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# Kaolin soil and its stabilization potentials as nanostructured cementitious admixture for geotechnics purposes

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**Abstract**

The use of nanostructured kaolin as an additive in the stabilization of lateritic soils and its effect at different percentages on the natural soil were investigated. A UV–vis spectrophotometric characterization was conducted to determine the absorbance and average particle size of the nanostructured kaolin. The preliminary tests on the soil showed that it was a poorly graded (GP) soil on USCS. The soil sample was also observed to be silty clayey sand. The consistency limits result showed a liquid limit (LL) of 47% and plastic limit (PL) of 25.15%. The soil was observed to be highly plastic, of high swelling potential and medium expansion properties. Further, the effect of the addition of Nanostructured kaolin (NK) in the proportions of 3%, 6%, 9%, 12% and 15% by weight of the treated lateritic soil recorded the following results; the consistency limits results showed that the addition of variable proportions of nanostructured kaolin (NK) improved the plasticity index of the stabilized soil and gave 11.77%-a medium plastic material at 15% NK by weight addition compared to the preliminary result at 0% by weight additive which gave 21.85%-a highly plastic material. The strength properties test also showed significant improvements with the addition of NK; CBR test results recorded 23% at 15% by weight proportion of NK, which satisfies the material condition for use as a sub-base material and the UCS test results similarly improved consistently and recorded a maximum of 340.18 kN/m$^2$ at 15% by weight proportion of NK addition, which satisfies "very stiff" material consistency for use as a sub-base material. With the foregoing, NK has shown to be a good admixture material for soil stabilization towards solving the myriad pavement and environmental failures and problems with our road pavements.


*Keywords:* Kaolin soil; Soil stabilization; Sub-grade soil; Nanostructured kaolin; Environmental geotechnics

## 1. Introduction

It has been observed that in Nigeria and the developing countries, road construction is mostly done with lateritic soil as subgrade and sub-base materials. When it rains, water percolates on the base and sub base materials and eventually seeps down to the subgrade foundation and dissolves them, causing long damage to the road [1–2]. The base/sub base material dissolves because of high percentage of clay soil present or as a result of improper stabilization procedures. This depicts the need for special additives in pavement material stabilization to ensure improvement in the engineering properties of the soil such as volume stability, strength properties, permeability and durability [2]. Soil stabilization is one of the methods of improving the weight bearing capabilities and performance of the soil. This is also the alteration of soils to enhance their physical properties. Stabilization can increase the shear strength of a soil and control the shrink swell properties of a soil, thus improving the load bearing capacity of a sub-grade to support pavement and foundations [2]. Nanostructured kaolin (with average particle

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size measure at the nanoscale), that is an essential ingredient in the manufacture of China and porcelain and is widely used in the making of paper, rubber, paint, and many other products belongs to the group of nanomaterials. Nanomaterials are defined as materials with one external dimension in the size range from approximately 1 to 999 nm [1,3–11]. Soil that is highly susceptible to volume and strength changes can cause severe roughness and accelerates the deterioration of the pavement structure in the form of increased cracking and decreased quality when exposed to truck traffic. Generally, the stiffness (in terms of resilient modulus) of some soils is highly dependent on moisture and density [12–18,1919]. In some cases sub-grade soil can be treated with various materials to improve the strength and stiffness characteristics of the soil.

Stabilization of soil is usually performed for the following reasons;

(i) As a construction platform to dry very wet soils and facilitate compaction of the upper layers for this case the stabilized soil is usually not considered as a structural layer in the pavement design process.
(ii) To strengthen a weak soil and restrict the volume change potential of a highly plastic or compressible soil for this case, the modified soil usually gives some structural value or credit in the pavement design process.
(iii) To reduce moisture susceptibility of fine grain soil.
(iv) To improve the California bearing ratio of in situ soil by 4–6 times.
(v) To improve the in-situ material to create a solid and strong sub-base and base courses.

