

Geotechnical Properties Of Cement Stabilized Sand Partially Replaced With Kaolinite (A Case Study Of Arola Village, Ede, South Western, Nigeria)

Olabisi Ismaila Ogundiji^a *, Olugbenga Oludolapo Amu^b,

^aDepartment of Civil Engineering, Faculty of Engineering, Federal University Oye Ekiti

^bDepartment of Civil Engineering, Faculty of Engineering, Federal University Oye Ekiti

Abstract

The persistent requirement for sustainable construction practices in recent times necessitates the need to execute more research on possible sustainable construction materials. An example of a possible way to reduce the emission of greenhouse gases and consequent global warming is to substitute cement with another sustainable construction binder such as kaolinite. The commercial production of cement is a major stakeholder in releasing CO₂ into the environment, hence the need for more studies on substitute binders. The current study therefore explored the soil geotechnical properties of partially replaced cement with kaolinite clay in some cement-stabilized sand samples of controlled quantities. The adopted mix design of the studied soil samples is such that 0 - 100% of Arola sands were stabilized with 6% cement, which serves as the controlled sample. Thereafter, the control sample were replaced with 0 - 100% of industrial kaolinite, respectively. The soil sample were subjected to geotechnical and strength properties test. The specific gravity of the kaolinite is 2.4 while that of the sand sample is 2.62. In accordance with the American Association of state highway officials classification system, the Arola sample was categorized as A-7-5, fair to poor soil or poorly graded sand. The optimum shear properties were found at 50:50% of cement to kaolinite, whereas sand samples containing 6% cement exhibited the best with least plasticity index and 50:50% as best strength properties values when the latter was substituted with the former. Therefore, this research contributed to further understanding of sustainable construction materials.

Keywords: Geotechnical properties, Cement, Stabilization, Sand, Kaolinite

Introduction

Sustainable construction materials are those that have minimal negative impacts on the environment and promote the conservation of resources throughout their life cycle, from extraction and manufacturing to disposal or reuse. These materials aim to reduce the ecological footprint of the construction industry, which is traditionally resource-intensive and pollutes the environment. Sustainable materials are selected based on factors such as renewability, energy efficiency, durability, recyclability, and their ability to minimize waste and emissions.

The current study focuses on the assessment of the geotechnical characteristics and strength properties of some laboratory-constituted sand-cement-kaolinite soil matrix relative to a controlled sand-cement sample of 0-100% percentage by weight. The 6% cement content were latter replaced with 25% interval by weight of kaolinite clay, respectively.

Growing knowledge of environmental damage, resource depletion, and climate change has prompted more attention on sustainable building methods. Creating environmentally friendly buildings and infrastructure that are energy-efficient, have reduced carbon footprints, and advance the well-being of people depends

critically on sustainable building materials. Green concrete, which includes recycled elements like fly ash, slag, and other naturally occurring materials, e.g., kaolinite clay which takes less energy to manufacture, is a typical example of a common sustainable building material [31]. One of the main causes of global warming and other climate change agents is the increasing CO₂ generation into the surroundings [20].

Projects using sustainable building materials may have social, financial, and environmental advantages as well as cheaper running costs, less pollution, and better comfort and health for building occupants.

Mostly consisting of the mineral kaolinite, an aluminium silicate (Al₂Si₂O₅) [8], kaolinite clay, often known as china clay, is a fine, white clay mineral. It is formed by the weathering of feldspar-rich rocks, particularly in warm, moist climates. Kaolinite is highly valued for its wide range of applications, particularly in ceramics, paper production, rubber, and cosmetics, due to its excellent chemical inertness, fine particle size, whiteness, and ease of dispersion in water. Kaolinite clay is naturally deposited in Nigeria in abundance. Therefore, its economic exploration and application needs to be harnessed. Hence, the inspiration of the current study.

1.1 Description and Geology of the study area

The Arola Village in Ede, near Oshogbo, the Osun state capital Nigeria, lies in Latitude 7.6491740 and Longitude 4.4737140 is in Osun State, southwestern region of Nigeria.



Figure 1.1: Study area Map adapted from Google imageries

Arola Village is underlain by an ancient Precambrian Basement Complex dominated by metamorphic and igneous rocks such as granite, schist, and gneiss, which contribute to the mineral richness of the soils. Overlying these hard rocks is a weathered soil layer of variable thickness that serves as the primary groundwater source for wells and boreholes in the area. The soils are predominantly sandy-clay with moderate to high permeability, influencing drainage characteristics and agricultural productivity. Lateritic soils, rich in iron and aluminium oxides and typically reddish in colour, are widespread due to intense tropical weathering and support specific crops and vegetation types. Groundwater occurs mainly within fractured and weathered zones of the basement rocks, forming discontinuous aquifers with variable yields,

while seasonal rainfall significantly affects groundwater recharge and water table levels. The terrain is gently undulating with low to moderate hills that promote surface runoff during the rainy season, leading to the formation of seasonal streams and small rivers that are vital for local agriculture and water supply. Vegetation, originally typical of the tropical rainforest zone, has been altered by urban development and farming activities, resulting in a landscape dominated by scattered trees, shrubs, and grasslands adapted to lateritic soil conditions

Methodology

2.1. Materials and Equipment

This study adopts a combined experimental and analytical research design to investigate the geotechnical characteristics of a sand–cement–kaolin mixture. This approach is aimed at evaluating the influence of kaolin on the strength properties and overall behaviour of the sand–cement system under varying conditions, including its strength, stiffness, durability, and deformation characteristics. To achieve this, a detailed and systematic research methodology is employed throughout the study. The materials used are carefully selected and characterized because their properties directly affect the performance of the mixture. Arola sand, classified as fine to medium sand, is selected and examined for key physical properties such as particle shape, specific gravity, particle size distribution, and gradation. Ordinary Portland Cement (OPC) is used as the binding agent, with emphasis placed on its type, composition, and hydration characteristics. Kaolin clay, chosen for its known particle size distribution, mineral composition, and purity, is also incorporated into the mixture and tested for specific gravity, plasticity index, and chemical composition to better understand its role and behaviour within the sand–cement–kaolin system.

