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PERFORMANCE EVALUATION OF THE EFFECT OF METAKAOLIN ON STRENGTH PROPERTIES OF NON-LATERITIC SOIL

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ABSTRACT

This study explored the potentials of metakaolin (Mk) for the improvement of the properties of non-lateritic soil (NLS) intended for use as a road construction material. The soil was classified as A-7-6(14) and CL according to the American Association of State Highway and Transport Officials (AASHTO M 145-2012) and the Unified Soil Classification System (ASTM D 2487-2011). The soil is treated to evaluate the effectiveness of Mk in treating non-lateritic soil with 5, 17.5 and 30 % concentrations of Metakaolin by dry weight of the soil. Index properties, compaction (British standard light (BSL), West African standard (WAS) and British standard heavy (BSH)) and Unconfined compressive strength (UCS) tests were conducted on the NLS/MK admix blend. The results obtained show a general improvement in the engineering properties of the soil with increase in Mk content, particularly, when compacted at the BSH energy level. However, the results showed that the soil did not meet the 1500-3000 kN/m^2 7 days UCS criterion stipulated by the Nigerian General Specification for road base courses, but the 30 % NLS/MK blended soil compacted using the BSH energy level did 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 (2013).

Keyword: *Non-lateritic soil, Metakaolin, Road*

INTRODUCTION

Understanding the close link between development and transport by development agencies is reflected in the continued support for transport sector projects. Transport services are considered to be essential for the social and economic development of poor rural and urban populations alike. The importance of the provision of transport services is recognised by the World Bank with 23 % of its loans allocated to the transport sector (Porter, 2013). Transport is an intermediate service industry providing added value to investments in other sectors and contributing to economic growth (O'Neill and Greening, 2010).

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 8kms from a health center. Transport is also recognised as an essential ingredient in achieving the Millennium Development Goals (MDGs) and is key for inclusive, sustainable globalization to overcome poverty, promote growth, access challenges in fragile states and for Public Private Partnership (Juhel, 2008).

Good all-weather road is an essential component in provision of reliable transport services required for safe access to markets, employment opportunities, education facilities, health centres, etc that comprise the components of social and economic development. However, in most cases the roads have to be constructed on a soft foundation soils where large deformations usually occur, which causes increases in maintenance cost and lead to interruption of traffic service, especially during the wet season.

In order to take care of such circumstances it is necessary to stabilize or improve the in-situ soils, either 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 condition. These binders are cement and/or lime, which bind the soil particles together through chemical reactions (Jamsawang *et al.*, 2014). 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 (Provis and Deventer, 2013). Hence the focus of this study to provide an alternative to reduce usage of cement.

Metakaolin is a dehydroxylated form of kaolinite, following the chemical removal of the bonded hydroxyl ions from the kaolinite minerals, typically through heating to approximately 750°C. As kaolin contains no carbonates, no CO_2 is released during heating leading to reduced embodied CO_2 in the final materials when replacing cement or lime (Ilić *et al.*, 2010). Due to the pozzolanic properties of metakaolin, there has been growing interest in its use as a cement replacement as well as an additive to lime (Mejía de Gutiérrez *et al.,* 2008; Ramezanianpour and Jovein, 2012). Thus, this study intends to determines the engineering properties of non-lateritic soil treated with Metakaolin for road construction works.

MATERIALS AND METHODS

Materials

Non-lateritic soil

The non-lateritic soil (NLS) used in the study were obtained by using the method of disturbed sampling from an area near the Abubakar Umar Secretariat, in Bauchi, Bauchi State, Nigeria (latitude 10°18'7.59"N and longitude 9°49'31.41"E), at a depth of at least 900 mm below ground level.

Metakaolin

The raw material for the production of metakaolin (MK) is kaolin clay, which was sourced from Alkaleri, Alkaleri Local Government Area of Bauchi State. The kaolin would be burnt at a temperature ranging from 700^{o}C - 800^{o}C in a kiln at the Department of Industrial design, Faculty of Environmental Technology, Abubakar Tafawa Balewa University, Bauchi to obtain the metakaolin.

Water

The water used is portable drinking water and therefore, no laboratory test was conducted on it.

METHODOLOGY

The study was conducted in two phases. Phase one involves the determination of engineering properties of the soil without addition of the additive, index properties, compaction (British standard light (BSL), West African standard (WAS) and British standard heavy (BSH)) and unconfined compressive strength (UCS) tests were carried out in accordance with BS 1377:1990. The second phase involves the addition of varying proportions of metakaolin by dry weight of the soil to determine the engineering properties when MK 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 in order to increase the engineering properties of the soil. Index properties, compaction (British standard light (BSL), West African standard (WAS) and British standard heavy (BSH)) and unconfined compressive strength (UCS) tests were carried out on the treated soil in accordance with BS 1924(1990).