From an engineering perspective, soil is any uncemented or weakly cemented accumulation of material particles formed by the weathering of rocks and contains void spaces between particles, which are filled with water and air [20]. He also defined soil as a material having three components which includes, solid particles, air particles and weathering which can occur either chemically when the minerals of a rock are altered through climate effect, such as freeze, thaw and erosion [21]. The soil is said to be residual soil, if the present location of the soil is that in which the original weathering of the present rock occurred otherwise, the soil is referred to as transported. On the other hand, laterite is a soil group which is formed under weathering systems produced by the process of laterization (decomposition of ferroailumino-silicate mineral, leaching of the combined silica and base, and the permanent deposition of sesquioxide) within the pre-filled. The silica left un-leached after laterization will form secondary clay silicate minerals. Laterites usually form a poor soil full of concretionary lumps and very infertile because the potash and phosphate have been removed in solution, while only iron and silica are left behind [22].

### *1.1. Non-cementitious additive stabilization*

There are lots of additive that have been experimented on with the effect to improve the engineering properties of soils at lower cost by replacing certain percentages of cementitious stabilizers with non cementitious additives [2,16,23]. Some of these non cementitious stabilizers include: Snail shells ash, Quarry dust obtained as waste in quarry sites, Egg shell ash, Palm bunch ash, Palm kernel shell ash, Sawdust and so on.

### *1.2. Nanostructured kaolin*

The word "Nano" refers to anything of a very small particle size and could be dispersed in a liquid medium (such as water), without the particles sinking to the bottom or floating to the surface. In the case of Nano minerals, this is due to their unique electromagnetic load and the extremely small particle size [1,3–12]. Particle size is an important factor for good mineral absorption, because a fundamental physical law states that the smaller the particle, the greater the relative particle surface. Nano-kaolin, is a soft white clay that is an essential ingredient in the manufacture of China and porcelain and is widely used in making of paper, rubber, paint and many other products [13–15].

## 2. Materials and methods

### *2.1. Materials*

The Laterite test soil sample used for this research exercise, was collected from a borrow pit along Olokoro at latitude 05°28′36.900″N and longitude 07°32′ 23.170″E as shown in location map in Fig. 1, from a depth of about 2.00 m at a distance of 5 km along Ubakala road from Umuahia the Abia State capital in Nigeria. The laterite was obtained having little content of moisture in it i.e., semi-solid state and it was reddish brown in colour. It has a particle size less than 2 μm and it also increases in volume with the addition of water when partially saturated, shrinks and greatly develops cracks on the surface. The admixture (Kaolin), $Al_2Si_2O_5(OH)_4$ used was collected from Ohiya in Umuahia South Local Government area of Umuahia, Abia State. Ohiya is at Latitude of 05° 35′59.99″N and Longitude 07°31′59.99″E as shown in location map in Fig. 2. And ordinary Portland cement was added at a fixed percentage of 2% for the untreated and treated soil.

### *2.2. Methods*

The following conventional tests were conducted on the natural and the NK treated soils; Sieve Analysis Test: this was conducted with a vertically arranged sieve sizes mounted on an automatic shaker in accordance with BS