2.2. Soil sampling and preparation

Different proportions of sand, cement, and kaolin are prepared to investigate the effects of varying mixture compositions on the geotechnical properties of sand–cement–kaolin systems. The control mixture consists of 95% sand and 5% cement by weight, while kaolin is introduced as a partial or total replacement of cement at proportions of 0%, 25%, 50%, 75%, and 100%. In all mixtures, the sand–cement ratio is maintained, and a constant water-to-cement ratio is adopted to ensure uniformity and comparability of results. The materials are carefully mixed to achieve homogeneity, with kaolin first dry-mixed with sand before the addition of cement and water. Sample preparation is carried out in accordance with the requirements of each laboratory test, with appropriate procedures and precautions observed under controlled conditions. Following preparation and curing, the geotechnical behaviour of the mixtures is evaluated through preliminary soil tests, compaction tests, and triaxial shear tests. Index property tests conducted for soil classification include moisture content determination, Atterberg limits, particle size distribution, and specific gravity, all of which are carried out in accordance with the provisions of BS 1377:1990.

2.3. Preliminary and geotechnical analysis of soil samples

A Preliminary and geotechnical analyses were carried out to evaluate the fundamental engineering properties of the soil samples and to establish a basis for assessing the influence of cement and kaolin stabilization. These analyses provide essential information on soil classification, behaviour, and suitability for engineering applications. The preliminary tests focused on determining the index properties of the natural sand and the stabilized mixtures, while the geotechnical tests assessed their strength and deformation characteristics.

The preliminary analysis included the determination of natural moisture content, particle size distribution, Atterberg limits, and specific gravity. Particle size distribution tests were conducted to classify the soil and to evaluate the effects of cement and kaolin addition on grading characteristics. Atterberg limits tests were performed mainly on the kaolin-modified mixtures to assess changes in plasticity behaviour resulting from the incorporation of fine clay particles. Specific gravity tests were conducted to support soil classification and to aid in compaction and strength analysis. All index property tests were carried out in accordance with BS 1377:1990.

Geotechnical analysis involved compaction and strength testing of the prepared sand–cement–kaolin mixtures. Standard compaction tests were conducted to determine the optimum moisture content and maximum dry density of each mixture, providing insight into the effects of varying kaolin replacement levels on compaction characteristics. Strength properties were evaluated using triaxial shear tests to determine parameters such as shear strength, cohesion, and angle of internal friction. These tests were carried out under controlled laboratory conditions to ensure consistency and reliability of results.

The combined results from the preliminary and geotechnical analyses enabled a comprehensive assessment of the engineering behaviour of the soil samples and the stabilized mixtures. This approach facilitated the evaluation of kaolin as a partial or total replacement for cement and its effectiveness in improving or modifying the geotechnical performance of sand–cement mixtures for construction and ground improvement applications.

3.0 Results and Discussion.

3.1 Results and Discussion of Geotechnical Properties of the Natural Soil

Results of the test carried out are presented for soil classification and to know the behaviour of the natural soil sample.

A. Specific gravity of natural soil Sample

Specific gravity is the ratio of mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at the same temperature. It indicates the density of the materials and in soil helps in further classification of the soil. The result of specific gravity of the soil sample are presented in Table 4.1. Specific gravity of the natural soil sample was obtained to be 2.62 and specific gravity for most real soil ranges between 2.60 and 2.90. as reported by [13], thus, soil samples from Arola village in Ede fall in these categories within the specified range. See table 1.1

Table 1.1: Result of Specific gravity of Natural soil sample

Weight of empty bottle (g)	27.64	26.65
Weight of bottle + Soil (g)	53.54	51.09
Weight of bottle + Soil + Water (g)	97.63	95.14
Weight of bottle + Water (g)	81.55	79.90
Specific Gravity	2.64	2.60
Average Value	2.62	

B. Particle size analysis of natural soil Sample

Figure 1.1 shows soil classification according to their texture and grains sizes. The soil sample was subjected to hydrometer test and graph of the grain size analysis performed on the soil sample is presented in Figure 4.1 below. It was observed that the soil sample is fine grained soil since it has a very higher percentage fines passing 75 μ m sieve that is greater than 35% according to AASHTO (1996). The percentage fines passing sieve no 200 is 69.62%, percentage of sand contained in the soil sample is 25.58%, percentage of gravel is 4.80%, while percentage of silt is 48.60% and percentage of clay is 20.70%. Therefore, the soil sample is described as fair to poor soil according to American Association of State Highway Transportation Official (AASHTO), the soil belongs to A-7-5 that is fair to poor in term of sub-grade flexible pavement rating. The engineering implication of soils with higher fines is that, they are poor for road works and such soils may require stabilization.

