Effect of Metakaolin on Strength Properties of Lateritic Soil Intended for Use as Road Construction Material

Ibrahim Ikara Abdulkarim [1], **Sa'eed Yusuf Umar** [1], **Abbagana Muhammed** [1],
Suleiman Arafat Yero [1]

[1] Abubakar Tafawa Balewa University
Tafawa Balewa Way, P. M. B. 0248, Bauchi, 740272, Nigeria

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Corresponding Author:
Ibrahim Ikara Abdulkarim
iaikara12@gmail.com

Abstract. An excellent all-weather road is essential in providing reliable transportation services that comprise social and economic development elements. However, in most cases, the road has to be constructed on a soft foundation soil where large deformations usually occur, which causes increases in maintenance costs and leads to interruption of traffic service, especially during the wet season. It is necessary to stabilize or improve the in-situ soils. This study explores the potential of using metakaolin to improve the geotechnical properties of lateritic soil for road construction materials. The soil classifies as A-6(4) and CL according to the American Association of State Highway and Transport Officials and the Unified Soil Classification System. The soil was treated with 5, 17.5 and 30 % concentrations of metakaolin by dry weight and was compacted using three compaction energies: British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests were carried out to evaluate the effect of metakaolin on the soil investigated. Results showed a general improvement in the engineering properties of the soil with an increase in metakaolin content, particularly when compacted at the BSH energy level. However, the results did not meet the 1500-3000 kN/m^2 7 days UCS criterion stipulated by the Nigerian General Specification for road base courses. However, 30 % lateritic soil/metakaolin blended soil compacted using WAS and BSH energy levels suffice for use as sub-base in road construction, having met the 750-1500 kN/m^2 7 days UCS criterion stipulated by the Nigerian General Specification. The Peak CBR value for the treated soil, compacted using the three energy levels of BSL, WAS, and BSH, occurred at 30 % metakaolin concentration with corresponding soaked CBR values of 17, 23 and 31 %. The Nigerian General Specification recommends a nominal strength criterion of a soaked CBR value of 30 and 80 % to be attained by material to be used as sub-base and base course in road construction. Based on the above criterion, only the 30 % metakaolin treated blend compacted at the BSH energy level met the 30 % requirement for sub-base materials.

Keywords: lateritic soil; metakaolin; roads; sub-base.

INTRODUCTION

The continued support for transport sector projects reflects the close link between development and transport by development agencies. Transport services are essential for the social and economic development of poor rural and urban populations. The World Bank recognizes the importance of providing transport services, with 23 % of its loans allocated to the transport sector. Transport is an intermediate service industry providing added value to investments in other sectors and contributing to economic growth [34]. Access to essential services by many people in developing countries is severely impeded by poor roads and the consequential poor transport services. It is estimated that some 1.2 billion people do not have access to an all-weather road and that 40–60 % are more than 8 km from a health centre. Transport is also essential in achieving the Millennium Development Goals. It is vital for inclusive, sustainable globalization to overcome poverty, promote growth, and access challenges in fragile states and for Public-Private partnerships [24]. An excellent all-weather road is essential in providing reliable transportation services required for safe access to markets, employment opportunities, education facilities, health centres, etc., comprising the elements of social and economic development. However, in most cases, the roads have to be constructed on a soft foundation soil where large deformations usually occur, which causes increases in maintenance costs and leads to interruption of traffic service, especially during the wet season.

Lateritic soil found in some locations is not usually suitable for subgrade, sub-base and base course due to several difficulties during construction, such as workability, field compaction, and insufficient strength. Furthermore, the acidic nature of the tropical soils has raised doubts about the efficiency of soil-lime reactions in a low pH environment and hence the long-term improvement [3].

It is necessary to stabilize or improve the in-situ soils with other selected soils/aggregates or with binders, to build a strong road network to support heavier vehicles or higher traffic flows and serve in all-weather conditions [2]. These binders are cement and/or lime, which bind the soil particles together through chemical reactions [21]. However, cement production has severe environmental impacts, using vast amounts of fossil fuels and being responsible for the emission of more than 5 % of all the carbon dioxide worldwide [47]. Hence the focus of this study is to provide an alternative to reduce cement usage.

Metakaolin is a dehydroxylated form of kaolinite, following the chemical removal of the bonded hydroxyl ions from the kaolinite minerals, typically heating to approximately 750 °C. As kaolin contains no carbonates, no CO_2 is released during heating, reducing embodied CO_2 in the final materials when replacing cement or lime [16]. Due to the pozzolanic properties of metakaolin, there has been growing interest in its use as a cement replacement and an additive to lime [29, 49]. Thus, this study intends to determine the effect of treating lateritic soil with metakaolin during road construction.

METHODOLOGY

The study was conducted in two phases. Phase one involves the determination of engineering properties of the soil without the addition of the additive, index properties, and compaction: British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH), Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests were carried out by [10]. The second phase involves adding varying proportions of metakaolin by the dry weight of the soil to determine the engineering properties when metakaolin is used as a stabilizing agent. In the case of tests on the stabilized/treated soils, 5, 17.5 and 30 % concentrations of metakaolin by dry weight of the soil were added to the soil to increase the engineering properties of the soil. Similar tests were out on the treated soil by [9].