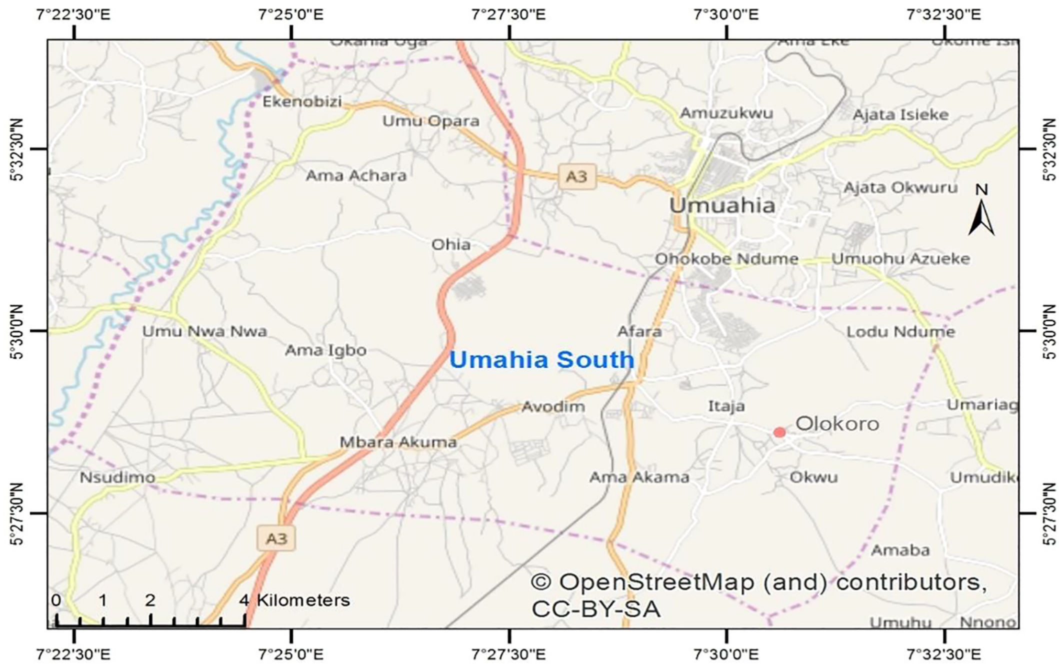


Fig. 1. Test soil sample location map.

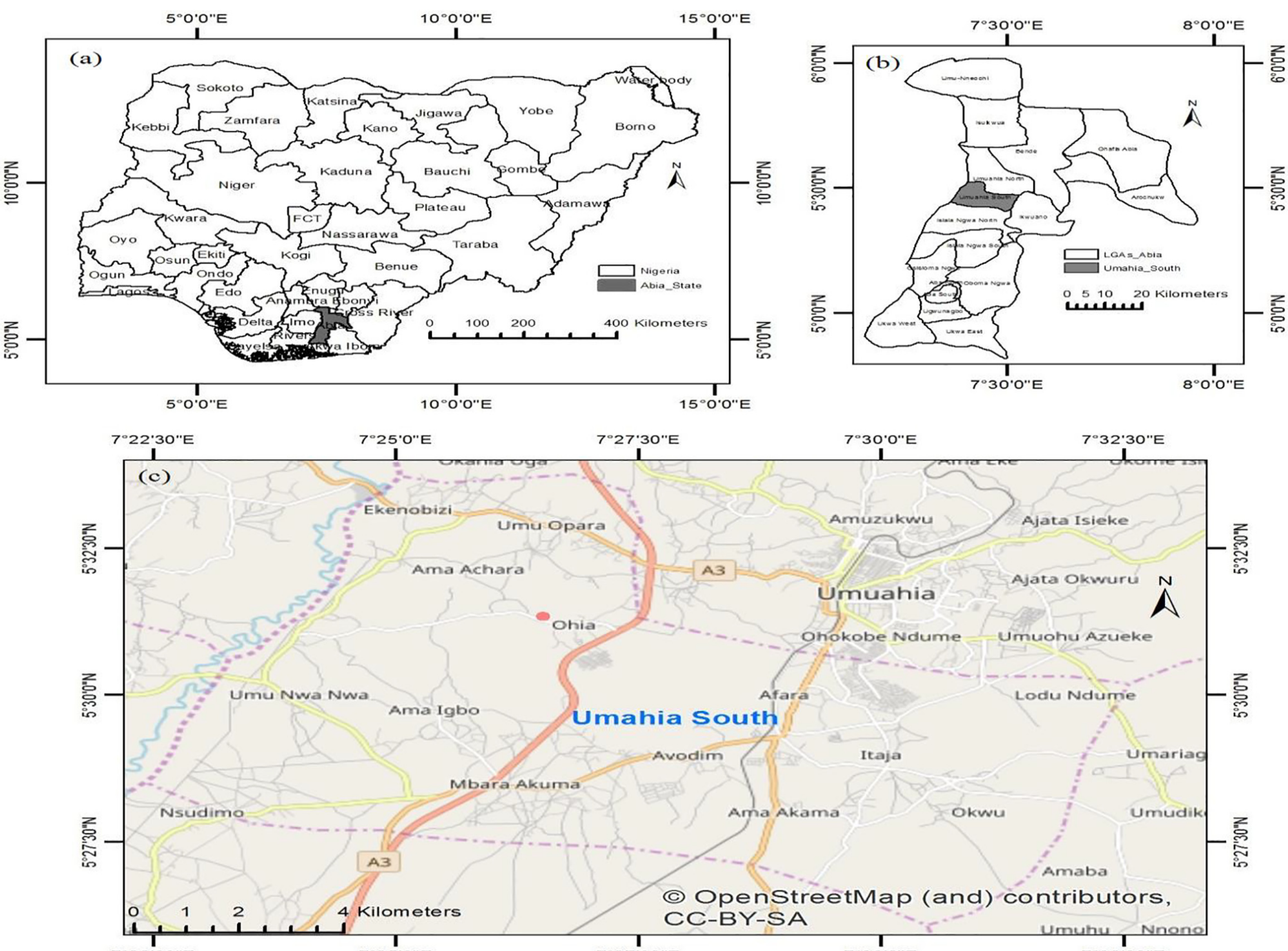


Fig. 2. Test material kaolin sample location map.