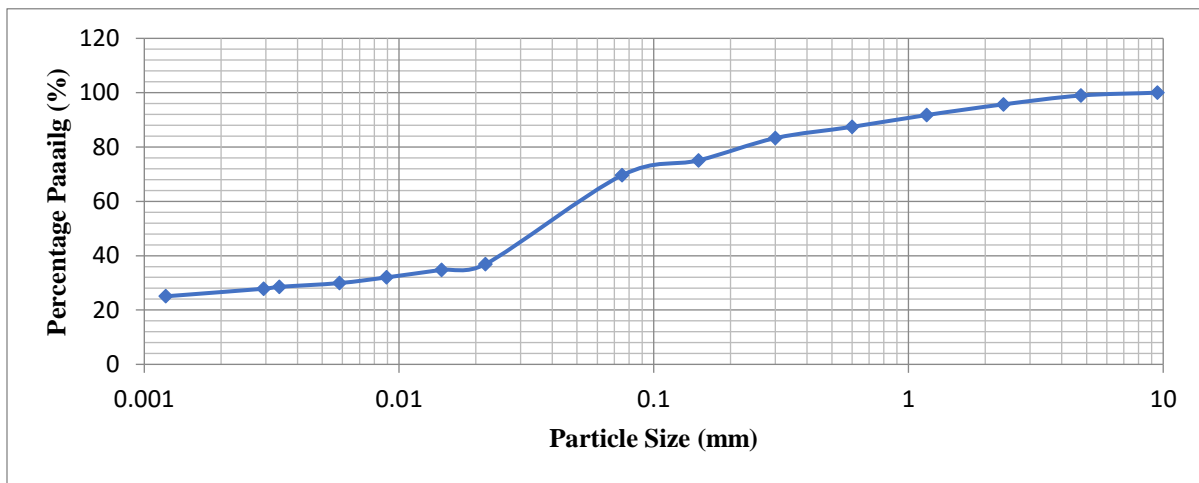


Figure 1.1: Graph of Particle size distribution of Natural soil sample.

C. Atterberg limit of natural soil Sample

Atterberg limits evaluate the relationship between the moisture content and soil consistency. The result of Atterberg limits' behaviour of the natural soil sample is presented in Table 4.2. The Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL) and the Plasticity Index (PI), which is the difference of LL and PL are presented below.

The results of Atterberg limits presented showed that Liquid limits of the soil sample is 56.80%, plastic limit is 30.48%, shrinkage limit is 9.52% and the plasticity index is 26.32%. The difference between Liquid limit and Plastic limit was recorded as the Plasticity limit and FMWH (1997) stated that liquid limit (LL) and Plastic limit (PL) shall not greater than 35 and 12% respectively for materials suitable for subgrade, sub-base and base courses. The results of the Atterberg limit test showed that the sample did not meet this requirement of FMWH 1997 and therefore need for improvement of the soil sample.

D. Preliminary strength test of natural soil Sample

The results of preliminary strength tests of the selected soil sample are presented in table 1.2. The Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) for the soil sample from the studied location are as followed Maximum Dry Density of 1832 Kg/m³, Optimum moisture content is 17.50%, California Bearing Ratio of 14.40%, and unconfined compressive strength is 481.34 kN/m². FMWH (1997) stated that MDD, OMC, CBR and UCS shall not be less than 1680 kg/m³, 18%, 5% and 103kN/m² for cure strength respectively. (i.e. MDD > 1680

kg/m³, OMC<18%, CBR>5% for cure strength and UCS minimum of 103kN/m² for cured strength) respectively for materials to be suitable for sub-grade course.

Table 1.2 Preliminary results of Natural soil sample

		Results
Colour		Reddish Brown
Specific Gravity (G _s)		2.62
Particle size analysis	% Gravel	4.82
	% Sand	25.58
	% Fine	69.90
	% Silt	48.60
	% Clay	20.70
Atterberg limits test	LL (%)	56.80
	PL (%)	30.48
	PI (%)	26.32
	SL (%)	9.52
Compaction	MDD (kg/m ³)	1832.00
	OMC (%)	17.50
California Bearing Ratio (%)		14.35
Unconfined Compressive Strength (kN/m ²)		481.34

AASHTO classification	A-7-5
Laterite class ($\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$)	0.997
Soil Type	Laterite

E. Atterberg limit of stabilized State

Atterberg limits is used in determine the plasticity of soil in its natural and stabilized state with different percentages of selected soil (kaolinite) through the determination of the liquid and plastic limit. Liquid limit is arbitrarily defined as the amount of water content present in a given soil in percent, which is soil path in a cup cut by grooving tool will flow together at the base of the groove. Plastic limit is the moisture content that defines where the soil changes from semi-solid to plastic state.