MATERIALS AND METHOD

The lateritic soil was obtained using the same method of disturbed sampling from a borrow pit at Fankacen Dumi village behind an industrial estate, Bauchi State, Nigeria (latitude 10°16'46.54"N, longitude 9°51'54.25"E). The soil is reddish brown.

The raw material for the metakaolin production is kaolin clay, sourced from Alkaleri, Alkaleri Local Government Area of Bauchi State. The kaolin would be burnt at a temperature ranging from 700–800 °C in a kiln at the Department of Industrial design, Faculty of Environmental Technology, Abubakar Tafawa Balewa University, Bauchi, to obtain the metakaolin.

The water used is portable drinking water; therefore, no laboratory test was conducted.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Lateritic Soil and Metakaolin. Results of the physical properties test for the untreated soil are presented in Table 1.

Table 1 – Test results of the natural soil

Property	lateritic soil
Natural moisture content (%)	9
Liquid limit (%)	37
Plastic limit (%)	24
Plasticity index (%)	13
Specific gravity	2.61
Percentage passing No 200 sieve	52
Percentage Sand fraction (0.075–4.76 mm)	52
Percentage Silt fraction (<0.075 mm)	36
Percentage Clay fraction, (<2 μm)	16

Property	lateritic soil
Maximum dry density BSL (Mg/m^3)	1.82
Maximum dry density WAS (Mg/m^3)	1.86
Maximum dry density BSH (Mg/m^3)	1.90
Optimum moisture content BSL (%)	18.0
Optimum moisture content WAS (%)	16.5
Optimum moisture content BSH (%)	15.9
Unconfined compressive strength BSL (kN/m^2)	247
Unconfined compressive strength WAS (kN/m^2)	472
Unconfined compressive strength BSH (kN/m^2)	630
Soaked California bearing ratio BSL (%)	11
Soaked California bearing ratio WAS (%)	12
Soaked California bearing ratio BSH (%)	14
Colour	Reddish brown
AASHTO classification	A-6 (4)
USCS classification	CL
Silica Sesquioxide Molar Ratio of Iron and Aluminium	1.98

From the results, the soil contains 52 % sand fraction, 36 % silt fraction and 16 % clay fraction. The preliminary result also showed that the soil has a moisture content of 9 % and classifies as A-6(4) by the American Association of State Highway Transportation Officials [1] soil classification system and CL by the unified soil classification system [7]. It is reddish brown with a plasticity index of 13 %. The Optimum Moisture Content & Maximum Dry Density values recorded for the three energy levels of BSL, WAS, and BSH were 18, 16.5, 15.9 % and 1.82, 1.86, 1.90 Mg/m^3, with corresponding soaked CBR values of 11, 12 and 14 % and Unconfined Compressive Strength values of 247, 472, 630 for the energy levels. These classifications showed that the soil is a silty clay soil of low plastic. The liquid limit and plasticity index values of 37 % and 13 % confirmed that the soil is indeed low plastic [7]. Existing literature has credited that Atterberg limits results have been handy indicators of soil behaviour [22]. These classifications, coupled with the low values of Maximum Dry Density, Unconfined Compressive Strength and CBR recorded, show that the soil falls below the standard recommendation for most geotechnical construction works. Especially for sub-base or base courses in highway construction [2, 11, 13, 33, 35, 39, 40].

The Oxide composition of the lateritic soil was determined using XRF spectroscopy, and the result is summarized in Table 2.

Table 2 – Oxide Compositions of lateritic soil and metakaolin

Oxide	Concentration (%)	
	Lateritic soil	Metakaolin
Silicon oxide (SiO_2)	47.18	48.71
Aluminium oxide (Al_2O_3)	16.71	28.35
Iron oxide (Fe_2O_3)	7.023	1.685
Calcium oxide (CaO)	2.244	7.980
Magnesium oxide (MgO)	0.205	0.022
Sulfur Oxide (SO_3)	0.622	0.602
Potassium oxide (K_2O)	3.965	0.053
Sodium oxide (Na_2O)	0.614	0.081
Lead oxide (P_2O_5)	0.009	0.036
Manganese oxide (Mn_2O_3)	0.081	0.023
Titanium oxide (TiO_2)	0.515	2.023

The result revealed that the major components of the soil are Aluminium oxide (Al_2O_3), Silicon oxide (S_iO_2), Iron oxide (Fe_2O_3), and Potassium oxide (K_2O), having a concentration of 16.71 % Al_2O_3, 47.18 % S_iO_2, 7.023 % Fe_2O_3 and 3.965 % K_2O. This result indicates that lateritic soil possesses a silica-alumina ratio of 3:1 with a requisite amount of Alumina and silica. The soil's silica sesquioxide molar ratio [$SiO_2/(Al_2O_3+Fe_2O_3)$] was 1.98. In laterites, these ratios are less than 1.33. At the same time, those between 1.33 and 2.0 indicate lateritic soils, and those greater than 2.0 indicate other tropical soils, i.e. non-lateritic soils [8]. From these results, it is evident that lateritic soil is lateritic soil.