RESULTS AND DISCUSSION

Natural soil and Metakaolin

Preliminary tests conducted to determine the properties of the soil is presented in Table 1 while the particle size distribution curve is shown in Figure 1. The particle size distribution curve showed that the soil contains 34 % sand fraction, 32 % silt fraction, 34% clay fraction and a moisture content of 13 %. The preliminary tests also classify the soil as A-7-6 (14) based on (AASHTO M 145-2012) soil classification and CL based on the unified soil classification system (ASTM D 2487-2011), it has a grayish brown colour with a plasticity index of 23 % and soaked CBR values of 6.6, 8.0 and 9.8 %, UCS values of 201, 390 and 419 kN/m^2, OMC & MDD values of 17.5, 22, 21 % and 1.61, 1.63, 1.69, for the three energy levels of British Standard Light (BSL), British Standard Heavy (BSH) and West Africa Standard (WAS). These classifications showed that the soil is an inorganic silty clayey soil of medium plasticity. The liquid limit and plasticity index values of 49 % and 23 % confirmed that the soil is indeed medium plastic (ASTM D-2487), existing literatures have given credence to the fact that Atterberg limits results have been a very useful indicators of soil behaviour (Jefferson and Rogers, 1998). These classifications coupled with the low values of MDD, UCS and CBR recorded show that the soil fall below the standard recommendation for most geotechnical construction works especially for sub-base or base courses in highway construction (Butcher and Sailie, 1984; Oyediran and Williams 2010; Nigerian General Specification 2013; Ojuri *et al*., 2017; Ejeta *et al*., 2017; Onyelowe *et al*., 2019; Onyelowe *et al*., 2020). From the chemical analysis results presented in Table 2, the major

oxides present in the soil are Aluminium oxide (Al_2O_3) 6.74 %, Silicon oxide (S_iO_2) 61.31 %, Iron oxide (Fe_2O_3) 14.02 %, and Potassium oxide (K_2O) 4.672 %. These results indicate that the soil possesses a silica-alumina ratio of 9:1 with a considerable quantity of Fe_2O_3 and a requisite amount of Alumina and silica. The silica sesquioxide molar ratio [SiO_2/ (Al_2O_3+Fe_2O_3)] of the soil was found to be 2.96. In laterites these ratios are less than 1.33 while those between 1.33 and 2.0 are indicative of lateritic soils, and those greater than 2.0 are indicative of other types of tropical soils i.e non-lateritic soils (Blight, 1997). From these results, it is evident that the soil is a non-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 chemical characteristics is summarized in Table 2. The oxide composition determined using the XRF spectroscopy show that the major 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 MK meets the ASTM C 618 (2012) requirement based on SiO_2, Al_2O_3, and Fe_2O_3 composition of 70.0% by mass, ASTM C 618 (2012). It is also below the SO_3 limit of 5% by mass, which is specified for Class N pozzolana.

Table 1: Test results of the soil

Property	**Results**
Natural moisture content (%)	13
Liquid limit (%)	49
Plastic limit (%)	25
Plasticity index (%)	24
Specific gravity	2.46
Percentage passing No. 200 sieve	65.2
Percentage Sand fraction (0.075 – 4.76mm)	34
Percentage Silt fraction (<0.075mm)	32
Percentage Clay fraction, (<2μm)	34
Maximum dry density BSL (Mg/m^3)	1.61
Maximum dry density WAS (Mg/m^3)	1.63
Maximum dry density BSH (Mg/m^3)	1.69

Optimum moisture content BSL (%)	17.5
Optimum moisture content WAS (%)	22
Optimum moisture content BSH (%)	21
Unconfined compressive strength BSL (kN/m^2)	201
Unconfined compressive strength WAS (kN/m^2)	390
Unconfined compressive strength BSH (kN/m^2)	419
Soaked California bearing ratio BSL (%)	7
Soaked California bearing ratio WAS (%)	8
Soaked California bearing ratio BSH (%)	10
Colour	Light brown
AASHTO classification	A-7-6 (14)
USCS classification	CL
Silica Sesquioxide Molar Ratio of Iron and Aluminium	2.96

Table 2: Oxide Compositions of soil and metakaolin

Oxide	Concentration (%)	
	NLS	MK
Silicon oxide (SiO_2)	61.31	48.71
Aluminium oxide (Al_2O_3)	6.74	28.35
Iron oxide (Fe_2O_3)	14.02	1.685
Calcium oxide (CaO)	1.166	7.980
Magnesium oxide (MgO)	0.155	0.022
Sulfur Oxide (SO_3)	0.629	0.602
Potassium oxide (K_2O)	4.672	0.053
Sodium oxide (Na_2O)	0.556	0.081
Lead oxide (P_2O_5)	0.006	0.036
Manganese oxide (Mn_2O_3)	0.063	0.023
Titanium oxide (TiO_2)	0.470	2.023

Index properties of treated non-lateritic soil

The variation of index properties of the NLS treated with MK are shown in Figure 2. The results showed a decreasing trend in liquid limit from 49 % to 37.8 % with increasing metakaolin content from 0 % to 30 % and this could be as a result of the porous nature of metakaolin replacing the soil fine particles. The gradual reduction in liquid limit could also be associated with the agglomeration and flocculation of Clay particles, which is as a result of ion exchange at the surface of the particles (Portelinha *et al*., 2012; Osinubi *et al*., 2015; Ishola *et al.*, 2019). Plastic limit generally decreased with higher metakaolin contents, from a value of 23.6 % to 19.1 % at 30 % MK content respectively. The reduction in liquid limit and plastic limit resulted in a general decrease in the plasticity index values of NLS/MK blends. Plasticity index value of 23.6 % was recorded for the NLS.