In this research, the stabilization of soil sample with cement to determine the optimum cement content and thereby replace the optimum cement content with kaolinite has been observed and cement generally decreased the plasticity index of the soil sample stabilized with cement to 6% content and thereafter increased the plasticity index. The 6% cement stabilized soil sample was replaced with kaolinite and it is noticed that the liquid limit, plastic limit and plasticity index of the stabilized soil sample is increasing with increasing optimum cement and kaolinite content and thereafter decreased with replacement with kaolinite

Table 1.3 Atterberg limit of cement stabilized soil sample

Cement content	LL (%)	PL (%)	PI (%)	SL (%)
0% cement	56.81	30.78	26.03	9.52
2% cement	49.81	32.97	16.84	9.5
4% cement	49.75	36.87	12.88	8.5
6% cement	47.75	35.55	12.20	7.04
8% cement	52.15	36.88	15.27	6.43
10% cement	52.08	35.85	16.23	6.43

Table 1.3 show that cement stabilization significantly improves the consistency and plasticity characteristics of the soil. The untreated soil exhibits high liquid limit and plasticity index, indicating high plasticity and poor engineering behaviour. As cement content increases up to about 4–6%, the liquid limit and plasticity index decrease markedly, reflecting reduced water affinity, improved workability, and enhanced soil stability due to cementation. The shrinkage limit also decreases with increasing cement content, indicating reduced volumetric changes on drying. At higher cement contents (8–10%), slight increases in liquid limit and plasticity index are observed, likely due to additional water demand for cement hydration; however,

these values remain lower than those of the natural soil. Overall, cement contents of approximately 4–6% provide the most effective improvement in plasticity and shrinkage characteristics.

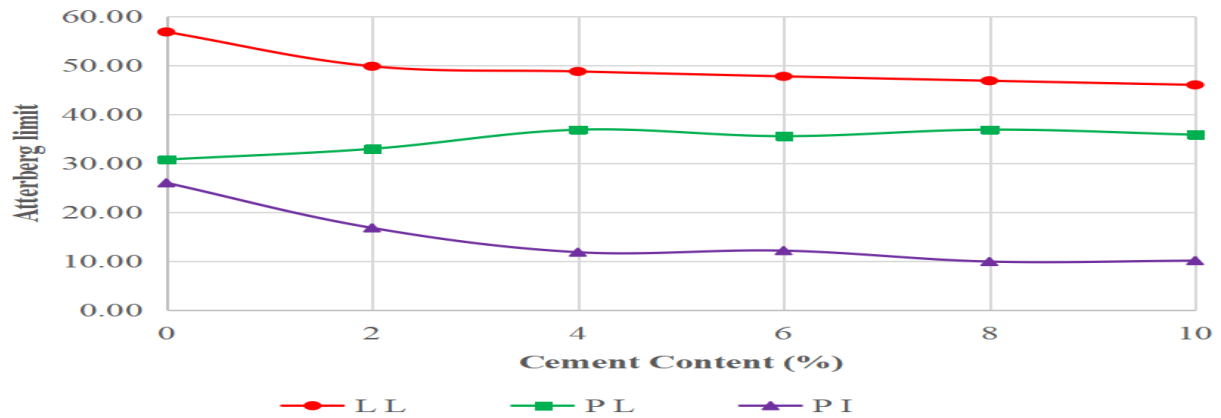


Figure 1.2 Graph of Atterberg limit with cement stabilized soil sample

Figure 1.2 shows that increasing cement content significantly improves the consistency characteristics of the soil. The liquid limit generally decreases with cement addition, indicating reduced water affinity, while the plastic limit increases, reflecting improved workability. The plasticity index decreases sharply as cement content increases, demonstrating effective reduction in soil plasticity and moisture sensitivity. The most notable improvement occurs between 4% and 6% cement content, beyond which further cement addition results in minimal changes. Overall, the graph confirms that cement stabilization enhances soil stability and engineering performance.

Table 1.4 Atterberg limit of sand cement-kaolinite stabilized soil sample

Cement : Kaolinite	LL (%)	PL (%)	PI (%)	SL (%)
6% cement:0% Kaolinite	47.75	35.55	12.20	7.04
25% cement:75% Kaolinite	47.25	35.87	11.38	6.50
50% cement:50% Kaolinite	48.05	37.65	10.40	6.00
75% cement:25% Kaolinite	47.15	36.95	10.20	6.05

0% cement:100% Kaolinite				
	47.05	36.07	10.98	6.05

Table 1.4 shows that replacing cement with kaolinite has a minimal effect on the liquid limit, as values remain nearly constant across all mixtures. The plastic limit generally increases with kaolinite inclusion, indicating improved workability, while the plasticity index decreases, showing reduced soil plasticity. The shrinkage limit also slightly reduces, suggesting better volumetric stability. Overall, the combined use of cement and kaolinite maintains or improves soil consistency characteristics, with balanced cement–kaolinite proportions giving the most favorable reduction in plasticity.

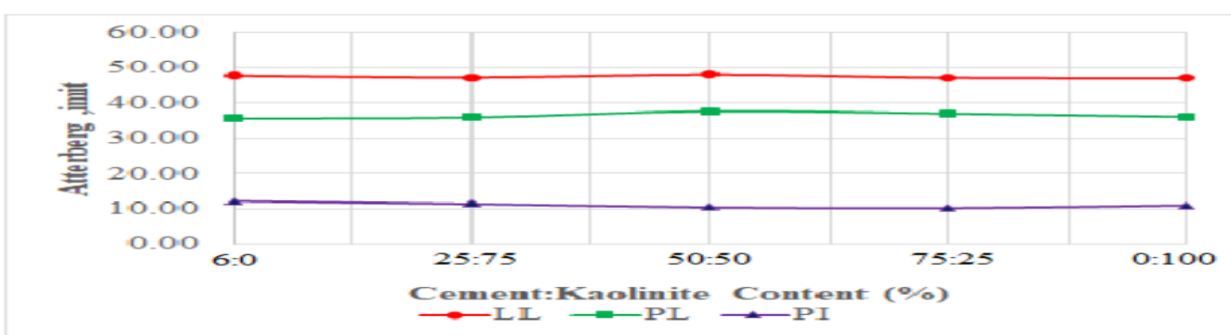


Figure 1.3 Graph of Atterberg limit of sand cement-kaolinite stabilized soil sample