The metakaolin has a specific gravity of 2.56, bulk density of 0.71 Mg/m^3, moisture content of 0.27 % and a pH value of 8.7, indicating that it is slightly alkali. The oxide composition is summarized in Table 2. The oxide composition determined using the XRF spectroscopy show that the significant oxide compositions are Silicon oxide (SiO_2), Aluminium oxide (Al_2O_3), Calcium oxide (CaO), Titanium oxide (TiO_2) and Iron oxide (Fe_2O_3), contributing 48.71, 28.35, 7.980, 2.023 and 1.681 %, of the total. The results indicate that metakaolin meets the [6] requirement based on SiO_2, Al_2O_3, and Fe_2O_3 composition of 70.0% by mass. It is also below the SO_3 limit of 5% by group, as specified for Class N pozzolana.

*Index properties***.** The variation of index properties of lateritic soil treated with metakaolin is shown in Figure 1.

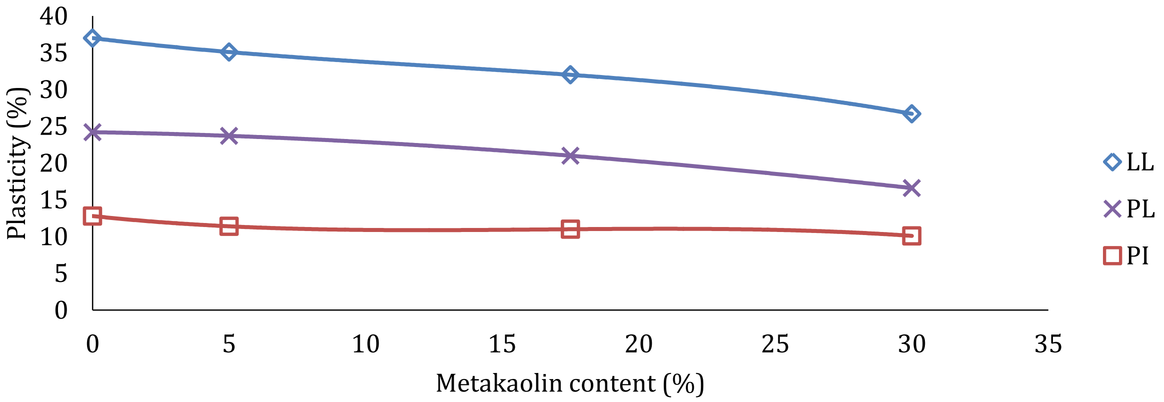


Figure 1 – Variation of Atterberg limits of lateritic soil treated with metakaolin content

The results showed a decreasing trend in the liquid limit from 37 % to 26.9 %, increasing metakaolin content from 0 to 30 %. This could be due to the porous nature of metakaolin replacing the fine soil particles. The gradual reduction in liquid limit could also be associated with the agglomeration and flocculation of Clay particles, which is a result of ion exchange at the surface of the particles [3, 15, 18, 42, 46]. Plastic limit generally decreased with higher metakaolin contents, from a value of 24.2 to 16.6 % at 30 % metakaolin content. The reduction in liquid and plastic limits resulted in a general decrease in the plasticity index value of the lateritic soil/metakaolin blend. A plasticity index value of 12.8 % recorded for the untreated soil was reduced to 10.1 % at 30 % metakaolin addition. The decrease in plasticity index is an indication of soil improvement. The decline in plasticity index is attributed to the effect of metakaolin on the affinity for H^+ ions of clay and silt fractions which caused the clay and silt fractions to spontaneously form flocs due to negative face charges and positive edge charges. These flocs adhere to each other, forming agglomerates [3]. This plasticity index reduction agrees with [5, 8, 26, 42].

Compaction Characteristics. Figure 2 shows the lateritic soil's relationship between moisture content and dry density. When compacted at the BSH energy level, the lateritic soil yielded the highest Maximum Dry Density value of 1.90 Mg/m^3, corresponding to an Optimum Moisture Content value of 15.9 %. Consolidated at WAS and BSL energy levels, the Maximum Dry Density values obtained are 1.86 and 1.82 Mg/m^3, corresponding to Optimum Moisture Content of 16.5 and 18.0 %, respectively. The trend observed is one of increasing Maximum Dry Density with an increase in compaction effort and a corresponding decrease in Optimum Moisture Content with higher compaction effort. The results are similar to those reported by [15, 31, 37]. In general, the compaction curve trend agrees with the findings of several researchers [3, 19, 23, 37, 48, 50].

