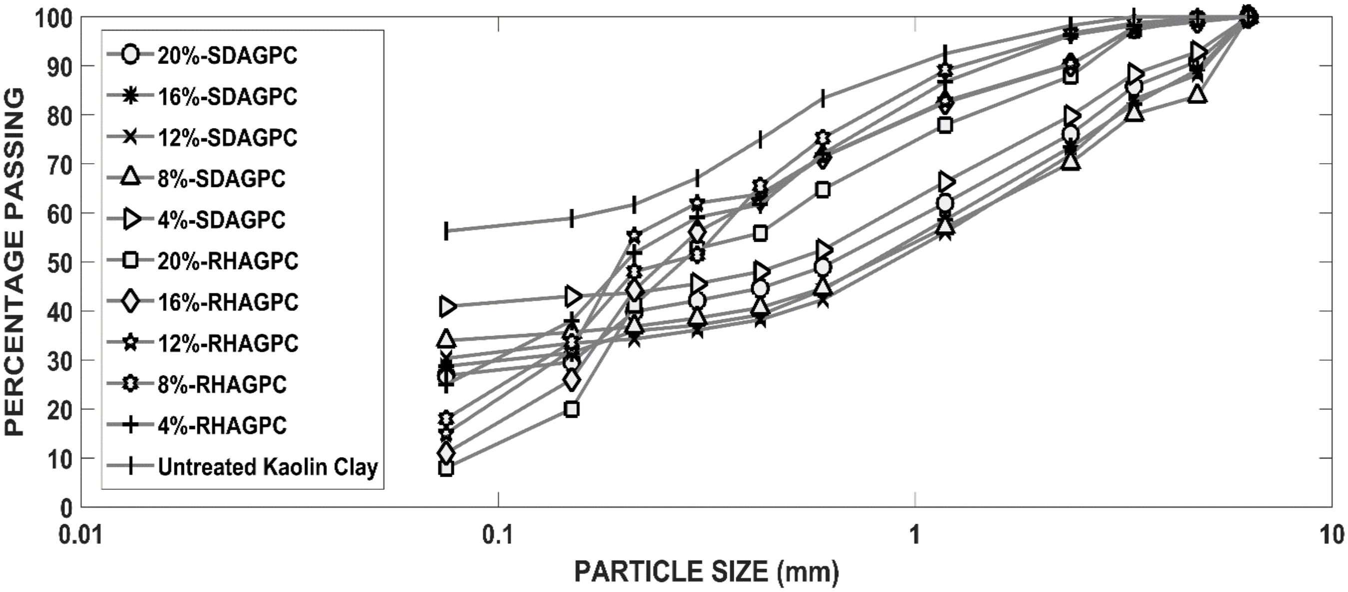

Figure 4: Particle size distribution curves of natural and geopolymer cement treated kaolin clay soil

This improvement is most obvious with SDA geopolymer cement treatments at larger particle sizes of the soil. However, RHA geopolymer cement outperformed the SDA geopolymer cement on the reaction with finer particles when they reduced the percentage passing the #200 sieve drastically. At 20% RHA geopolymer cement treatment, the percentage passing the #200 sieve was reduced to 8% against the 50.28% of the natural untreated soil. This is an indication of cementation reaction between geopolymer cement and kaolin clay minerals which enhanced the formation of coarser particles (Salahudeen *et al*, 2014).

C. *Consistency Limits of Geopolymer Cement Treated Kaolin Clay*

The consistency limits are very important soil characterization and classification parameters. The variation of Atterberg limits of treated and untreated kaolin clay soil with geopolymer cement content is shown in Figure 5. The addition of both RHA and SDA geopolymer cements into the soil resulted in a continuous decrease in the Atterberg limits. The decrease can be associated with the addition of geopolymer cements which added more pozzolanic substances into the soil specimen thereby reducing their plasticity. This observed trend is in agreement with Venkaramuthyalu *et al*. (2012), Sadeeq *et al*. (2015), Onyelowe *et al.* (2021). The plasticity index value of the natural kaolin clay of 18.52% was reduced to 7.24% at 20% RHA geopolymer cement content. This result satisfied the recommendation of the Nigerian General Specifications (1997) that specified a maximum value of 12 % plasticity index for materials to be used for flexible pavement sub-base.