Figure 1.3 shows that varying cement–kaolinite proportions causes only minor changes in the liquid limit, indicating stable water-holding capacity of the soil. The plastic limit increases slightly at intermediate replacement levels, reflecting improved workability, while the plasticity index generally decreases, showing reduced soil plasticity. The lowest plasticity occurs at balanced cement–kaolinite ratios, particularly around the 50:50 mixture. Overall, the graph confirms that partial replacement of cement with kaolinite maintains favorable consistency characteristics and improves soil stability.

3.2 Results and Discussion of Strength Properties of Sand – cement with Kaolinite Mixtures

A. Compaction

Compaction tests were carried out with the aim of determining the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of a soil sample. Compaction tests results carried out on the soil sample showed that increased in MDD of the soil was achieved when stabilizing with cement compared with the natural soil sample. Table 1.5 presented the summary results of stabilized soil sample with cement and kaolinite mixture, as the mix content is been varied the strength of the soil is increasing to 50:50% of cement and kaolinite mixture before its later declined. Table 1.5 and figure 1.4 show that there are variations in the maximum dry density and optimum moisture content for different contents which leads to increase in MDD and OMC of the stabilized soil sample before the MDD decreased afterward. The decreased in MDD with increasing cement and kaolinite mixture content is not unconnected to the initial simultaneous flocculation and agglomeration of clay particles caused by cation exchanged leading to increase in volume and decrease

in dry density. This is in line with the works of [30] and [17]. The stabilized soil sample meet up with the recommended values of > 1760 kg/m³ MDD for subgrade but did not meet the requirement of > 2000 kg/m³ for sub-base and base courses as specified by AASHTO (2011).

Table 1.5 Compaction results of soil cement – Kaolinite varied stabilized soil sample

Cement : Kaolinite	MDD (kg/m ³)	OMC (%)	CBR (%)	UCS (kN/m ²)
0% cement:0% Kaolinite	1832	16.65	14.75	482.56
6% cement:0% Kaolinite	1852	14.48	15.78	507.99
25% cement:75% Kaolinite	1888	14.05	18.95	511.75
50% cement:50% Kaolinite	1930	13.85	19.01	523.78
75% cement:25% Kaolinite	1902	13.00	19.55	465.25
0% cement:100% Kaolinite	1895	13.55	18.78	460.15

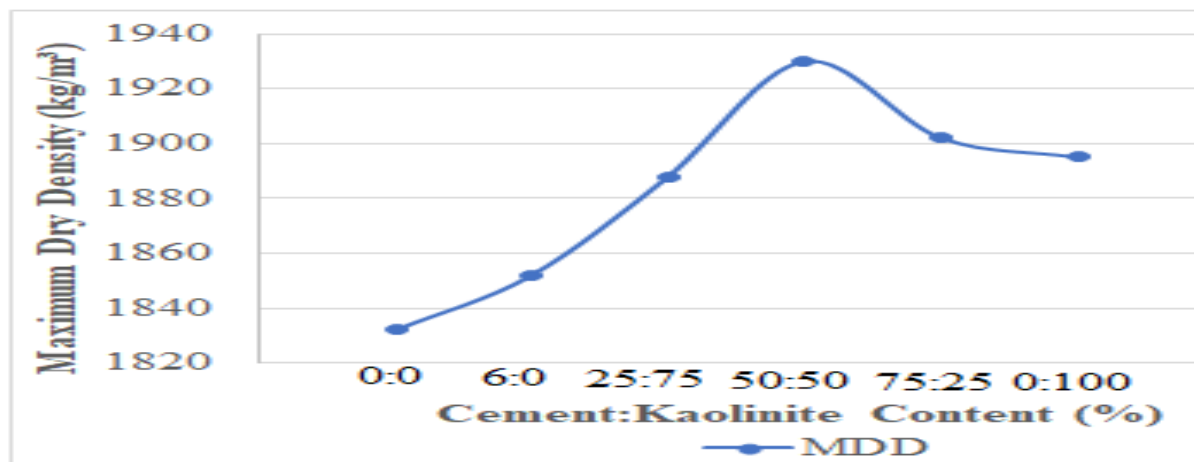


Figure 1.4 Graph of Compaction characteristics test (MDD) of sand cement – Kaolinite Stabilized soil sample