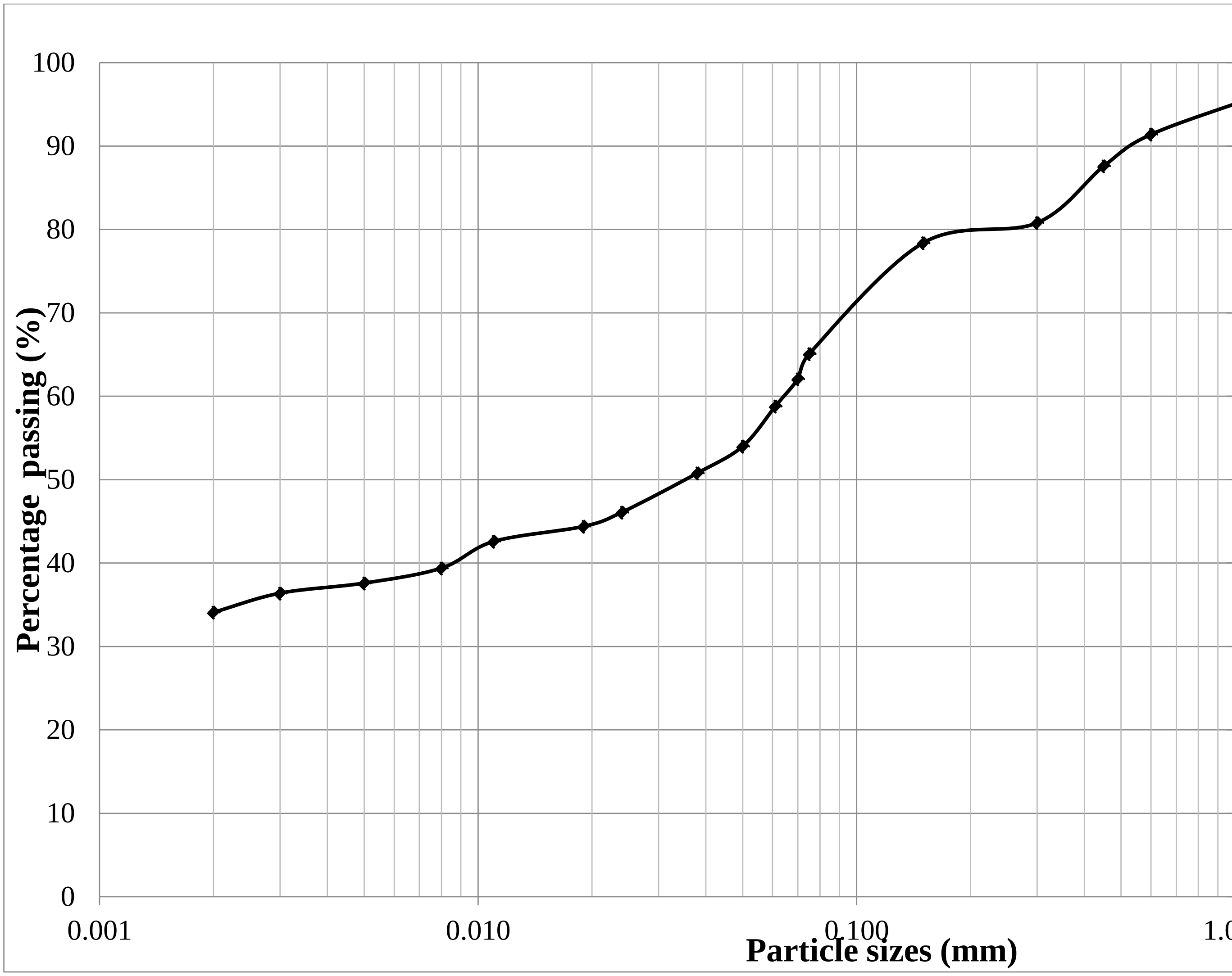


Figure 1: *Particle size distribution curve*

This value reduced to 19.1 % at 30 % MK, the general decrease in plasticity index is an indication of improvement of the soil. This decrease in plasticity index is attributed to the effect of MK on the affinity for H^+ ions of clay and silt fractions which courses the clay and silt fractions to spontaneously form flocs due to negative face charges and positive edge charges and these flocs in the course of interacting with one another tends to adhere to each other there by forming agglomerates. This reduction in plasticity index is in agreement with the findings of (Amu *et al*., 2011; Osinubi *et al.*, 2015; Karatai *et al.*, 2017; Ishola *et al.*, 2019).