Suhail *et al.* (2008) and Venkaramuthyalu *et al.* (2012) concluded that the reduction in plasticity index with chemical modification is as a result of the depressed double layer thickness due to cation exchange by calcium, potassium and ferric ions. From the oxide composition analyses of the RHA and SDA used for this study, these mentioned ions are significantly present. According to Nath *et al.* (2018), these desired changes in engineering properties of the treated soil are technically attributed to flocculation of the clay minerals, cation exchange reaction, agglomeration process and pozzolanic reactions. In general, the improvement of the consistency properties of kaolin clay is higher when treated with RHA geopolymer cement than SDA geopolymer cement treatment.

D. *Moisture-Density Properties*

The maximum dry density (MDD) of a soil is an important parameter that is used to determine the amount of compaction and densification of achieved both in the laboratory and in the field. It has a direct link with the strength potential of the soil. The variation of maximum dry density (MDD) of the treated and untreated kaolin clay is presented in Figure 6. The MDD decreased upon introduction of geopolymer cements (4% RHA/SDA content) and thereafter increased with higher geopolymer cements content. The initial observed decrease in MDD may be due to the lower specific gravity of RHA and SDA compared with that of soil and insufficient geopolymer cement content for pozzolanic reaction and agglomeration of clay particles (Sadeeq *et al.* 2015a). The subsequent increase in MDD could be as a result of the flocculation and agglomeration of clay particles due to exchange of ions (Osinubi, 2000). The trend is in agreement with the findings reported by Iorliam *et al.* (2012) and Sadeeq *et al.* (2015a; b). Peak values of 1.93 and 1.88 Mg/m^3 were obtained at 20% RHA and SDA geopolymer cement content respectively.

The variation of optimum moisture content (OMC) of kaolin clay with geopolymer cement content is shown in Figure 7. The OMC increased continuously with increase in geopolymer cement content. This trend conforms with results reported by Nath *et al*. (2018). This may be due to additional water demands for the formation of $Ca(OH)_2$ compounds and its dissolution into Ca^{2+} and OH^- ions which is required to release more Ca^{2+} ions for cation exchange reaction. Salahudeen *et al*. (2014) opined that the this trend was as a result of increased demand for moisture to balance up with the higher content of geopolymer cement needed for its hydration