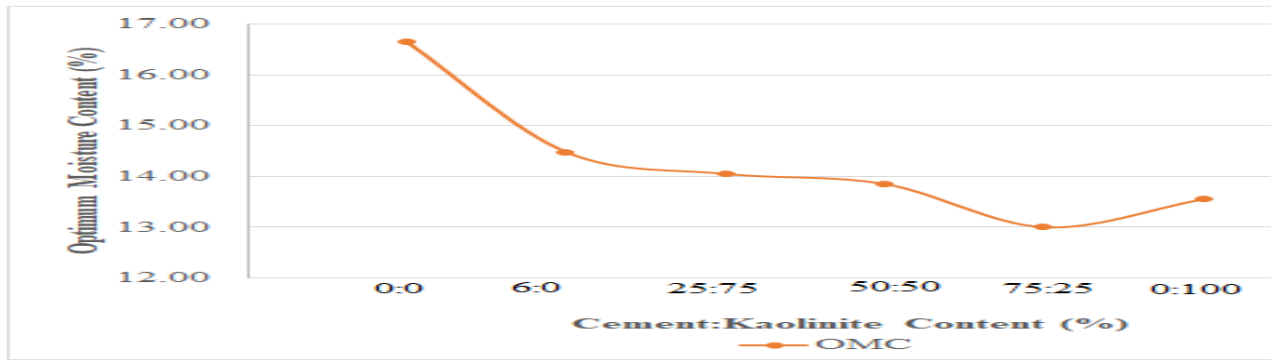


Figure 1.5 Graph of Compaction characteristics test (OMC) of sand cement – Kaolinite Stabilized soil sample

B. California bearing ratio (CBR)

The results of California Bearing Ratio values of additives with optimum cement content and cement with kaolinite stabilized soil sample are shown in Figure 1.6 below. From the test result shown below there were significant effects of the cement with kaolinite used for the research on the stabilized soil sample. When stabilizing the soil sample, there were increased in strength to 75% cement to 25% kaolinite content thereafter decrease is recorded at 0% cement:100% Kaolinite content and the results obtained was still able to exhibit the minimum standard required for sub-grade but not meeting requirement for sub-base and base for CBR meet the minimum standard required for sub-grade FMWH (1997) recommended a CBR value > 30% for sub-base, must not be lesser than 80% for base and CBR value > 5% for sub-grade materials.

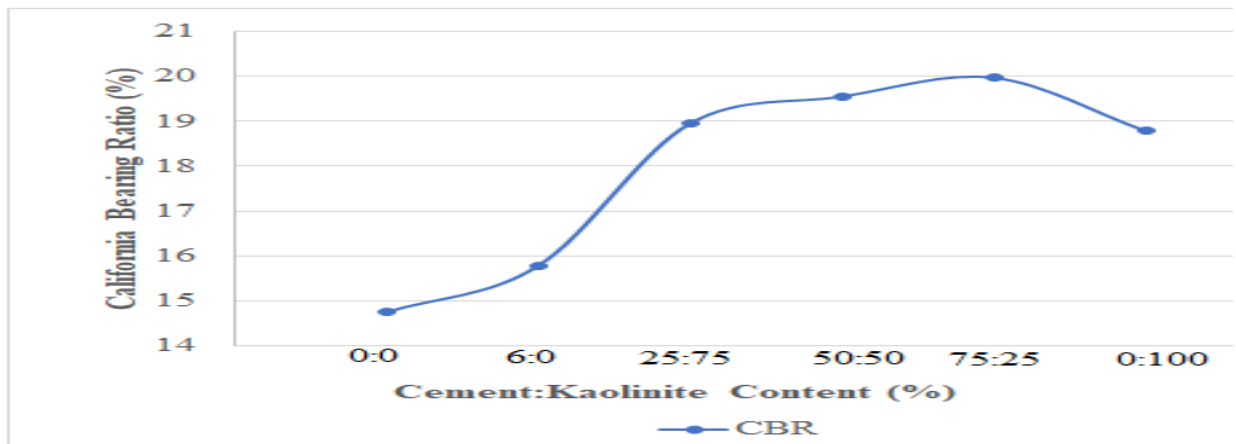


Figure 1.6 Graph of California bearing ratio test of sand cement – Kaolinite Stabilized soil sample

C. Unconfined compressive strength (UCS)

Unconfined compressive strength (UCS) test is a special type of unconsolidated-undrained test that is commonly used for clay specimens where the confining pressure (δ_3) is zero and the major principal stress (δ_1) is the unconfined compressive strength (q_u) according to [9]. Unconfined compressive strength is also the test for the determination of the required amounts of additives to be used in the stabilization of the soil [28]. The results of the unconfined compressive strength test of the soil sample shown significant improvement in strength as the stabilizing materials. The improvement in the strength of the soil increases as the cement:Kaolinite content increases but decreases with increased to 75% cement:25% Kaolinite content which is a typical of the additives behaviour as reported in line with the work of [17]. The results of test results was presented figure 1.7.

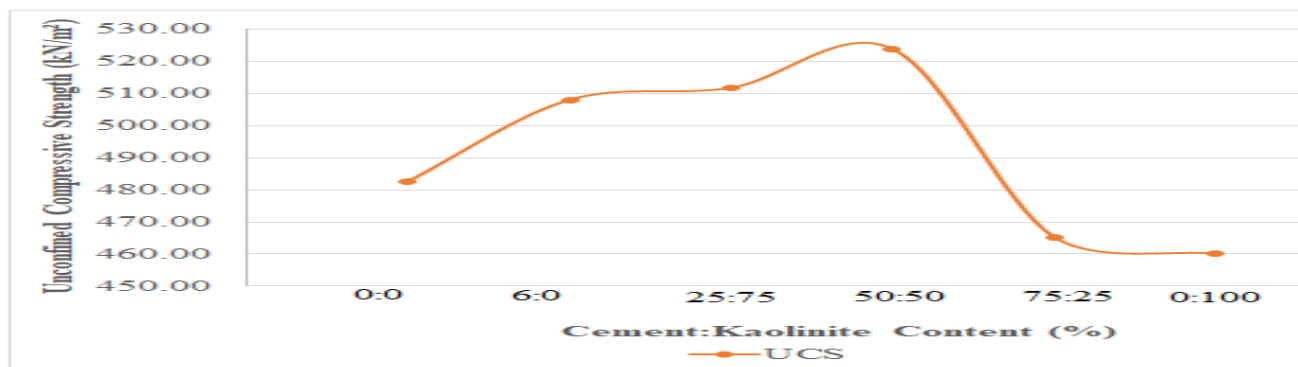


Figure 1.7 Graph of unconfined compressive strength test of sand cement – Kaolinite Stabilized soil sample