1377-2 [24] and NGS [25], Compaction Test (Standard Proctor Test): this was conducted with 2016 ELE Automatic Compactor Machine in accordance with BS 1377-2 [24]; BS 1924 [26] and NGS [25], California bearing ratio test (CBR) and Unconfined Compressive Strength test (UCS): conducted with a 2015 S211 KIT CBR penetration machine, motorized 50 kN ASTM used to load the penetration piston into the soil sample at a constant rate of 1.27 mm/min (1 mm/min to BS Spec.) and to measure the applied loads and piston's penetrations at determined intervals in accordance with BS 1377-2 [24]; BS 1924 [26] and NGS [25], Atterberg Limit Test: was conducted using a 2013 cassagrande apparatus in accordance with BS 1377-2 [24]; BS 1924 [26] and NGS [25], Specific Gravity Test was conducted by Pycnometer method in accordance with BS 1377-2 [24] and NGS [25], and Chemical Oxides Composition Test on the test soils and the test materials in accordance with BS 1377-2 [24] and NGS [25]. The NK proportion was added as 3%, 6%, 9%, 12% and 15% by weight of treated soil and results were tabulated, plotted and presented in the following pages.

#### 2.2.1. UV–vis spectrophotometric tests

This was conducted at the spectroscopic laboratory of the National Root Crop Research Institute, Umudike on the nanostructured kaolin to determine the constituent elements of the studied admixture (NK), $Al_2Si_2O_5(OH)_4$ and at the Chemistry Lab of Michael Okpara University of Agriculture to determine the spectrophotometric characterization of both lateritic soil and nanostructured Kaolin.

## 3. Results and discussion

The results of the laboratory stabilization exercise have been presented in tables and graphs in the following pages. It can be deduced from Table 1, that the lateritic soil;

- Has a plasticity index of 21.85% > 17% and that condition satisfies that Umuntu Olokoro lateritic soil is a highly plastic soil. Also the plasticity index falls between 20% and 35%, a condition for high swelling potential and between 25% and 41%, a condition for a high degree of expansion [27].
- Has, from the consistency limits tests, the soil relative consistency and liquidity index of 1.69% > 1 and 0.91% < 1 respectively showing that the soil is in a semi-solid or solid state, very stiff and plastic [27].
- Is classified as A-2-7 soil on AASHTO soil classification, poorly graded, GP on USCS, the group index of 0 and of silty, clayey gravel and sand material [27].
- Has an optimum moisture content (OMC) of 13% and maximum dry density (MDD) of 1.84 g/cm$^3$.
- Has Unconfined Compressive Strength (UCS) of 230.77 kN/m$^2$ at 28 days curing time, which falls between 200 and 400 kN/m$^2$, a condition for soils of very stiff consistency with respect to UCS, which satisfies the material condition for use as sub-grade material [25,27,28].
- Has a California bearing ratio of 14%, which makes it good for the sub-grade material [25,28].

It can be deduced that the soil is a well graded soil with Cc equals 0.09 and Cu equals 10, has a maximum absorbance of 1.154 nm at a wavelength of 800 cm while the NK has a maximum absorbance of 1.077 nm at 550 nm from the UV–vis spectrophotometric characterization of the soil and nanostructured kaolin from Figs. 3 and 4 and Table 2.

