EVALUATION OF GEOTECHNICAL PROPERTIES OF LATERITIC SOIL STABILIZED WITH METAKAOLIN AND LIME AS CEMENT SUBSTITUTE

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Abstract: *In order to explore the application of metakaolin and lime as substitute materials for lateritic soil stabilization, this study investigates the geotechnical characteristics of lateritic soil stabilized with metakaolin and lime. Liquid Limit (LL), Plasticity Index (PI), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Particle Size and Specific Gravity were the geotechnical properties taken into consideration. In order to assess these qualities, a lateritic soil sample was combined with metakaolin and lime in amounts of 2, 4, and 6% by soil weight. The mixture was then homogeneously mixed and put through laboratory tests for specific gravity, compaction, particle size distribution, and Atterberg limits. LL, PI, MDD, OMC, fines, sand, and gravel were found to range in levels from 26 to 32%, 2 to 16%, 1850 to 1982 kg/m^3, 9.92 to 12.10%, 0.10 to 2,84%, 14.18 to 15.30%, 82.98 to 84.60%, and 2.00 to 2.60, respectively, according to the results. The percentages of specific gravity and fine particles increased along with the admixture content (lime + metakaolin), while all other parameters decreased. The soil sample that was taken before treatment is suitable as subgrade material, while after treatment, it becomes suitable as base and subbase courses materials. This study demonstrated that lateritic soil could be stabilized by using metakaolin and lime. It indicated that the ideal admixture quantity to be utilized was 6% lime + 6% metakaolin. However, further research is required in other to find out how to raise the MDD of lateritic soil while increasing the admixture.*

Keywords: Lateritic soil, lime, metakaolin, stabilization, sustainable construction materials

Introduction

The tight relationship between sustainable infrastructures and construction materials is all encompassing. The suitability of construction materials is paramount for safety and serviceability of all civil engineering works and general infrastructural development. Therefore careful selection of the materials' constituent used in construction industries is in the frontline. Cement as common binder for aggregates in production of concrete and stabilizing agents for soil has an adverse effect on the environment due utilization of a lot of fossil fuel during its manufacture and contribution to more than 5% of global carbon dioxide emissions (Alrubaye et al., 2022). Thus, researchers across the globe are gearing efforts towards the production of eco-friendly construction materials with good cementation properties.

Empty palm fruit bunch ash, cassava peel ash, metakaolin and other pozzolanas with less CO_2 have been investigated and found suitable to replace cement (Adetoro et al., 2024; Amusan *et al*., 2021; Abdulkarim et al., 2020 and Amusan *et al*., 2017). Kumar, et al. (2022) submitted that using additional carefully selected soils, aggregates, or binders, the in-situ soil stabilization is achieved to build a strong foundational material that can resist higher impact load suitable in all weather conditions. Thus, there is a need to provide an alternative material to reduce the quantity of cement needed for soil stabilization. The purpose of this study is to assess or explore the application of metakaolin and lime as substitute materials for lateritic soil stabilization.

Metakaolin, a dehydroxylated form of kaolinite, usually produced by heating to between 500 and 850 °C. Because of its pozzolanic properties, metakaolin is being considered for use as a cement alternative and as an additive to lime (Ashioba and Udom, 2023; Afrin, 2017). Many studies have used metakaolin to stabilize lateritic soil in the recent past; some even combine metakaolin with additional chemicals, as Table 1 shows. Among them are metakaolin and groundnut shell ash blend, metakaolin and ashcrete blend, cement and metakaolin (Onyelowe et al., 2023; Wang et al., 2023; Abdulkarim et al., 2022; Phuc-Lam et al., 2022; Muhammad et al., 2020; Abdu et al., 2017).

Table 1: Reviewed works on use of metakaolin for lateritic soil stabilization

Journal article title	Author	Findings	Gap
Compaction behavior of lateritic soil stabilized with blends of groundnut shell ash (GSA) and metakaolin (MK).	Abdu et al. (2017)	2 – 10% GSA and 5 - 25% MK was used. The result met acceptable requirements of Nigeria road layers.	Lime and MK was used in this study.
Assessment of lateritic soil stabilized using metakaolin	Muhammad et al. (2020)	Optimum of 6% MK could be used to achieve a desired subbase material for light traffic roads.	Lime and MK was used in this study.
Effect of MK on strength properties of lateritic soil intended for use as road construction material	Abdulkarim et al. (2022)	30% MK met the 30% requirement for subbase material	Lime and MK was used in this study.
Effect of metakaolin on the mechanical properties of lateritic soil	Phuc-Lam et al. (2022)	Optimum of 6% MK is the best for lateritic soil stabilization	Lime and MK was used in this study.
Effect of MK and ashcrete blend on the mechanical properties of lateritic soil for sustainable subgrade and subbase construction	Onyelowe et al. (2023)	The blend fulfilled the requirements for the construction a subgrade and subbase.	Lime and MK was used in this study.
Strength performance and stabilization mechanism of fine sandy soils stabilized with cement and metakaolin	Wang et al. (2023)	The study provides reference for application of cement and metakaolin in soil stabilization.	Lime and MK was used in this study.