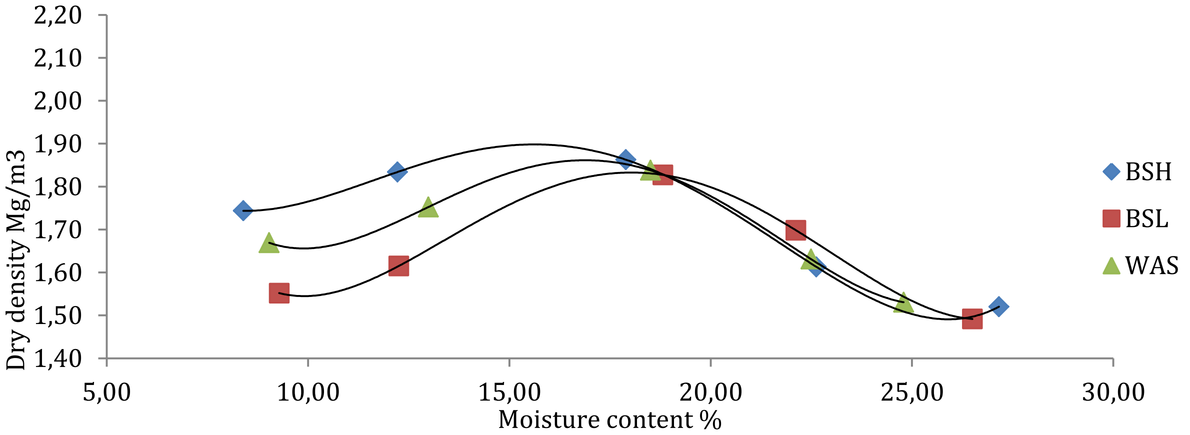
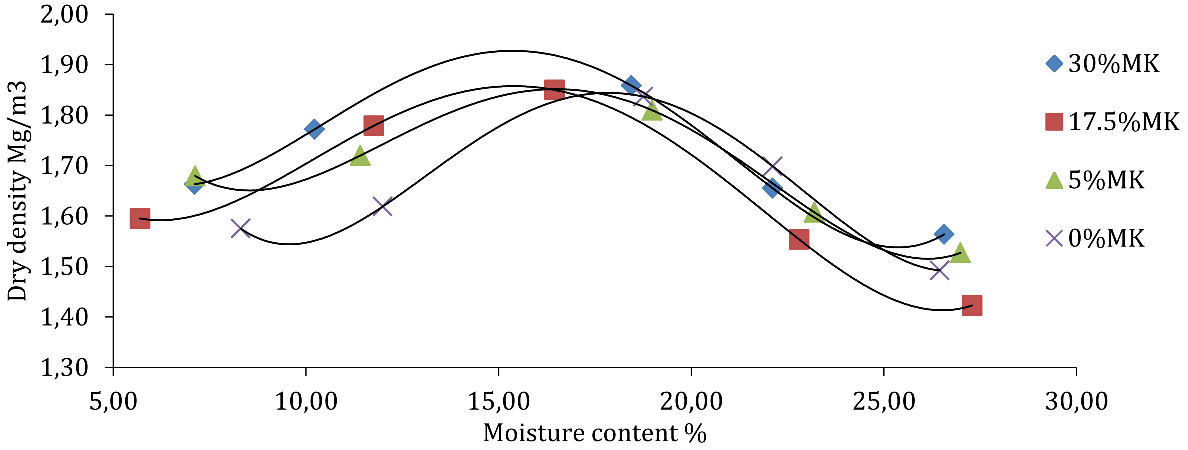
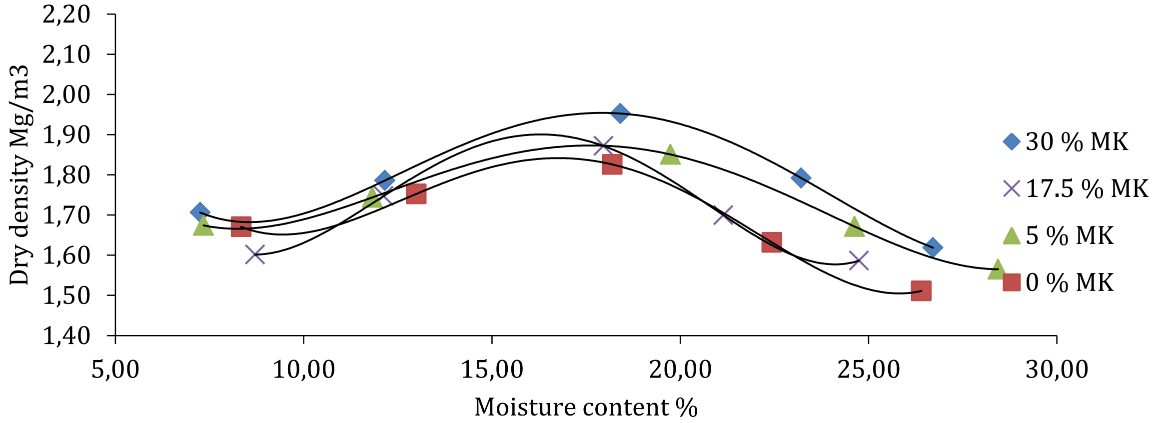


Figure 2 – Moisture - Density Relationship of the Lateritic Soil

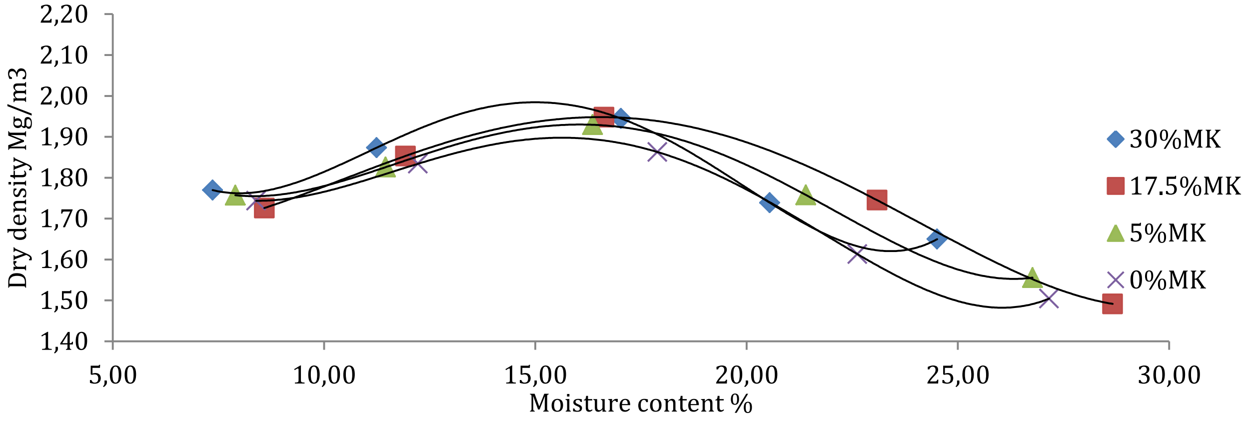
Compaction Characteristics of Treated Lateritic and Non-lateritic Soil. The Moisture-density relationship of the various dosages of metakaolin on lateritic soil for the three compaction efforts used is presented in Figure 3 (a, b &c).