Table 2 shows the bonding potentials of the nanosized kaolin (NK) which satisfies that material bonding is a very important factor in soil improvement and stabilization because the soil and stabilizers need to form a cohesive bond. Material requirement for cementing materials is that the sum of the percentage composition of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ should not be less than 70%. The result of the anal-

Table 1
Geotechnical properties of the test soil.

| Test soil properties/unit | | Test results |
|---|---|---|
| % Passing BS No. 200 sieve | | 25.40 |
| Natural moisture content (%) | | 10 |
| Liquid limit (%) | | 47 |
| Plastic limit (%) | | 25 |
| Plasticity index (%) | | 22 |
| Coefficient of curvature, $C_c = \frac{D_{30}^2}{D_{10} x D_{60}}$ | | 0.09 |
| Coefficient of uniformity, $C_u = \frac{D_{60}}{D_{10}}$ | | 10 |
| Specific gravity | | 2.67 |
| USCS | | GP |
| Condition/general subgrade rating | | Poor |
| Optimum moisture content (%) | | 13 |
| Maximun dry density (g/cm$^3$) | | 1.84 |
| California bearing ratio (%) | | 14 |
| Unconfined compressive strength (kN/m$^2$) | 28 days | 230.77 |
| | 14 days | 219.11 |
| | 7 days | 194.26 |
| Colour | | Reddish brown |

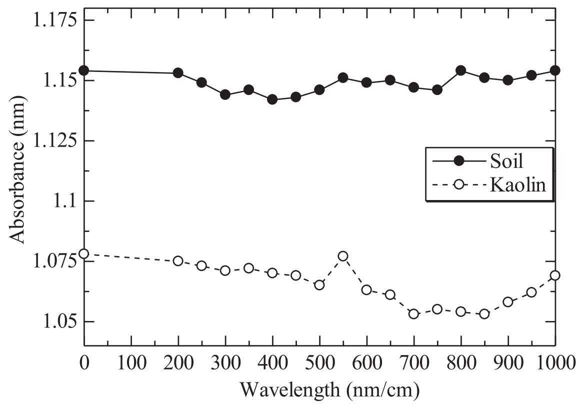


Fig. 3. Variation of absorbance against wavelength for the lateritic soil at wavelength in cm and nanostructured kaolin at wavelength in nm using UV/VIS spectrophotometer at 25 °C.

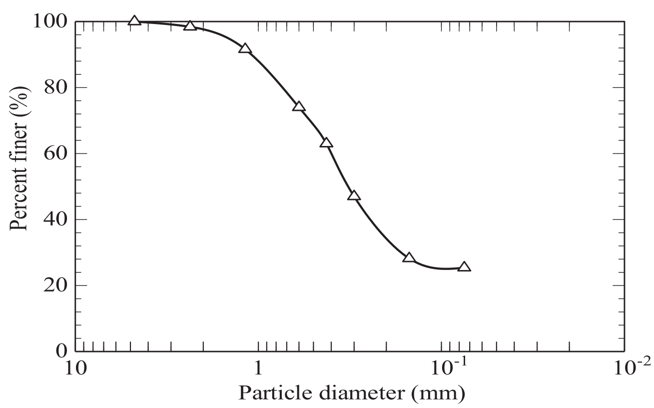


Fig. 4. Particle size distribution curve of the test lateritic soil.

Table 2
Chemical composition of nanostructured kaolin.

| Constituents | OH | $Fe_2O_3$ | $Al_2O_3$ | $SiO_2$ | $P_2O_5$ |
|---|---|---|---|---|---|
| % wt in NK | 1.43 | 0.75 | 41.80 | 56.48 | 0.29 |

ysed NK shown in Table 3 shows that the percentage of $SiO_2 + Fe_2O_3 + Al_2O_3$ is 99.03% greater than 70%, which makes the admixture sample a highly cementitious material [29]. This property is of great advantage because it brought about a high degree of interaction and bonding between the studied soil and the additive.