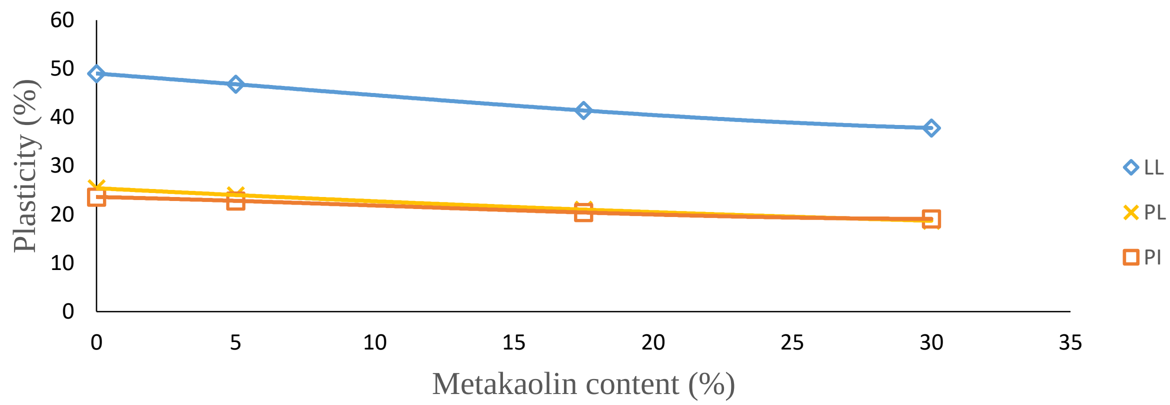


Figure 2: *Variation of Atterberg limits of NLS treated with MK content*

Compaction Characteristics of non-lateritic soil

The relationship between moisture content and dry density for NLS is presented in Figures 3. The NLS when compacted at BSH, WAS and BSL energy levels, yielded MDD values of 1.69 Mg/m^3, 1.63 Mg/m^3 and 1.61 Mg/m^3 with corresponding OMCs of 21 %, 22 % and 17.5 % respectively. The trend observed is one of increasing MDD with an increase in compactive effort and corresponding decreasing in OMC with higher compactive effort. The results are similar to those reported by (Muhammad *et al.*, 2011; Oluremi, 2015, Umar et al., 2016). In general, the trends of the compaction curves are in agreement with the findings of a number of researchers (Oluremi, 2015; Umar *et al.*, 2015; Joel and Joseph, 2015; Sharma, 2018; Ishola *et al.*, 2020).

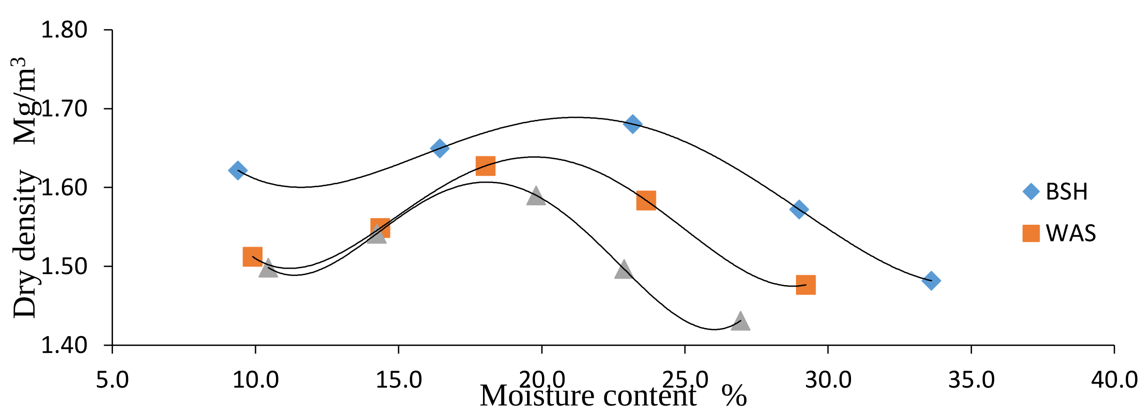
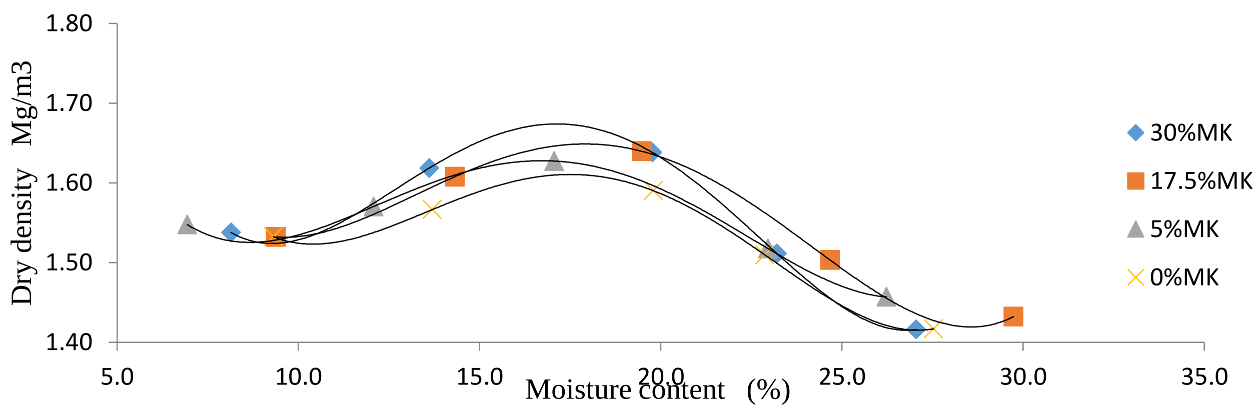