3.3 Results and Discussion of Optimal Kaolinite Contents of Cement Stabilized Sand

The results of strength test i.e., Compaction characteristics, California bearing ratio and unconfined compressive strength tests reveal that optimum kaolinite content of cement stabilized sand was achieved with addition of 50:50 of cement and kaolinite for compaction characteristics, 75:25% of cement to kaolinite content for California bearing ratio and 50:50% of cement to kaolinite ratio for unconfined compressive strength and its in line with the work of Amu et al., 2010.

The optimum values shows an increased in strength properties with addition of cement and kaolinite in ratio before decrease were recorded with the strength properties which is in line with the work of [29]

4. Conclusion

This study extensively investigated the geotechnical properties of sand stabilized with cement partially replaced by kaolinite. The sand obtained from the study area was classified as lateritic soil and identified as clayey soil (A-7-5), reddish-brown in colour, and generally unsuitable for use as base course material in road construction due to its fair-to-poor engineering quality. Cement stabilization carried out at 2%, 4%, 6%, 8%, and 10% revealed that an optimum cement content of 6% produced the most favorable improvement in soil properties. Based on this optimum cement content, kaolinite was introduced as a partial replacement and blended with the cement to further stabilize the soil. The results showed that the inclusion of kaolinite significantly enhanced the strength characteristics of the cement-stabilized soil, with strength

parameters increasing as the cement–kaolinite mixture content increased. An optimum maximum dry density (MDD) of 1930 kg/m³ was achieved at a 50% cement–50% kaolinite ratio, while the optimum California Bearing Ratio (CBR) of 19.55% occurred at a 75% cement–25% kaolinite mixture. The highest unconfined compressive strength (UCS) of 523.78 kN/m² was recorded at a 50% cement–50% kaolinite proportion. These findings demonstrate that partial replacement of cement with kaolinite can achieve high stabilization efficiency, reduce cement consumption, and provide a cost-effective and sustainable alternative to conventional soil stabilization methods, with kaolinite acting effectively as a supplementary binder in the presence of optimum cement content. ronmental impact, and promote sustainable waste utilization.

References

- [1] American Association of State Highway and Transportation Officials, AASHTO (1993). Recommended Practice for the classification of soils and soil-Aggregate Mixtures for highway construction purposes: AASHTO designation M 145-91, standard specifications for transportation materials and methods of sampling and testing. Washington DC, USA.
- [2] Abdullah, M. E., Jaya, R. P., Shahafuddin, M. N. A., Yaacob, H., Wan Ibrahim, M. H., Nazri, F. M., Ramli, N. I., & Mohammed, A. A. (2018). Performance of Kaolin Clay on the Concrete Pavement. IOP Conference Series: Materials Science and Engineering, 358, 012049. <https://doi.org/10.1088/1757-899X/358/1/012049>
- [3] Adeniyi, A. G., Iwuzor, K. O., & Emenike, E. C. (2023). Material Development Potential of Nigeria’s Kaolin. Chemistry Africa, 6(4), 1709–1725. <https://doi.org/10.1007/s42250-023-00642-2>
- [4] Ahmadullah, T., & Chrysochoou, M. (2024). Relationship between strength development and pozzolanic reactions in lime stabilized kaolinite. International Journal of Geo-Engineering, 15(1), 11. <https://doi.org/10.1186/s40703-024-00212-6>
- [5] Ali, A. K., & Hussain, Z. (2018). Shear strength of cement-stabilized desert sand with partial kaoline replacement. Journal of Geotechnical Engineering, 144(2), 109–118.
- [6] Amu, O.O., Aransiola, J.O. and Ogunbona, T.P. (2010). Influence of palm kernel shell with the husk ask on cement-stabilized lateritic soil. Electronic Journal of Geotechnical Engineering 15/E: 449-460, USA.
- [7] Archibong, G. A., Sunday, E. U., Akudike, J. C., Okeke, O. C., & Amadi, C. (2020). A review of the principles and methods of soil stabilization. International Journal of Advanced Academic Research: Sciences, Technology and Engineering, 6(3), 89–105.
- [8] Aroke, U. O. , E.-N. U. A. , O. O. A. (2013). Properties and characterization of kaolin clay from Alkaleri North-Eastern Nigeria. International Journal of Emerging Technology and Advanced Engineering, 3(11), 387–392.