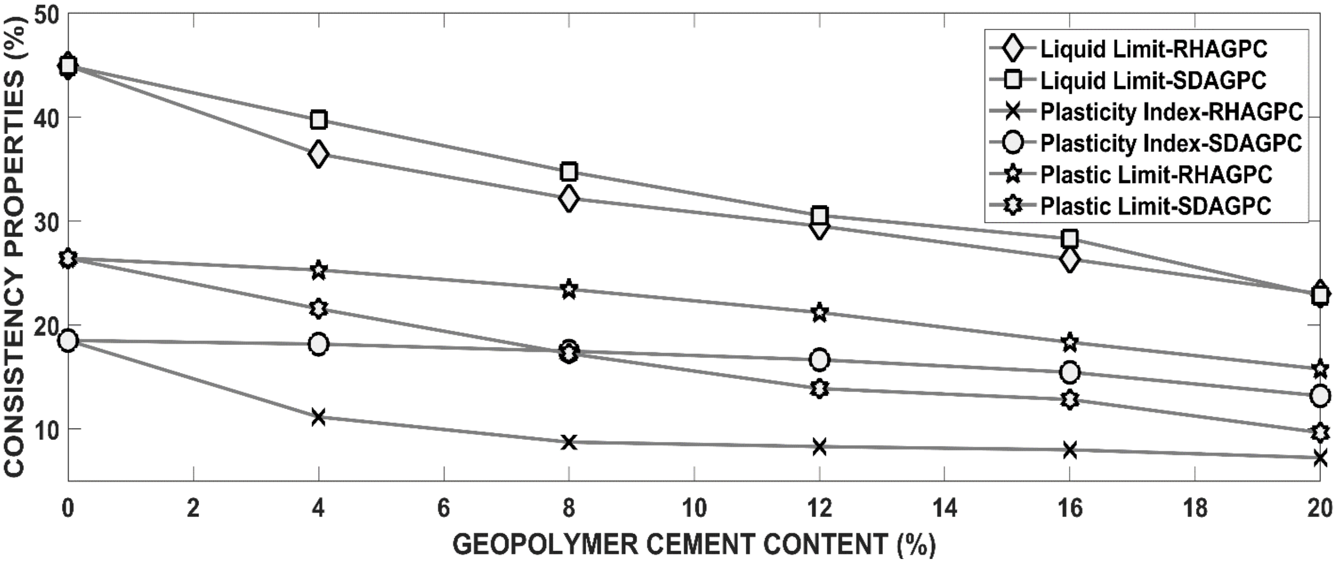

Figure 5: Consistency limits of natural and geopolymer cement treated kaolin clay soil

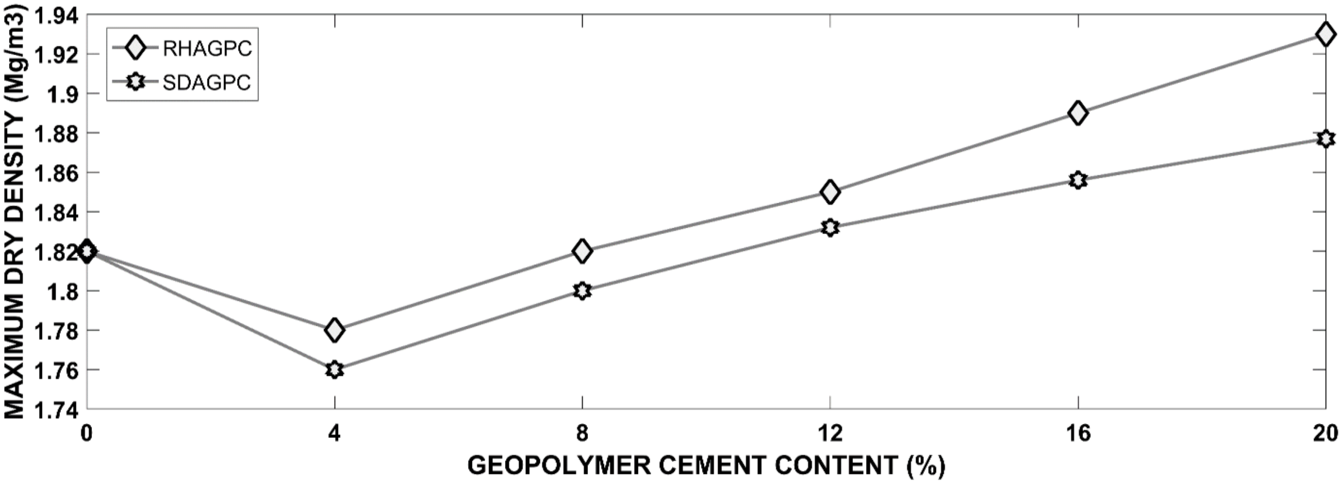

Figure 6: Variation of maximum dry density of natural and geopolymer cement treated kaolin clay soil