### 3.1. Effect of nanosized kaolin on the consistency limits of the lateritic soil

The results of consistency limits tests conducted are shown in Table 3 and Fig. 5. The preliminary tests were conducted and summarized in Table 1. It can technically be deduced that the plasticity of the stabilized soil reduced consistently with the addition of variable proportions of NK; 3%, 6%, 9%, 12% and 15%. At 15% NK addition by weight of dry soil, a PI of 11.77% was recorded which showed an improved plasticity, from highly plastic material to medium plastic material. This behavior agrees with Meegoda and Ratanweera [30], who showed that if water is used as pore fluid, the influence of the mechanical factors would remain same with a general decrease in LL on addition of an admixture. However, if an organic fluid other than water is used, the physical properties of the fluid such as viscosity and density would influence the LL. With the varying behavior with the addition of NK, it can be seen that the LL depends on the mechanical factors other pore fluid viscosity and density [31] and to a lesser degree on the physicochemical properties. The lowering of the LL and PI is therefore as a result of the mechanical factors; nanosization of Kaolin, increased the reactive surface and physicochemical factors of the soil such as a low dielectric constant, resulting from high absorbance values which causes the clay particles to behave more like a granular matrix with attendant reduction in adsorbed water and the physicochemical factors of the admixture such as carbon and hydroxide contents which lead to the formation of calcium silicates and aluminates with soil when mixed as a stabilized mass [2]. Moreover, ashes do not exhibit plasticity even when the clay size fraction is present. The fraction is pozzolanic since it is a product merely of crushing of coarser particles, hence the reduction in the plasticity index of the stabilized mass. This satisfies a better material condition for use as a sub-base material.

Table 3
Effect of nanosized kaolin % on the Atterberg limits of the lateritic soil.

| Atterberg limits | Proportion of kaolin (%) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 |
| LL (%) | 47.0 | 48.45 | 49.96 | 50.67 | 52.11 | 52.27 |
| PL (%) | 25.15 | 28.86 | 33.39 | 34.51 | 37.22 | 40.5 |
| PI (%) | 21.85 | 19.59 | 16.57 | 16.16 | 14.89 | 11.77 |

### 3.2. Effect of nanosized kaolin on the compaction of the lateritic soil

The results from compaction tests conducted are shown in Table 4 and Fig. 6. The dry density of the stabilized sample improved at 12% addition of NK to 1.85 mg/cm$^3$ which recorded the highest density, though with the highest OMC

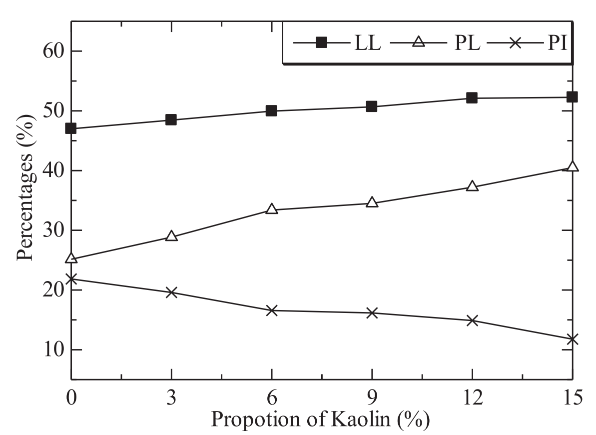


Fig. 5. Consistency behavior of test soil treated with nanostructured kaolin.

Table 4
Effect of nanosized kaolin on the compaction of the lateritic soil.

| | Proportion of kaolin (%) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 |
| MDD ($mg/cm^3$) | 1.84 | 1.77 | 1.79 | 1.82 | 1.85 | 1.70 |
| OMC (%) | 13 | 13.29 | 13.05 | 13.07 | 14.06 | 14.65 |

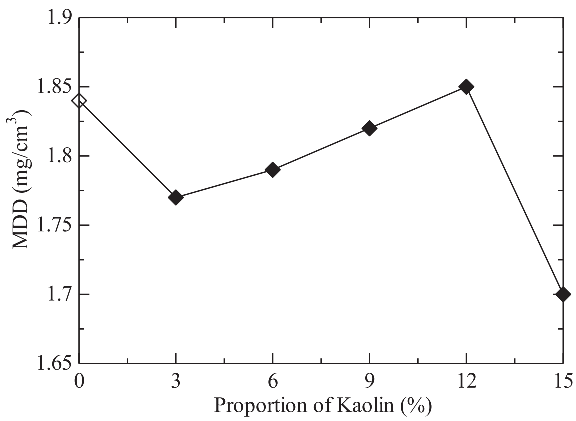


Fig. 6. Maximum dry density (MDD) behavior of test with NK additive.