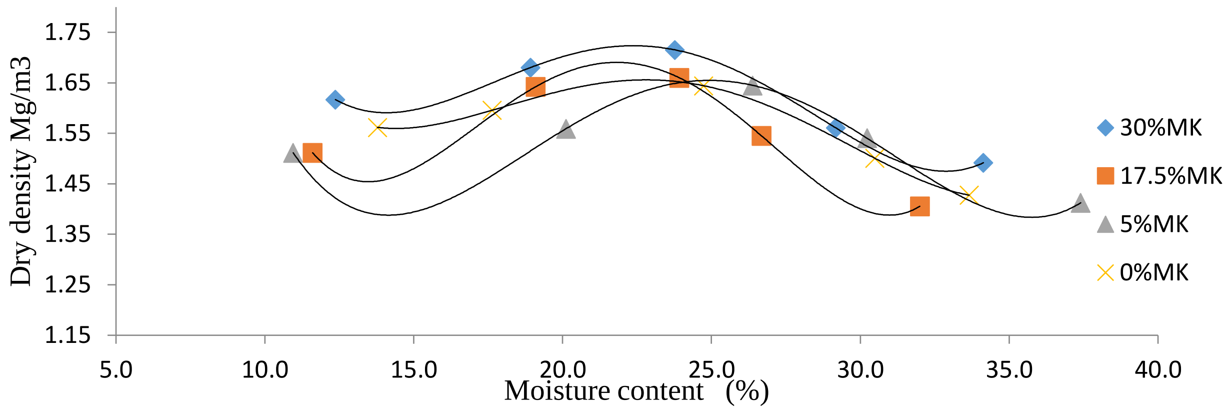
Figure 3: *Moisture - Density Relationship of the Non-Lateritic Soil (NLS)*

Compaction Characteristics of the Treated Non-lateritic Soil

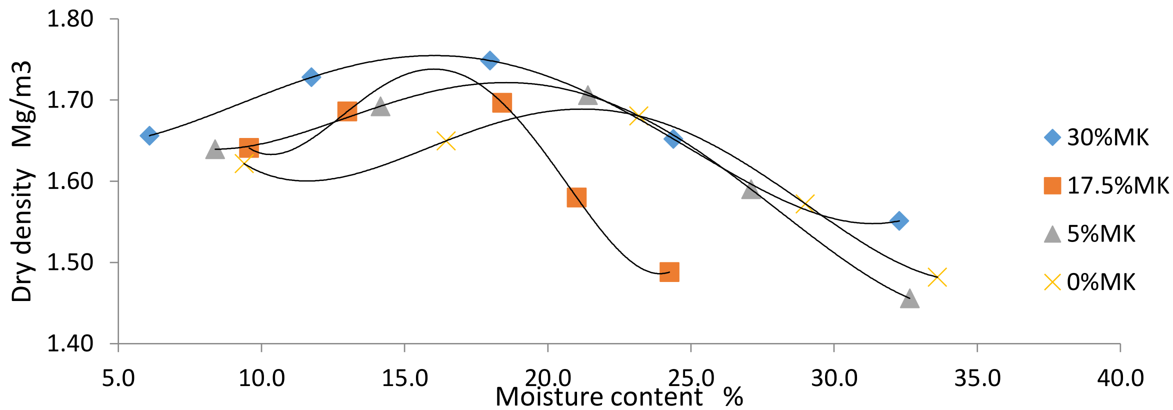
The Moisture-density relationship of the various dosages of MK on NLS for the three compactive effort used are presented in Figure 4. From the Figures, it can be observed that with the addition of MK, the dry density increases. There was a 104 % increase observed on addition of 5 %, 17.5 % and 30 % MK to NLS when using the BSL energy level. Interestingly, such trends were observed when WAS and BSH compactive effort were used with the same 5 %, 17.5 % and 30 % MK content being admixed. As it's a well-known fact, soil particles are randomly oriented on the dry side while on the wet-side, the soil particle are oriented in parallel, in the parallel orientation, the extra water forms water film surrounding the soil particles, enhancing workability and contact between the soil particles Cetin *et al.*, 2007. Basically, at wet-side of the OMC, soil particles were arranged in parallel direction creating more contact surfaces particles, resulting in easy mixing, compaction and better reaction between soil-MK mixtures. It is evident from the plot of the MDD and OMC, the best results were achieved using the BSH compactive effort. The effects of the various replacement levels on the moisture contents showed a divergent behavior. As the replacement levels are increasing, the moisture content decrease which is an indication of better performance achieved at 30 % replacement level of the soil-admixtures.



(a) BSL compaction



(b) WAS compaction



(c) BSH compaction

Figure 4: Moisture - Density Relationships of Non-Lateritic Soil Treated with Metakaolin

Effect of Metakaolin on Compaction Characteristics of Non-lateritic soils

The variation of maximum dry density (MDD) of NLS/MK mixtures for BSL, WAS and BSH compactive effort are presented in Figure 5. It was observed that MDD values increased with increase in MK content for the three compactive efforts considered. An increase of about 104 % in MDD was also recorded when BSL compactive effort was used. The trend observed for WAS and BSH compacted soils were similar to that of the BSL compacted soils. In that regards, MDD values recorded increased from 1.63 and 1.69 Mg/m^3 to peak values of 1.69 and 1.77 Mg/m^3 at 30 % MK when WAS and BSH compactive efforts where used. Phanikumar and Sharma (2004), Jadhao and Nagarnik (2008), Kumar and Puri (2013) as well as Osinubi *et al.*, (2015), Pereira *et al.*, (2018) and Ishola *et al.*, (2020) reported similar trend of increasing maximum dry densities in their respective researches. The increase in MDD recorded for the compactive efforts considered, may be due to flocculation and agglomeration of the clay particles primarily due to cation exchange and in addition the particles filling the voids within the soil matrix (Oriola & Moses, 2010; Umar *et al.*, 2015 and Firoozi *et al.*, 2017). The increase could also be as a result of MK replacing the soil particles thus resulting in the formation of a mixture with higher MDD as reported by Ishola (2014), Osinubi *et al.* (2015) and Umar *et al.*, (2015). It could also be due to increase in surface area of particles at higher dosage of MK.