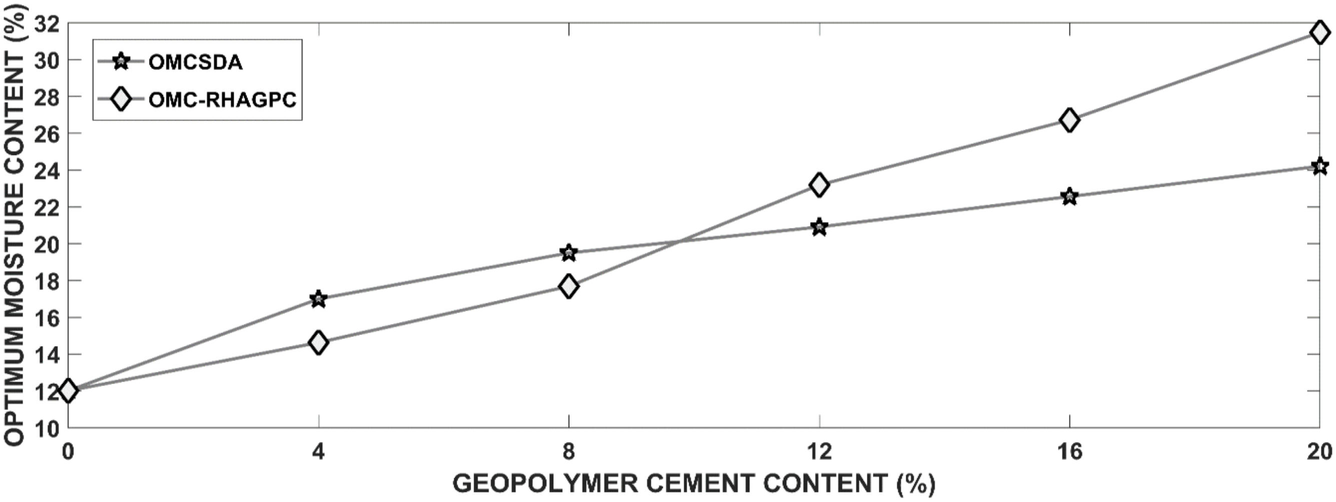

Figure 7: Variation of optimum moisture content of natural and geopolymer cement treated kaolin clay soil

reaction and dissociation required for cation exchange reaction.

E. *Strength Characteristics*

1) *Unconfined Compressive Strength*

The unconfined compressive strength (UCS) test is one of the most competent strength tests for soils which indicates the soil's load bearing capacity under axial compression. The variation of UCS of kaolin clay with geopolymer cement content for 7, 14 and 28 days curing periods are shown in Figure 8. The UCS values generally increased with increase in geopolymer cement content. The observation may be due to ion exchange that takes place at the surface of clay particles. In this process, the Ca^{2+} in geopolymer cement reacted with the lower valence metallic ions in the kaolin clay microstructure to cause agglomeration of the clay particles (Sadeeq and Salahudeen 2017; 2018). Additionally, that increase in UCS values could be as a result of chemical compounds formations which include calcium silicate hydrates and calcium aluminate hydrates and changes in the micro fabrics, which are in charge of strength gain in the soil matrix (Osinubi *et al*., 2011; Sadeeq *et al*., 2015b).