This study, therefore, assess some geotechnical characteristics of lateritic soil samples stabilized with metakaolin and lime, to enhance its properties for foundation purposes and most importantly in road construction for stable transportation services essential for socio-economic growth.

Material and Methods

Materials sourcing

Lateritic soil, metakaolin, lime, and potable water were utilized in this investigation. As seen in Figure 1, the lateritic soil sample utilized in the study was obtained from Ogere Ajura village in Ogun State, Nigeria, with coordinates of latitude 10° 16' 46.54" N and longitude 9° 51' 54.25" E. Lateritic soil sample were taken at a depth between 0.8 m and 1.0 m. The experimental sample were packed in sack bags. Following the available standard procedures of ASTM E1727 (2020), FMWH (2013), and BS 1377 (1990), each bag was appropriately labeled, sealed, and packed.
The metakaolin utilized was obtained in Ajebo, Abeokuta in Ogun State. This was made by calcining kaolin clay at 700 degrees Celsius (Figure 1). Calcium carbonate, or limestone, is chemically changed into calcium oxide to produce quicklime. The calcium oxide was prepared by heating calcium carbonate (i.e. limestone) in a lime kiln to temperature between 500 and 600 °C, breaking it down into carbon (IV) oxide and calcium oxide – this process is called calcification (Adetoro et al., 2024). The studies were carried out at Olabisi Onabanjo University's Ibogun campus, at the Department of Civil Engineering laboratory, where potable water is readily available.

Methods

After calculating the soil weight, lime and metakaolin (0, 2, 4, and 6%) were added to the resulting lateritic soil sample and thoroughly mixed.

Fig. 1. Lateritic soil and metakaolin

Atterberg limits, compaction, particle size distribution, and specific gravity tests were used in the laboratory to assess the geotechnical qualities of the samples. There were two phases to the testing. The first part dealt with determining the geotechnical properties of the soil without the use of additives, while the second phase addresses the assessment of geotechnical properties of the lateritic soil stabilized with lime and metakaolin additives.

Atterberg limits tests

Atterberg limits experiments determine the moisture content at which physical changes occur in fine-grained clay and silt soils as they transition between the solid, semi-solid, plastic, and liquid phases. The Casagrande apparatus, a device for testing liquid limits, was used to determine the liquid limit. The liquid limit, and plastic limit of soils are tests determined by direct measurements of the water content using recognised test protocols (ASTM D318, 2017). According to AASHTO T89

(2022), the liquid limit is the lowest water content at which soil will begin to flow when a typical shearing force (dynamic loading) is applied. The treated and untreated soil samples underwent the Atterberg limit tests in compliance with ASTM D318 (2017). Equations (1) and (2) were used for determination of Liquidity Index (LI) and Plasticity Index (PI), respectively.

$$\mathrm{LI} = \frac{(W - PL)}{(LL - PL)} \quad (1)$$

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \quad (2)$$

Where W is the natural water content.

Compaction test

The test is used to calculate the ideal moisture content and dry unit weight of soil samples. In compliance with ASTM D698 (2021), tests of the moisture density relationship were performed on both treated and untreated soil samples. % Relative Compaction (RC) is determined using Equation (3).

$$\mathrm{LI} = \frac{Dd}{MDd}\ X\ 100\% \quad (3)$$

Where Dd is the dry density of the sample and MDd is the maximum dry density from the compaction curve.

Particle size distribution test

Grain size or distribution is one of the most significant physical properties of soil because of its complex nature. This test was performed in order to determine the grading and particle size distribution of the treated and untreated soil samples. When classifying soil according to ASTM or AASHTO standards, it is essential. Following ASTM D6913 (2009), the test was performed on soil samples that had been treated as well as those that had not.