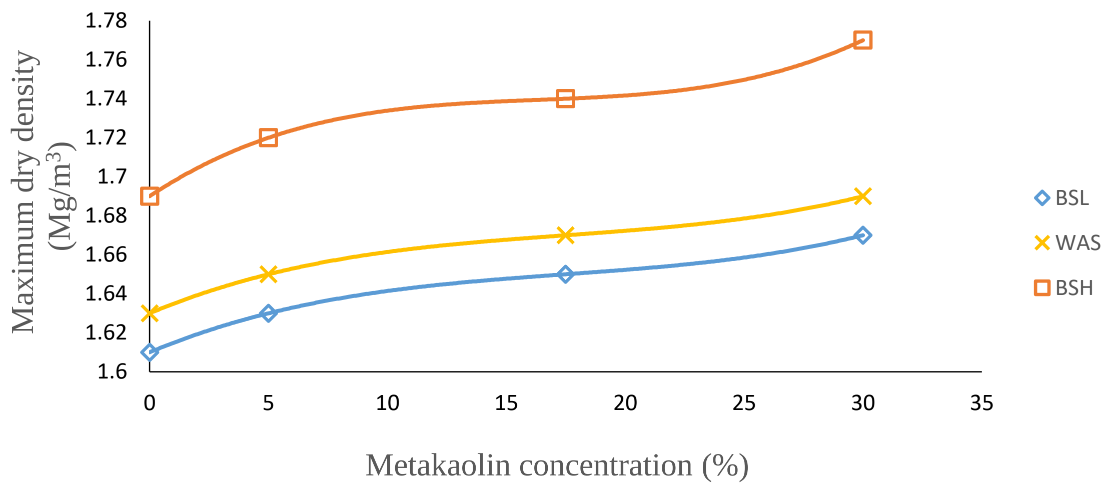


Figure 5: *Variation of Maximum Dry Density of Non-Lateritic Soil with Metakaolin*

The general trend observed in Figure 6 is that of decreasing OMC with increase in the percentage of the additive. This is an indication that the additives require little amount of water for pozzolanic reaction with the silt and clay fractions of the soil. 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. Furthermore, the soil specimen produces heavier agglomerate particles with attendant rise in the density of the soil. The result is consistent with those reported by Muhammad *et al.* (2011) for peat soil modified with kaolin and heated kaolin. There for, using MK treatment for the soil is beneficial in terms of improvement on the mechanical properties of the soil-additive mixtures. Also, as previously stated, at wet-side of the OMC, soil particles are arranged in parallel direction creating more contact surfaces particles, resulting in easy mixing, compaction and better reaction between soil-MK mixtures.

Effect of MK on unconfined compressive strength of NLS

The variation of UCS with various percentages of MK treated NLS blends compacted at BSL, WAS and BSH compaction and cured for 7 days, 14 days and 28 days is shown in Figures 7 – 9, respectively. A general improvement in the compressive strength of all blends was observed with age of curing, MK concentration and compaction energy. The results are similar to a study on expansive soil treated with up to 10 % metakaolin conducted by Ahmed and Hamza (2015).

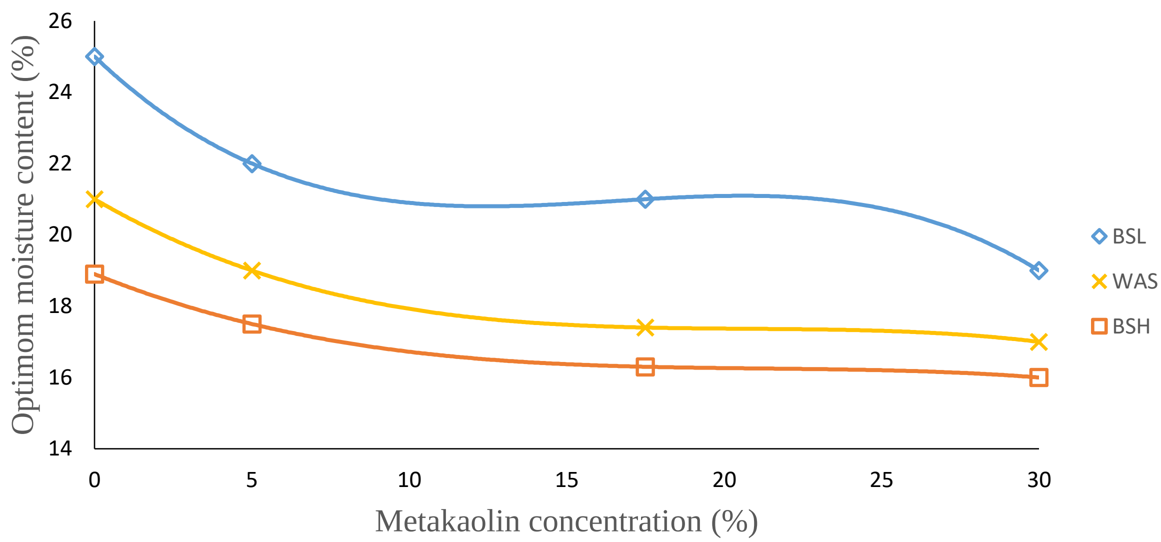


Figure 6: *Variation of Optimum Moisture Content of Non- Lateritic Soil with Metakaolin*

The increase in UCS could be attributed to hydration reactions of the soil–MK mixtures induced by the high pH of the mixture caused by the MK content and also due to improvement in the grain packing of the specimens by reduction of pores by the MK, and thus given rise to a dense and strong structure. Jung and Bobet (2008), Okonkwo (2009), Kumar (2012) as well as Umar *et al.*, (2015), gives assertion to this credence. Furthermore, the reactive silica present in metakaolin which reacts and produce cementitious materials and bind the soil particle together also causes a strength gain (Mubarak *et al.*, 2011; Negi *et al.*, 2013).