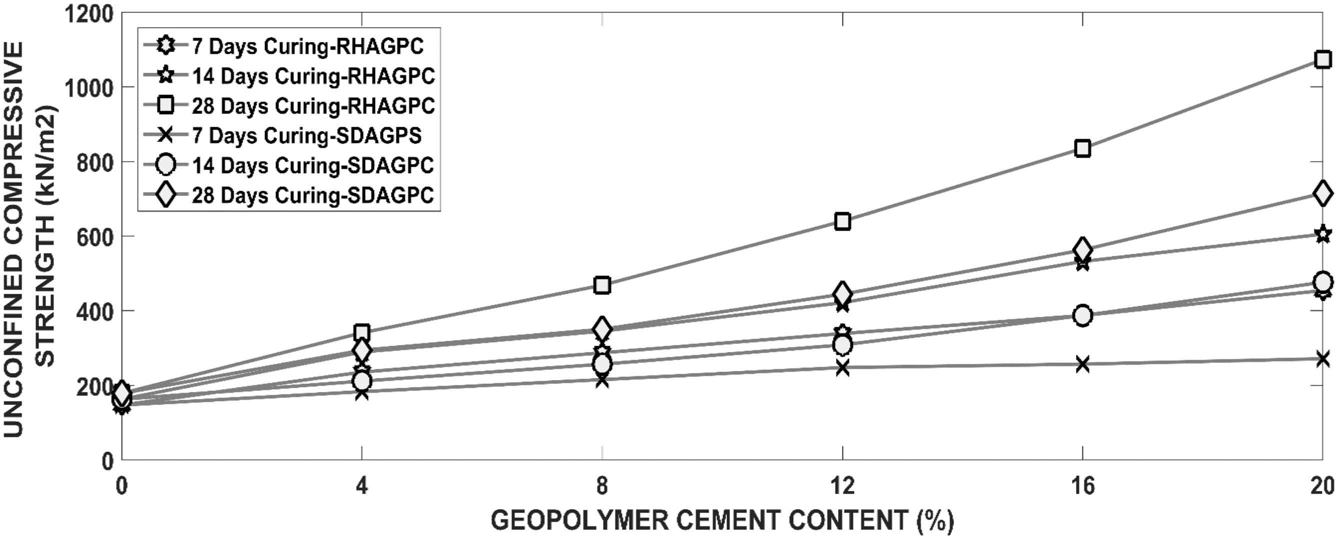

Figure 8: Variation of unconfined compressive strength of natural and geopolymer cement treated kaolin clay soil

It was observed that the UCS values increased with increase in geopolymer cement content and also with increase in curing age. A very commonly associable reason for this improvement is formation of cementing gels or hydrates resulting from the reactions between the soil's Al_2O_3 and SiO_2 and CaO of ash. This reaction resulted in agglomeration of the kaolin soil fine particles into larger particle sizes that caused the increased compressive strength. The peak values of 1073.35 and 714.94 kN/m^2 respectively for RHA and SDA geopolymer cements were observed at 28 days curing period. This result is in similar to the observations of Osinubi *et al*., (2011), Salahudeen *et al*. (2014) and Sadeeq *et al*. (2014). It should be noted that, though the strength of the natural deficient kaolin clay soil (with UCS value of 178.65 kN/m^2 at 28 days curing period) improved with both RHA and SDA geopolymer cements treatment, the values fell short of the 1710 kN/m^2 UCS value recommended by TRRL (1977) as a condition for adequate stabilization with Ordinary Portland Cement. However, the peak values of 1073.35 kN/m^2 (600.81% increment from the untreated sample value) for the RHA geopolymer cement treatment and 714 kN/m^2 (400.19% increment) for the SDA geopolymer cement treatment are recommendable for use in relatively low traffic flexible pavements. The observed gain in strength is proved from the scanning electron microscopy of the samples as presented in Figure 9. All samples were tested after 28 days of curing. For the treated soils Figure 9 (b) and (c), 10% treatment was considered for economy of the geopolymer cement.

2) *California Bearing Ratio*

The variation of the 6 days cured and 24 hours soaked CBR values of the kaolin clay soil with geopolymer cement contents are presented in Figure 10. Generally, the CBR values increased with increase in geopolymer cement contents. This increase may be as result of the abundant quantity of Ca needed for the formation of the two major compounds responsible for strength development (calcium silicate hydrate and calcium aluminate hydrate).

The CBR value increased from 5.45% for the untreated soil to peak values of 40.75 and 25.98% for the RHA and SDA geopolymer cement contents respectively. These peak CBR values satisfied the 20 – 30% requirement recommended by Gidigasu and Dogbey (1980) for sub-base materials compacted at OMC. These achieved CBR values are satisfactory for subgrade and sub-base materials.

IV. CONCLUSION

The kaolin clay soil used in this study was classified as A-6 soil according to AASHTO classification system. The soil has plasticity index of 18.52%, unconfined compressive strength value of 178.65 kN/m2 after 28 days curing and California bearing ratio of 5.45%. This soil in its natural state is not suitable for pavement construction and is in need of improvement to be usable for civil engineering applications.