Specific gravity test

The relative density test, as it is officially called, measures a substance's density in relation to water's density and is mathematically expressed in Equation (4). In order to determine specific gravity, water at its densest point of 4 degrees Celsius (39.2 degrees Fahrenheit) is used for liquids and solids, and room temperature air for gases. In compliance with ASTM D854 (2023) and (ASTM D4439, 2023), the test was performed on soil samples that had been treated and those that had not.

$$\text{Specific Gravity (SG)} = \gamma_S/\gamma_w \quad (4)$$

Where γ_s is the lateritic soil sample density and γ_w is the density of water.

Results and discussion

The untreated soil's geotechnical characteristics

The test results for the chosen geotechnical characteristics of the untreated soil are shown in Table 2. It's clear that the untreated lateritic soil sample has a lower percentage of finer particles, particles with a percentage of less than 35% at 0.10%. The soils were made up of 84.60% and 15.30% of sand and gravel, respectively. These results demonstrated that the soil contains a sizable number of granular particles. The sample's Liquid Limit (LL) was 32, and its Plasticity Index (PI) was 16%. Based on the data, the soil was assigned an A-2-6 classification. With typical sorts of important constituent materials, the lateritic soil received an overall excellent rating as a subgrade material. Granular materials were the general classification given to it (ASTM D3282; AASHTO M145, 2018).

Table 2. A Summary of geotechnical characteristics of the untreated soil

S/No.	Test Names	Value obtained	Reference (Standard)
1	Liquid Limit	32%	ASTM D4318 (2017)
2	Plastic Limit	16%	ASTM D4318 (2017)
3	Plasticity Index	16%	ASTM D4318 (2017)
4	Grain size - Fine (% < 35%)	0.10%	ASTM D6913 (2009)
5.	Grain size - Sand	84.60%	ASTM D6913 (2009)
6.	Grain size – Gravel	15.30%	ASTM D6913 (2009)
7.	Soil Classification	A-2-6	AASTHO M145 (2018)
8.	Specific Gravity	2.00	ASTM D854 (2023)
9.	Optimum Moisture Content (%)	9.92	ASTM D698 (2021)
10.	Maximum Dry Density (g/cm^3)	1.982	ASTM D698 (2021)

According to Table 2, the maximum dry density (MDD) of the untreated soil is 1.982 g/cm^3. According to the rating of FMWH (2013), the soil sample satisfied the standards for subgrade (LL ≤ 80%, PI ≤ 55%, and MDD > 1760 kg/m^3). However, it did not meet the requirements for subbase and base (LL ≤ 35%, PI ≤ 12%, and MDD > 2000 kg/m^3) course materials because of its low MDD (i.e., MDD = 1982 kg/m^3) and PI > 12% (i.e. 16%). Table 2 displays the Optimum Moisture Content (OMC) value, which is 9.92%. Because the Figure is within the range (5–15%) given by FMWH (2013) for engineering construction, the soil has a favorable moisture content. It has been demonstrated that values in this range increase the shear strength of certain materials used in road construction. It is thus appropriate for use as subgrade material (Faluyi et al., 2023).

Moisture contents of different soils typically range from 10 to 15% for granular soil, 15 to 30% for silty soil, and 30 to 50% for clayey soil, according to Vincent et al. (2020). For clayey, silty clayey, and granular soil, respectively, MDD typically varied between 1.44 and

1.69 g/cm^3, 1.60 and 1.85 g/cm^3, and 1.75 and 2.17 g/cm^3. Therefore, results in Table 2 indicated that the untreated soil fell into the granular soil range (that is, OMC = 9.92% and MDD = 1.982 g/cm^3), which is consistent with AASHTO M145 (2018)'s initial categorization. This agrees with the findings in previous studies (Emmanuel et al., 2021; Oyelami and Van Rooy, 2016).

Vincent et al. (2020) also proposed that a good lateritic soil should have a specific gravity between 2.50 and 2.75. The untreated sample under review was not good enough because its specific gravity was outside of the stated range (specific gravity = 2.00). The poor specific gravity and excess PI indicated that the untreated soil needed to be stabilized in order to be used as subbase and base course materials for road construction (Vincent et al., 2020; Faluyi et al., 2023).

Atterberg limits test results

When constructing new roads, Atterberg limits are used to determine the strength and settling properties of the soil. Figure 2 displays the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) following the addition of metakaolin and lime. The subbase standards (i.e., LL < 35% and PI ≤ 12%) at 2% Lime + 2% MK as mandated by FMWH (2013) were not fulfilled, however the subgrade requirements (LL ≤ 80%, PI ≤ 55%) were met. However, with 4 and 6% mixtures of MK and lime, the specifications for base course, subbase, and subgrade materials were satisfied. Therefore, when treated with 4% Lime + 4% MK, the untreated soil can become good subgrade, subbase, and base materials with the addition of the additives at 4%.