Considering BSL compaction, it was observed that at 7 days curing period the UCS value increased. However, the peak 7-days UCS value of 571 kN/m^2 was recorded at 30 % NLS/MK blend. This observed trend of BSL compaction energy was similar to that of WAS and BSH compaction energy levels and the peak UCS values at these energy levels are higher than those in the BSL compaction energy as shown in Figures 8 and 9. The peak UCS values of NLS/MK blends occurred at 30 % MK concentration with a corresponding UCS value of 619 kN/m^2 and 814 kN/m^2 for WAS and BSH compactive effort. Generally, with the addition of MK content, the strength was affected.

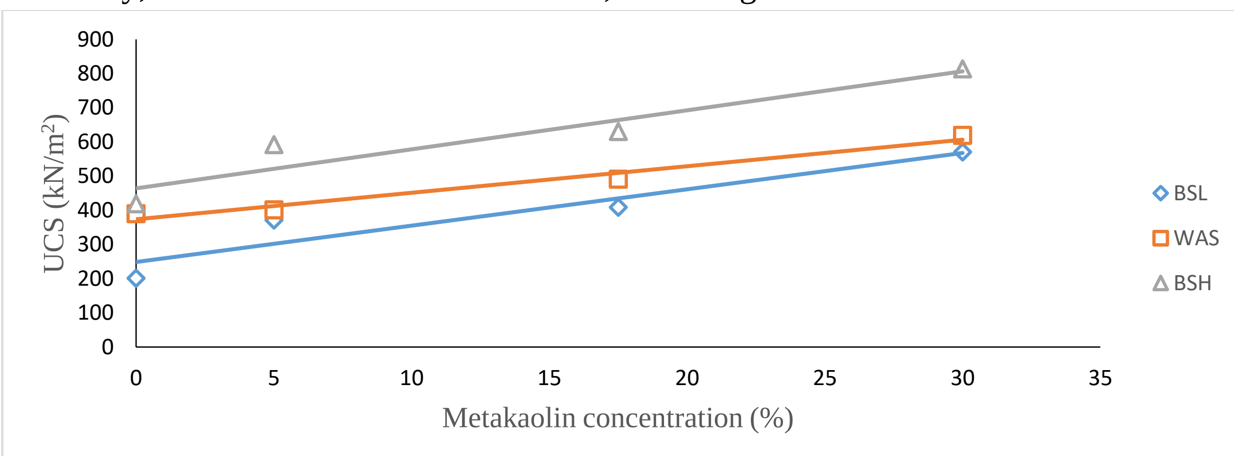


Figure 7: Variation of UCS (7days curing period) of NLS with MK content

The UCS results indicates that MK mixtures have progressive strength development with longer curing period, and mainly advantageous in the long run. This trend can be attributed to time dependent strength gain of the mixture due to pozzolanic reaction. The results are consistent with those reported by Wong *et al.* (2013), Osinubi et al., (2015), Ojuri *et al., (2017),* Ishola *et al.*, (2019), Ishola *et al.*, (2020) and Onyelowe *et al.*, (2020)