a) BSL compaction



b) WAS compaction



c) BSH compaction

Figure 3 – Moisture - Density Relationships of Lateritic Soil Treated with Metakaolin

From Figure 3a, it can be observed that with the addition of 5, 17.5 & 30 % metakaolin, the dry density increases, and the maximum dry density recorded are 1.83, 1.86 and 1.91 Mg/m^3, respectively. This increase is 105 %, higher than the Maximum Dry Density of the lateritic soil without adding metakaolin. Interestingly, such trends were observed when WAS, and BSH compaction efforts were used on the soil with the same 5, 17.5 and 30 % metakaolin content being admixed. From observation, it is concluded that the Maximum Dry Density and Optimum Moisture

Content of the soil-metakaolin mixtures largely depend on the soil type, the fineness of the metakaolin particles and the plastic nature of the soils. It has been well documented that soil particles are randomly oriented on the dry side, while on the wet side, the soil particle is oriented in parallel. In the parallel orientation, the extra water forms a water film surrounding the soil particles, enhancing workability and contact between the soil particles [12]. On the wet side of the Optimum Moisture Content, soil particles are arranged in parallel directions creating more connections of surface particles, resulting in easy mixing, compaction and better reaction between soil-MK mixtures. It is evident from the plot of the Maximum Dry Density and Optimum Moisture Content that the best results were achieved using the BSH compaction effort. The effects of the various replacement levels on the moisture contents showed a divergent behaviour. As the replacement levels increase, the moisture content decrease, which is an indication of better performance.

*Effect of Metakaolin on Compaction Characteristics of Lateritic soil***.** The variation of Maximum Dry Density of lateritic soil/metakaolin mixture for BSL, WAS, and BSH compaction effort is presented in Figure 4.

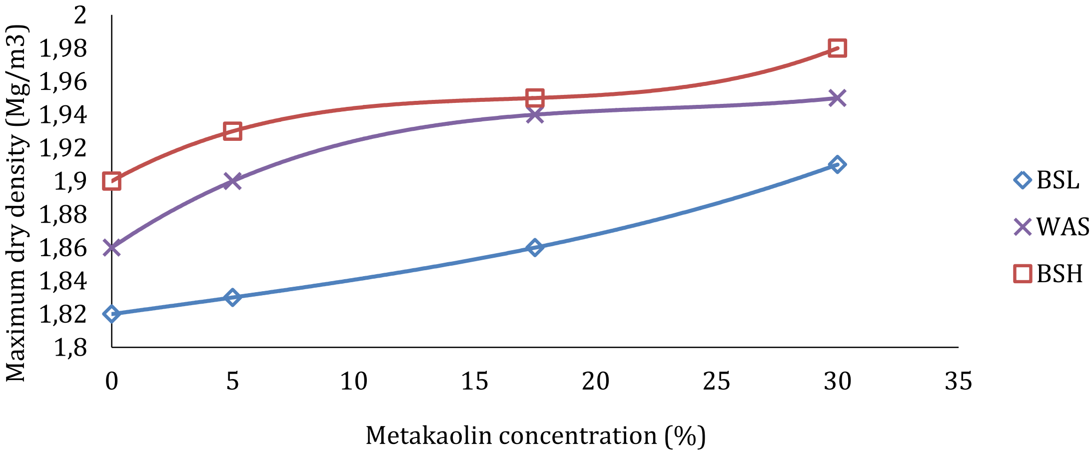


Figure 4 – Variation of Maximum Dry Density of Lateritic Soil with Metakaolin

The observed Maximum Dry Density values increased with an increase in metakaolin content for the three compaction efforts considered. An increase in Maximum Dry Density from a weight of 1.82 Mg/m^3 for the natural soil to 1.91 Mg/m^3 was observed at 30 % metakaolin when BSL compaction effort was used. The trend observed for WAS and BSH compacted soils are similar to that of the BSL compacted soils. For lateritic soil/metakaolin, Maximum Dry Density values increased from 1.86 and 1.90 Mg/m^3 to peak values of 1.95 and 1.98 Mg/m^3 at 30 % metakaolin when WAS and BSH compaction efforts were used. The variation plot for lateritic soil/metakaolin with Maximum Dry Density for the three energies used is presented in Figure 5.