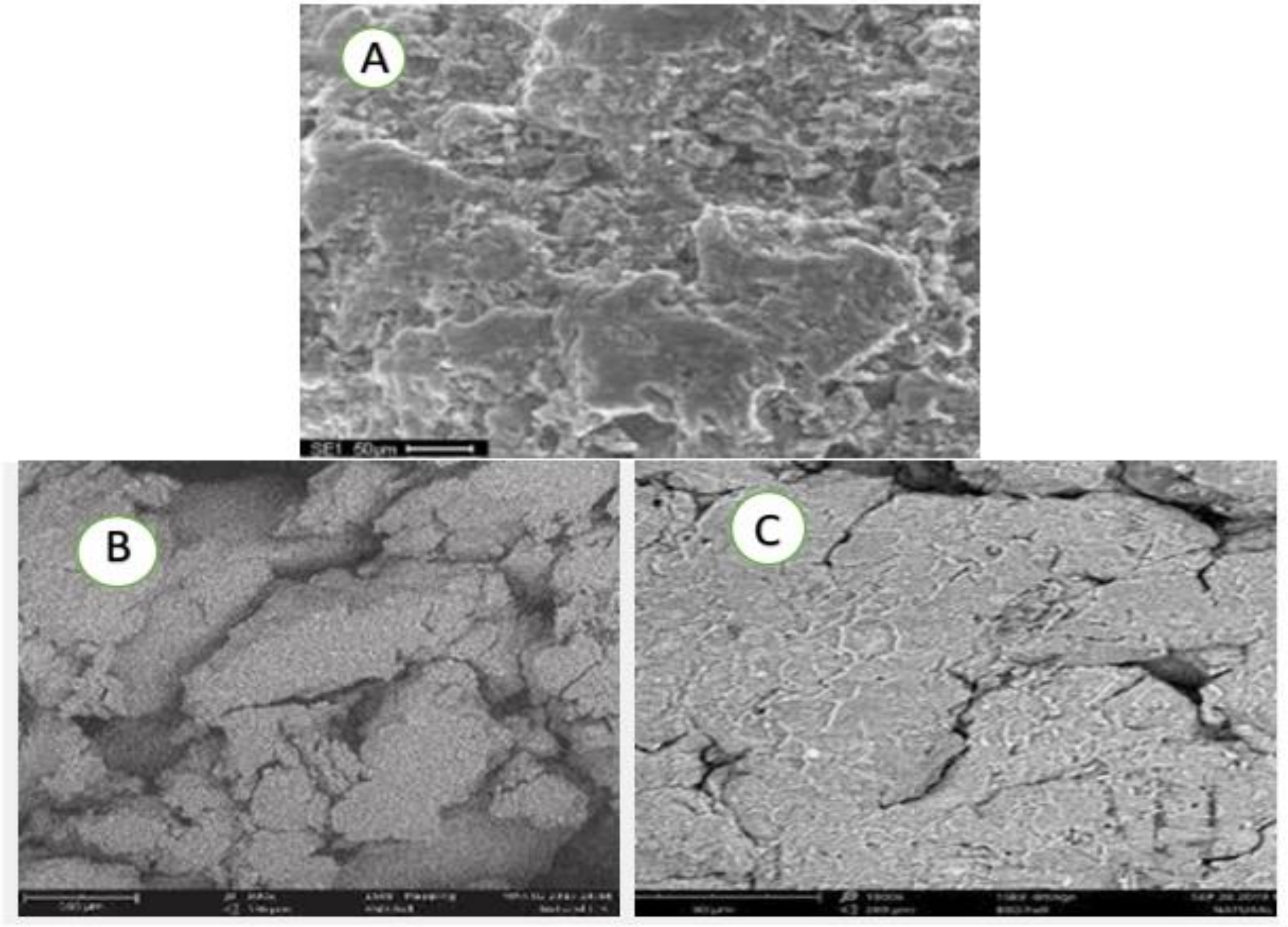

Figure 9: Scanning electron microscopy of (a) natural kaolin soil (b) RHA-GPC (c) SDA-GPC