compared to the control experiment. It is only understandable that the decrease in MDD recorded as shown in Table 6 is as a result of the low relative density of the NK compared to the soil sample. However, above 6% addition of NK, there was a possibility that the formation of new compounds occurred which consequently led to the increase in the MDD at 9% and 12% of NK content and also due to molecular rearrangement in the formation of transitional compounds which showed a high density at 12% NK addition. However, there were reductions in MDD at 3% and 15% NK content which could be attributed to the replacement of the soil by NK which has a low specific gravity compared to the soil. The cementing property of the NK may have caused the increased OMC due to the high heat of hydration and also demand for water by various cations and the clay mineral particles from both soil sample and admixture to also undergo the hydration reaction. This is as a result of the increased reactive surface and the pozzolanic property of the nanosized kaolin mixed with the lateritic soil, thereby achieving higher density at lower moisture content. This behavior may also be due to cation exchange reactions and the admixture occupying the void within the soil matrix and in addition, the flocculation and agglomeration of the clay particles due to exchange of ions [32]. The subsequent reduction in MDD may be due to the fact that for any soil/admixture, there is always water content to produce maximum strength. The trend is in conformity with the results reported by [32]. An explanation that was offered for this trend is that there was increasing desire for water, which is commensurate with the higher amount of additives because more water was required for the dissociation of admixtures with $Ca^{2+}$ and $OH^-$ ions to supply more $Ca^{2+}$ for the cation exchange reaction. The decrease in the OMC with increased proportions of admixture content might be due to cation exchange also that caused the flocculation of clay particles. Moreover, the NK is a highly pozzolanic material and requires water for hydration thereby improving the strength gain of the NK + soil mixture.

### 3.3. Effect of nanosized kaolin on the California bearing ratio (CBR) of the lateritic soil

The results from the CBR test conducted are shown in Table 5 and Fig. 7 and the following can be deduced; that the stabilized lateritic test soil improved from 14% of the control experiment to 19% with the addition of the 3% NK. This also recorded a reduction in the CBR of values

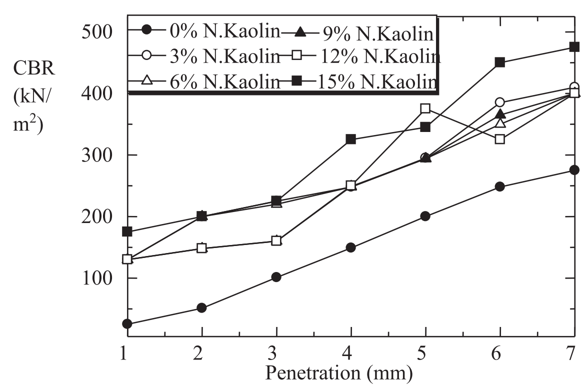


Fig. 7. Effect of nanostructured kaolin on the CBR of stabilized lateritic soil.

Table 5
Effect of nanosized kaolin on the CBR of the treated soil.

| Penetration (mm) | CBR of soil treated with NK proportions % by weight | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 |
| 1.0 | 25 | 130 | 130 | 130 | 130 | 175 |
| 2.0 | 51 | 200 | 200 | 148 | 148 | 200 |
| 3.0 | 101 | 225 | 220 | 160 | 160 | 225 |
| 4.0 | 149 | 248 | 248 | 249 | 250 | 325 |
| 5.0 | 200 | 295 | 294 | 294 | 375 | 345 |
| 6.0 | 248 | 385 | 350 | 365 | 325 | 450 |
| 7.0 | 275 | 410 | 400 | 400 | 400 | 475 |

17%, 18% and 18% of the stabilized studied material at 6%, 9% and 12% addition of NK. These values also satisfy the material condition for use as improved sub-grade material on Nigeria's south eastern roads. At 15% addition of NK, the material CBR improved to 23% > 20%, which satisfies the material condition for use as improved sub-grade material according to the Nigerian General Specification for roads and bridges as shown in Table 8 [25,33]. The increase in the CBR with the addition of NPBA could be due to the presence of adequate amount of calcium required for the formation of Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which are the major compounds responsible for strength gain. The soil + 15% NK mixtures passed to meet the minimum CBR value of 20–30% specified by [26] for materials suitable for use as base course materials when determined at MDD and OMC. This is close to the findings of Gidigasu and Dogbey [34], which stated that the minimum CBR value of 20–30% is required for sub-bases when compacted at optimum moisture content (OMC). Increase in CBR, an implication of the increase observed in MDD is attributed to the compatibility of the grains of soil due to the increased reactive surface and the high pozzolanic properties of the NK such that greater densification was achieved. The observed decrease in CBR recorded at 6% by weight addition of NK could be attributed to the failure under load of the soil particle matrix as a result of the fineness of the nanosized admixture.