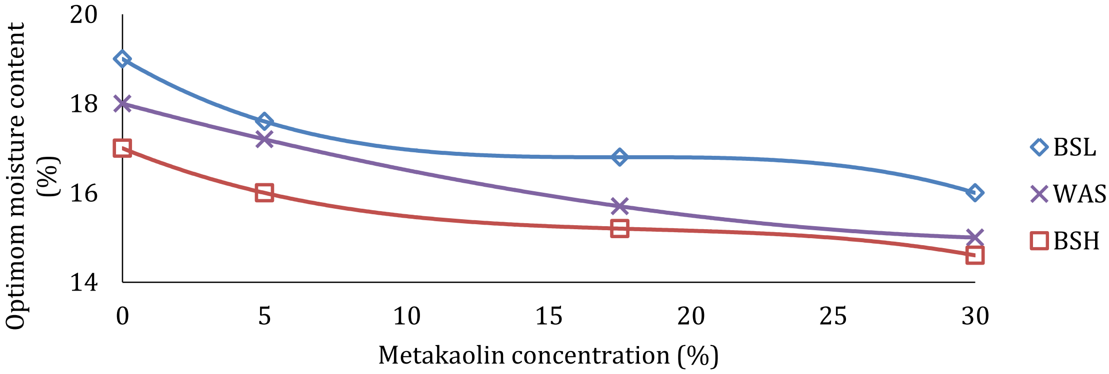


Figure 5 – Variation of Optimum Moisture Content of Lateritic Soil with Metakaolin

Authors [45, 20, 27] and [42, 44, 19, 3] reported a similar trend of increasing maximum dry densities in their respective research. The increase in Maximum Dry Density recorded for the compaction efforts may be due to flocculation and agglomeration of the clay particles, primarily due to cation exchange and the particles filling the voids within the soil matrix [14, 15, 41, 50]. The increase could also be due to metakaolin replacing the soil particles, thus resulting in the formation of a mixture with higher Maximum Dry Density, as reported by [17, 42, 50]. It could also be due to an increase in the surface area of particles at a higher dosage of metakaolin.

The general trend observed in Figure 5 is that of decreasing Optimum Moisture Content with the increase in the percentage of the additive. This indicates that the additives require little water for pozzolanic reaction with the silt and clay fractions of the soils. The presence of SiO_2, Fe_2O_3 and TiO_2 in the additives may, in part, be responsible for the enhancement of the mechanical properties of the soil specimens. A similar assertion was made by [3]. Furthermore, the soil specimens produce heavier agglomerate particles with an attendant rise in the density of the soil. The result is consistent with those reported by [31] for peat soil modified with kaolin and heated kaolin and [3]. There for, using metakaolin treatment material for the soil is beneficial in improving the mechanical properties of the soil-additive mixtures. Also, as previously stated, on the wet side of the Optimum Moisture Content, soil particles are arranged in a parallel direction creating more contact with surface particles, resulting in easy mixing, compaction and better reaction between soil-MK mixtures.

Strength Characteristics. Over the years, the Unconfined Compressive Strength test has been the most common and suitable method for evaluating stabilized soil strength.

The variation of Unconfined Compressive Strength with various percentages of metakaolin treated lateritic soil blend compacted at BSL, WAS and BSH compaction and cured for seven days, 14 days and 28 days is shown in Figures 6-9.

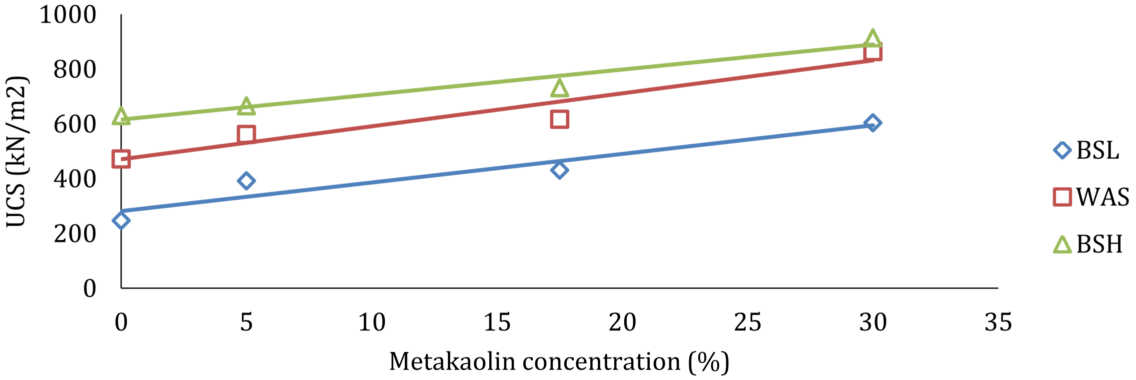


Figure 6 – Variation of Unconfined Compressive Strength (7 days curing period) of lateritic soil with metakaolin content