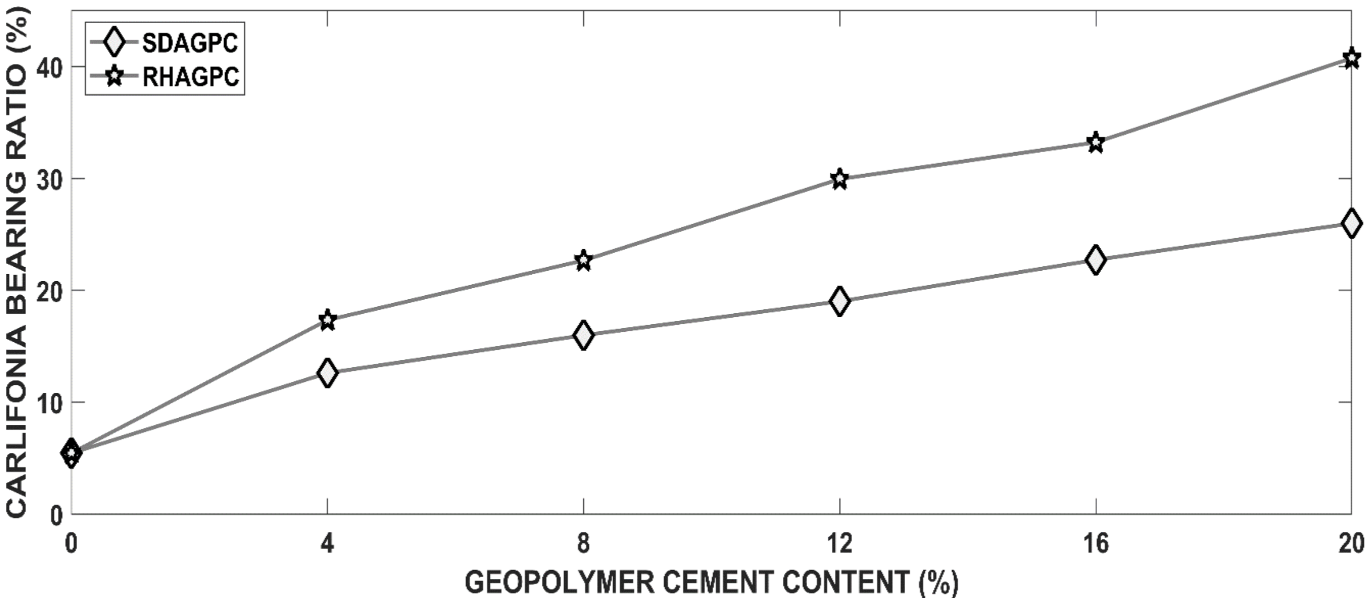

Figure 10: Variation of California bearing ratio of natural and geopolymer cement treated kaolin clay soil

The soil was stabilized using RHA and SDA geopolymer cements. The following conclusions were drawn from the study results:

1) Treatment of the soil with RHA and SDA geopolymer cements caused decrease in the percentage of fines. RHA geopolymer cement reduced the percentage passing the #200 sieve to 8% against the 50.28% of the natural untreated soil.

2) The plasticity index value of the natural kaolin clay of 18.52% was reduced to 7.24% at 20% RHA geopolymer cement content. This result satisfied the specification of the Nigerian General Specifications (1997) recommended the maximum acceptable value of 12 % plasticity index for sub-base materials.

3) The maximum dry density (MDD) peak values of 1.93 and 1.88 Mg/m3 obtained at 20% RHA and SDA geopolymer cement content respectively against the 1.82 Mg/m3 of the natural soil were desirable improvements on the soil.

4) The unconfined compressive strength yielded peak values of 1073.35 and 714.94 kN/m2 respectively for RHA and SDA geopolymer cements at 28 days curing period. Although the UCS value of 178.65 kN/m2 observed for the natural deficient kaolin clay soil subsequently improved with both RHA and SDA geopolymer cements treatment, none of the values satisfied the 1710 kN/m2 limiting value specified by TRRL (1977) as a condition for adequate stabilization using Ordinary Portland Cement. However, these peak values are recommendable for use in relatively low traffic flexible pavements.

5) The CBR value increased from 5.45% for the untreated soil to peak values of 40.75 and 25.98% after RHA and SDA geopolymer cement treatments respectively. These peak CBR values satisfied the 20 – 30% recommended value by Gidigasu and Dogbey (1980) for sub-base materials when compacted at OMC.

AUTHOR CONTRIBUTIONS

A. B. Salahudeen: Writing – original and final drafts, Conceptualization, Software, Validation, Supervision. **N. S. Kpardong and P. M. Francis:** Laboratory experimentation, Methodology.

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