- [9] Bello, A. A., Ojelade, A. E., & Oriaje, A. T. (2015). Stabilization of Soil with Cassava Peel Ash– Lime Admixture. *Stabilization of Soil with Cassava Peel Ash – Lime Admixture*, 7(11).
- [10] Bolarinwa, A. (2022). The Effects of Kaolinite-Clay on the Undrained Strength Characteristics and Static Liquefaction Behavior of East Coast Sand. Auckland University of Technology, Auckland, New Zealand.
- [11] Bumanis, G., Korjamins, A., & Bajare, D. (2022). Environmental Benefit of Alternative Binders in Construction Industry: Life Cycle Assessment. *Environments*, 9(1), 6. <https://doi.org/10.3390/environments9010006>
- [12] Cao, Y., Wang, Y., Zhang, Z., Ma, Y., & Wang, H. (2021). Recent progress of utilization of activated kaolinitic clay in cementitious construction materials. *Composites Part B: Engineering*, 211, 108636. <https://doi.org/10.1016/j.compositesb.2021.108636>
- [13] Das, B. M. (2010). *Principles of Geotechnical Engineering* (7th ed.). Stamford, USA: Cengage Learning.
- [14] Dawodu, F. A., & Akpomie, K. G. (2014). Simultaneous adsorption of Ni(II) and Mn(II) ions from aqueous solution onto a Nigerian kaolinite clay. *Journal of Materials Research and Technology*, 3(2), 129–141. <https://doi.org/10.1016/j.jmrt.2014.03.002>
- [15] Fatoye, F. B., & Gideon, Y. B. (2013). Geology and occurrences of limestone and marble in Nigeria. *Journal of Natural Sciences Research*, 3(11).
- [16] Federal Ministry of Works, Lagos (1997). Nigerian General Specification “Bridges and Road works” 11(4): 769-777.
- [17] Gupta, B.L. and Kumar, A. (2016). *Highway and Bridge Engineering*, 3rd edition, Standard Publishers Distributors, Delhi, 275-282.
- [18] Gushit, J. S., Olotu, P. N., Maikudi, S., & Gyang, J. D. (2010). Overview of the availability and utilization of kaolin as a potential raw material in chemicals and drug formulation in Nigeria. *Continental Journal of Sustainable Development*, 17–22.
- [19] Hailu, H., Chimdi, J., Gudissa, D., & Tadesse, F. (2021). The Effect of Partial Replacement of Cement with Kaolin Powder in the Production of C-25 Concrete. *Journal of Xidian University*, 15(5), 578–585. <https://doi.org/10.37896/jxu15.5/063>
- [20] Hossien, M., Alsawwaf, M., & Nasar, A. M. (2021). Shear strength characteristics of cemented clayey sand soil. *Journal of Engineering Research*, 5(2).
- [21] Kevin, O. K., Habibu, A. S., Adejoh, B. O., & Mustapha, A. (2023). Effect of Activated Lime and Kaolin as Partial Replacement for Cement in Concrete Structure. *Journal of Applied Sciences and Environmental Management*, 27(5), 1035–1038. <https://doi.org/10.4314/jasem.v27i5.23>

- [22] Khaiyum, M. Z., Sarker, S., & Kabir, G. (2023). Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context. *Sustainability*, 15(21), 15407. <https://doi.org/10.3390/su152115407>
- [23] Kolay, P. K., Burra, S. G., & Kumar, S. (2018). Effect of salt and NAPL on electrical resistivity of fine-grained soil-sand mixtures. *International Journal of Geotechnical Engineering*, 12(1), 13–19. <https://doi.org/10.1080/19386362.2016.1239378>
- [24] Kumar, R., & Sharma, A. K. (2017). Compressive strength of cement-stabilized sand with kaoline replacement. *Geotechnical Testing Journal*, 40(3), 245–255.
- [25] Nath, P., & Choudhury, S. (2022). Durability of kaoline-cement-stabilized sand under cyclic wetting and drying. *Journal of Materials in Civil Engineering*, 34(8), 102–112.
- [26] Niroumand, H., Balachowski, L., & Parviz, R. (2023). Nano soil improvement technique using cement. *Scientific Reports*, 13(1), 10724. <https://doi.org/10.1038/s41598-023-37918-z>
- [27] Odimegwu, J. I., Nkemhule, F. E., Eke, E. J.-S., Okunnuga, J., Buhari, A. O., Okwuegbuna, S. N., & Duru, C. R. (2021). Pharmaco-Chemical Analysis and in Vivo Toxicity Assays of Edible
- [28] Ogunribido, T. H. T. (2011). Potentials of Sugar Cane Straw Ash for Lateritic Soil Stabilization in Road Construction. *International Journal of Science Emerging Technology*, 3(5): 85-89
- [29] Ogunribido, T.H.T. (2012). Geotechnical Properties of Sawdust Ash Stabilized Southwestern Nigeria Lateritic Soils. *Environmental Research, Engineering and Management*, 2 (60), 29-33.
- [30] Osinubi, K.J and Oyelakin M.A. (2012). Optimizing Soil-Cement-Ash Stabilization Mix for Maximum Compressive Strength: A Case Study of the Tropical Clay Sub-base Material Stabilized with Cement-locust Bean Waste Ash. ‘Proceedings of West Africa Built Environment Research Conference (WABER 2012) Conference. Editors Dr. Samuel Laryea, Dr. Sena A. Agyepong, Dr. RoineLeiringer and Prof. Will Hughes. July 24 26, Abuja, Nigeria. 2:1207–1218.
- [31] Singh, D., Manojkumar, D., & Kumar, S. (2022). Strength characteristics of kaolin clay mixed with RHA, sand and lime. *Materials Today: Proceedings*, 60, 328–335. <https://doi.org/10.1016/j.matpr.2022.01.23>