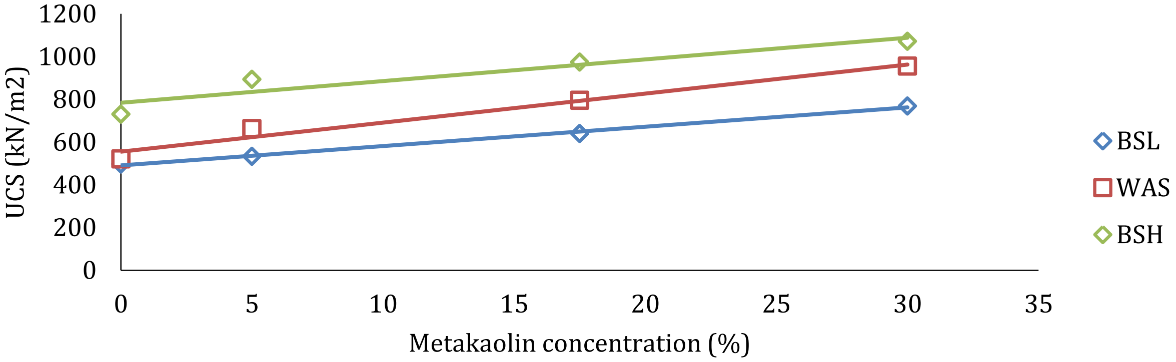


Figure 7 – Variation of Unconfined Compressive Strength (14 days curing period) of lateritic soil with metakaolin content

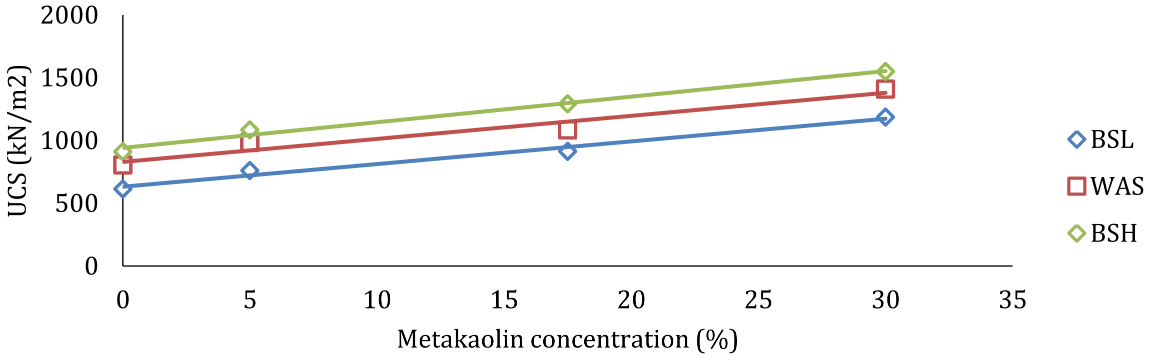


Figure 8 – Variation of Unconfined Compressive Strength (28 days curing period) of lateritic soil with metakaolin content

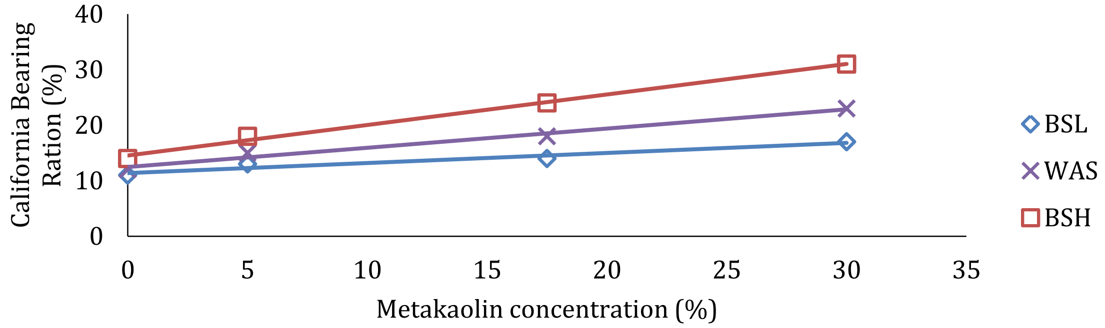


Figure 9 – Variation of Soaked CBR of lateritic soil with metakaolin content

A general improvement in the compressive strength was observed with the age of curing, metakaolin concentration and compaction energy. The results are similar to a study on expansive soil treated with up to 10 % metakaolin conducted by [4]. The increase in Unconfined Compressive Strength is attributed to hydration reactions of the soil-metakaolin mixtures induced by the high pH of the mixture caused by the metakaolin content and also due to improvement in the grain packing of the specimens by reduction of pores by the metakaolin, and thus given rise to a dense and strong structure. Authors [22, 36, 28, 50, 2] provide assertion to this belief. Furthermore, the reactive silica present in metakaolin, which reacts and produce cementitious materials and bind the soil particle together, causes a strength gain [30, 32].

It was observed that the Unconfined Compressive Strength value increased during the seven-day curing period. However, the peak seven days Unconfined Compressive Strength value of 604 kN/m^2 was recorded at a 30 % lateritic soil/metakaolin blend. This observed trend of BSL compaction energy was similar to that of WAS and BSH compaction energy levels. The peak Unconfined Compressive Strength values at these energy levels are higher than those in the BSL compaction energy, as shown in Figure 7. The height Unconfined Compressive Strength values of the metakaolin treated lateritic soil occurred at 30 % metakaolin concentration with a corresponding Unconfined Compressive Strength value of 864 kN/m^2 and 913 kN/m^2 for WAS and BSH compaction efforts.

The Unconfined Compressive Strength at 14 and 28 days showed an increase in Unconfined Compressive Strength with a corresponding increase in metakaolin concentration from one another and from that of the seven days curing period for all the three compaction efforts used, as shown in Figures 8 & 9. The Unconfined Compressive Strength results indicate that metakaolin mixtures have progressive strength development with a longer curing period which is advantageous in the long run. This trend is attributed to the time-dependent strength gain of the mix due to the pozzolanic reaction. The results are consistent with those reported by [2, 18, 19, 35, 39, 42, 51].