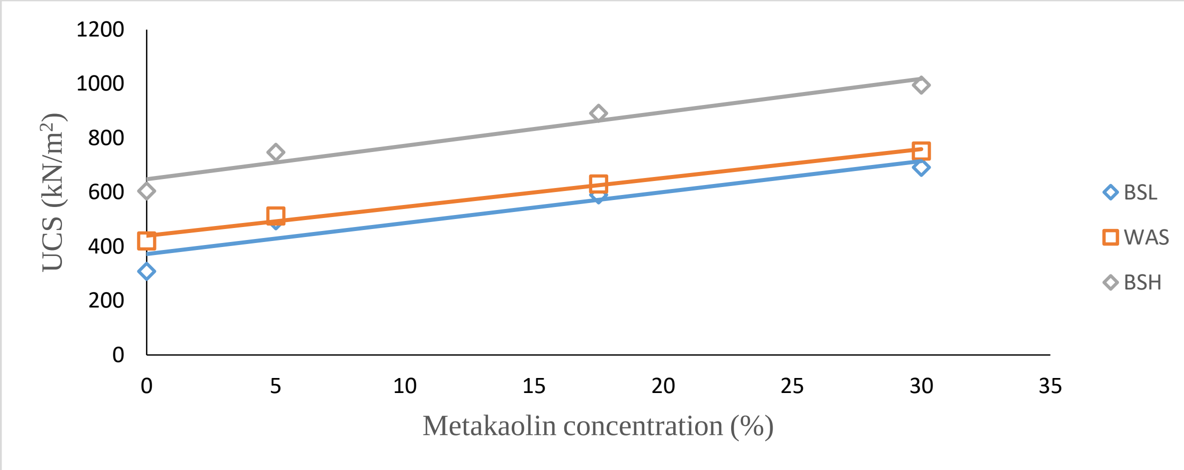


Figure 8: *Variation of UCS (14days curing period) of NLS with MK content*

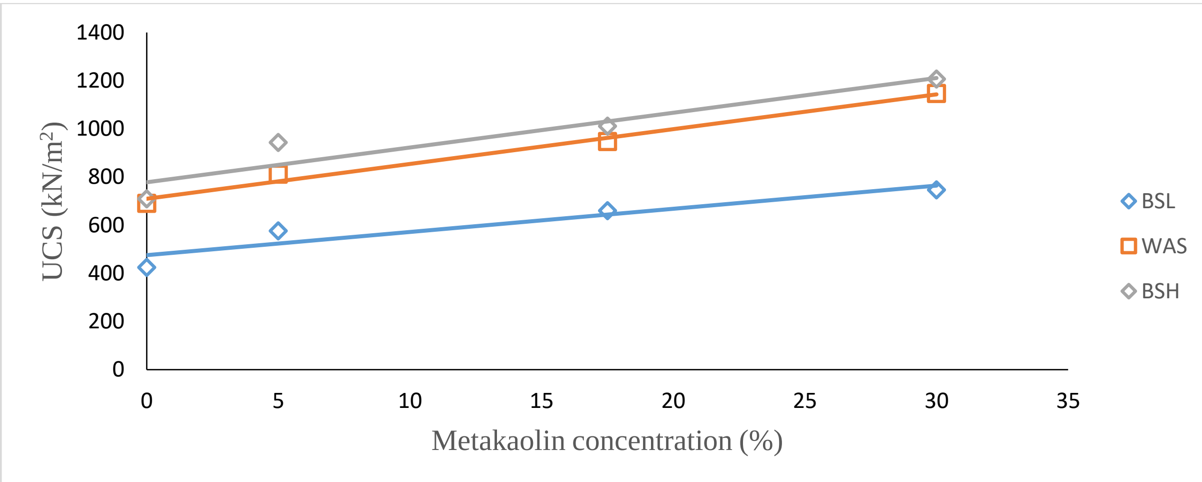


Figure 9: *Variation of UCS (28days curing period) of NLS with MK content*

Comparing the UCS values of the treated soil specimens compacted at the three energy levels indicate that specimens treated with 30 % MK and compacted at the BSH compactive effort yielded maximum UCS of 1207 kN/m^2 at 28 – day curing period which corresponds to an increase of 170 % when compared with the result obtained for the natural soil compacted at the same energy level and at 28 – day curing period. These results agree with various researches (Wong *et al.*, 2013; Osinubi et al., 2015; Onyelowe 2017; Ishola *et al.*, 2019; Onyelowe *et al.*, 2019).

Comparison of (UCS) results with recommended standard

The Nigerian General Specifications (NGS, 2013) nominal specifications for road construction layers recommends the range of 1500 - 3000 kN/m^2 for specimen cured for 7 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 UCS recommended value for base course, none of the recorded UCS values for the NLS/MK treated blends compacted using the three compactive effort met the criteria. However, for the sub-base criteria, only 30 % NLS/MK blend compacted at BSH compactive effort was adequate.

CONCLUSION AND RECOMMENDATION

This study explores the potentials of MK in the modification of the properties of non-lateritic soil obtain from Bauchi State, intended for use as a road construction material. Based on the results obtained in this study, the following conclusions were drawn.

i. The NLS classify as A-7-6 (14) in accordance with the American Association of State Highway Transportation Officials (AASHTO M 145-2012) soil classification system and base on the unified soil classification system (ASTM D 2487-2011), both soils classify as CL. This implies that the soil has appreciable quantity of clay and falls below the standard recommended for sub-base or base courses in highway construction.

ii. The oxide composition of the soil and MK determined using X-ray fluorescence (XRF) spectroscopy revealed that the Silica Sesquioxide Molar Ratio of Iron and Aluminium for the soil to be 2.96. The results also indicate that the soil possesses a silica-alumina ratio of 9:1 with a considerable quantity of Fe_2O_3 and a requisite amount of Alumina and silica. In the case of MK, the results revealed the presence of appreciable amount Al_2O_3, S_iO_2 and Fe_2O_3 required for materials to qualify as a class N pozzolana

iii. The geotechnical properties determine for the NLS falls below the standard recommended for use as sub-base or base course materials in road construction.

iv. With the addition of MK, there is substantial reduction in plasticity index when compared to the untreated soil

v. Combining the soil with MK improved the dry density with attendant decrease in moisture content, with BSH compactive effort yielding higher MDD due to the greater energy supplied. In terms of performance and workability, the treated soils would perform better as construction materials.

vi. A remarkable improvement in UCS was observed at 30 % MK concentration, yielding an average UCS value of 571, 619 and 814 kNm^2 at 7 days curing for BSL, WAS and BSH compactive efforts.

vii. In general, the 7 days cured UCS value of 30 % NLS/MK blend compacted using BSH effort falls within the range of 750 – 1500 kN/m^2 UCS value specified by the Nigerian General Specification (2013) for sub-base materials.

viii. Higher UCS values were recorded for all the compactive efforts at 28 days curing, this is attributed to the pozzolanic reaction of MK.

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