### 3.4. Effect of nanosized kaolin on the UCS of the lateritic soil

The results of UCS test conducted are shown in Table 6 and Fig. 8. The natural lateritic soil stabilized and cured at different days showed good material property for use as a sub-grade layer. It improved from 194.24 kN/m$^2$ at 7 days curing, 219.11 kN/m$^2$ at 14 days curing and finally to 230.77 kN/m$^2$ at 28 days curing. The compressive behaviour and property greatly improved with the variable proportional addition of the Nanosized Kaolin at 3%, 6%, 9%, 12% and 15%. The consistent improvement of the stabilized lateritic test soil has shown that at higher proportions of NK beyond 15%, the compressive strength will keep increasing. At 15% additive, the stabilized studied sample recorded 315.27 kN/m$^2$ at 7 days curing time, 316.82 kN/m$^2$ at 14 days curing time and 340.18 kN/m$^2$ at 28 days curing which are all very stiff consistency and satisfies the material condition for use as sub-base material in Nigeria's south eastern roads where roads have failed their structural value and use. The chemical composition of NK has also shown its high cementing property, hence the material property optimization [35]. The gain in strength is attributed to the spherical agglomeration of particles in the presence of the highly pozzolanic NK. A further observation was that the presence of the admixture in the soil increased the frictional angle of the stabilized mixture attributed to the physicochemical and pozzolanic properties of the admixture and to its ability to reduce adsorbed water thereby making soils with higher clay content to behave like granular soils.

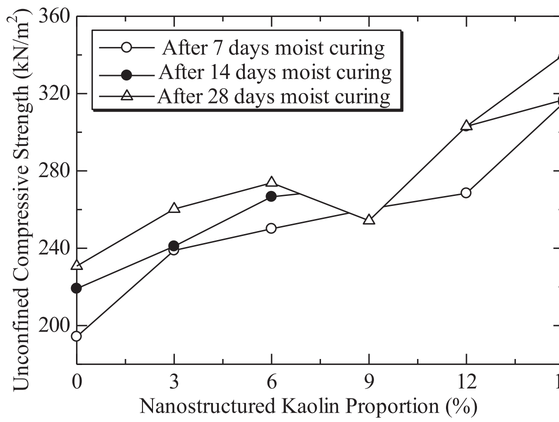


Fig. 8. Unconfined Compressive Strength (UCS) behavior with addition of nanostructured kaolin (NK).

## 4. Conclusion

From the foregoing, it can be concluded as follows;

1. That the nanosized kaolin has proved to be an excellent additive to the stabilization of the lateritic test soil by satisfying the index, compaction and strength properties of the stabilized soil-nanostructured matrix and met the conditions for use as improved subgrade and excellent subbase material for roads construction.
2. That the high cementitious property of the studied admixture was an advantage to its bonding, flocculation of the treated soil and improved strength property.
3. That the government of the south eastern states of Abia, Imo, Ebonyi, Enugu and Anambra states and the developing world generally whose roads are in a state of despair should refer to the results of this work to update their constructors, contractors, designers, engineers and professionals in the works and infrastructures ministries to ensure that subgrade soils explored and hauled

Table 6
Effect of nanosized kaolin on the unconfined compressive strength (UCS) of stabilized lateritic soil.

| UCS (kN/m$^2$) | Proportion of kaolin (%) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 |
| 7 days moist curing | 194.26 | 238.87 | 250.06 | 260.32 | 268.41 | 315.27 |
| 14 days moist curing | 219.11 | 241.01 | 266.61 | 271.97 | 303.04 | 316.82 |
| 28 days moist curing | 230.77 | 260.28 | 273.84 | 254.29 | 303.04 | 340.18 |

for construction purposes are improved with the abundance kaolin material occurring in its natural state at ohiya, Umuahia, Abia State, Nigeria.

4. That the kaolin material gotten at no cost will go long ways in solving many of the environmental problems facing Nigerian roads.

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