Comparing the Unconfined Compressive Strength values of the treated soil specimens compacted at the three energy levels indicate that specimens treated with 30 % metakaolin and compacted using the BSH compaction effort yielded maximum Unconfined Compressive Strength of 1550 kN/m^2 at 28 days of curing. This corresponds to an increase of 170 % compared to the result obtained for the natural soil compacted at the same energy level and cured for the same period. These results agree with various researches [2, 18, 38, 40, 42, 51].

Comparison of (UCS) results with the recommended standard. The Nigerian General Specifications [33] nominal specifications for road construction of layers recommend the range of 1500–3000 kN/m^2 for specimen cured for seven days as a base course material and the range of 750–1500 kN/m^2 as a sub-base material. Based on the 1500-3000 kN/m^2 Unconfined Compressive Strength recommended value for the base course, none of the recorded Unconfined Compressive Strength values of metakaolin / lateritic soil treated blends compacted using the three compaction efforts met the criteria. However, 30 % metakaolin/lateritic soil blend consolidated using WAS and BSH compaction effort met the sub-base criteria.

California Bearing Ratio. The California bearing ratio is a penetration test for evaluating the mechanical strength of road sub-grades and base courses. The results obtained by these tests are used with empirical curves to determine the thickness of pavement and its component layers. It is an important parameter used to indicate the strength and bearing capacity for base and sub-base in road construction. It is worth noting that the soaked CBR test was the primary CBR test carried out as the Nigerian General Specification [33] sub-base and base course requirements are based on saturated CBR values.

Soaked CBR. The variation of soaked CBR (96 hours soaking) of lateritic soil/metakaolin blends is shown in Figure 9. For BSL, WAS, and BSH compaction efforts, CBR values increased with higher additive contents compared with the natural CBR values. The peak values of 17, 23 and 31 % were recorded at 30 % metakaolin/lateritic soil blend for energies of BSL, WAS and BSH effort. It can be seen that the application of different compaction efforts and variation of additives give rise to a linear increase in the strength of soaked CBR values for an increase in additives and compaction effort. Generally, CBR values with higher compaction effort were observed in the order BSL, WAS and BSH compaction. The improvement in CBR is attributed to the cation exchange, flocculation and agglomeration reactions within the admixtures. The trend conforms with the results reported by [15]. Moreover, the additives are highly pozzolanic materials and require water for hydration, improving the admixtures' strength gain and durability. Various researchers reported similar trends [38, 35, 44, 40, 18].

The Nigerian General Specifications [33] recommend a nominal strength criterion of a soaked CBR value of 80 % for a material to be used as a base course and a wet value of 30 % for sub-bases, both when compacted at optimum moisture and 100 % WAS compaction. Based on the above criterion, it suffices to state that only 30 % metakaolin/lateritic soil blend, which has a CBR value of 31 %, met the 30 % requirement for sub-base materials when compacted at BSH compaction effort.

CONCLUSIONS

This study explores the potential of using metakaolin to improve the geotechnical properties of lateritic soil obtained from Bauchi State, intended for use as road construction material. Based on the results obtained in this study, the following conclusions were drawn:

1. The lateritic soil classifies as A-6(4) by the American Association of State Highway Transportation Officials [1] soil classification system, and based on the unified soil classification system [7], the soil classifies as CL. This implies that the soil has an appreciable quantity of clay and falls below the standard recommended for sub-base or base courses in highway construction.

2. The oxide composition of the soil and metakaolin determined using X-ray fluorescence (XRF) spectroscopy revealed that the Silica Sesquioxide Molar Ratio of Iron and Aluminium for the soil is 1.98. The results also indicate that lateritic soil possesses a silica-alumina ratio of 3:1 with a requisite amount of Alumina and silica. In the case of metakaolin, the results revealed the presence of an appreciable amount of Al_2O_3, S_iO_2 and Fe_2O_3 required for materials to qualify as a class N pozzolana.

3. The geotechnical properties determined for the soil fall below the standard recommended for use as sub-base or base course materials in highway construction. With the addition of me-

takaolin, there is a substantial reduction in plasticity index when compared to untreated soil.

4. Combining the soil with metakaolin improved the soil's dry density with an attendant moisture content decrease. BSH compaction effort yielded higher Maximum Dry Density due to the more incredible energy supplied. In terms of performance and workability, the treated soil would perform better as a construction material.

5. A remarkable improvement in Unconfined Compressive Strength was observed at 30 % metakaolin concentration, with an average UCS value of 604, 864 and 913 kN/m^2 at seven days of curing BSL, WAS, and BSH compaction efforts.

6. In general, the seven days cured UCS value of 30 % metakaolin/lateritic soil blend compacted using WAS and BSH effort falls within the range of 750–1500 kN/m^2 UCS value specified by the Nigerian General Specification for sub-base materials.

7. Higher UCS values were recorded for all the compaction efforts at 28 days of curing. This is attributed to the pozzolanic reaction of metakaolin, except 30 % metakaolin/lateritic soil blend compacted at BSH compaction effort, which met the 30 % Nigerian General Specifications nominal strength criteria of a soaked CBR value for sub-base materials. All other combinations fail to meet the requirements.

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