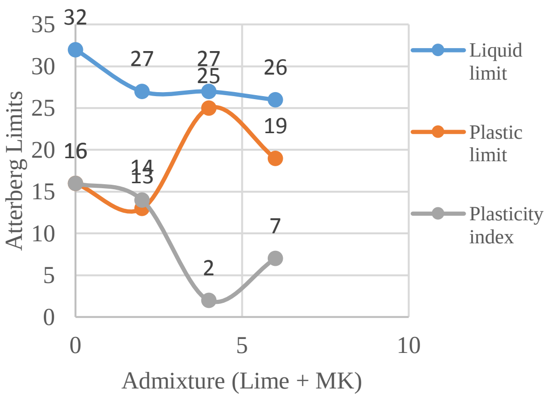

Fig. 2. Results of Atterberg limits for the treated soil

Result of compaction tests – Admixture effects on the MDD and OMC

The plot of MDD against the admixture for the treated soil is shown in Figure 3. The use of the soil as subgrade is in peril with an increase in the admixture up to 6% since there was a drop in MDD as the quantity of additive applied increased. According to FMWH (2013) and Faluyi et al. (2023), the treated soil at varied percentages still only meets the standards for maximum dry density for subgrade (i.e., MDD > 1760 kg/m^3), not subbase and base course (MDD > 2000 kg/m^3) materials. However, with 4 and 6% mixtures of MK and lime, the specifications for base course, subbase, and subgrade materials were satisfied. Therefore, when treated with 4% Lime + 4% MK, the untreated soil can become good subgrade, subbase, and base materials with the addition of the additives at 4%.

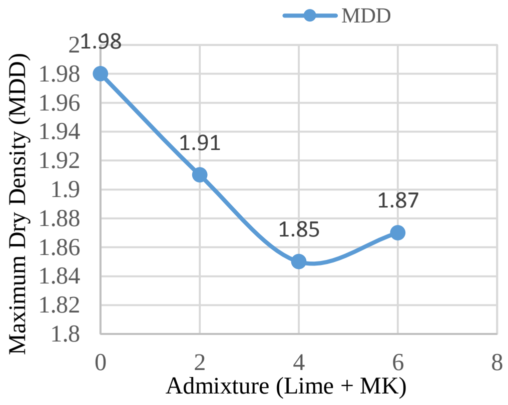

Fig. 3. Graph showing results of Maximum Dry Density for the treated soil

As the additive grew before declining, the OMC generally climbed up to 2% and peaked at 2% (Figure 4). Conversely, Figure 4's OMC value, which varied from 9.92 to 12.10%, indicates a favorable soil moisture content because it falls between the 5 and 15% range recommended for engineering construction by FMWH (2013) and Vincent et al. (2020).

Values in this range has been demonstrated to increase the shear strength of materials used in road construction. As a result, it works well as subbase and subgrade material. The fact that metakaolin and lime have lower densities than lateritic soil may be the cause of the MDD decrease. The previous studies conducted by Faluyi et al. (2023) and Onyelowe et al. (2023) supported this OMC behavior when additives like lime and MK were added.

Table 3 trends of OMC with MDD for the treated soil demonstrated an initial increase in OMC as MDD fell before declining.

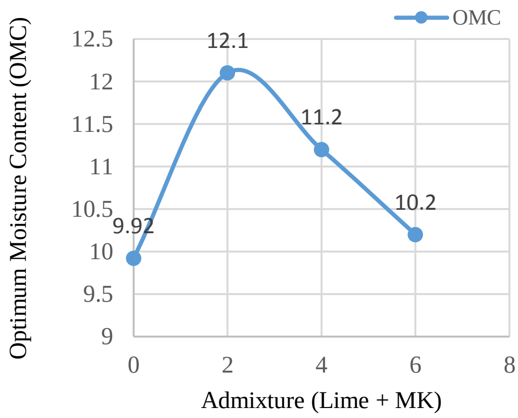

Fig. 4. Results of Optimum Moisture Content for the treated soil

The first increase was caused by a rise in water content, which is necessary for the lateritic soil and additives to work. After that, it is anticipated that when the amount of additive added increases, the OMC will rise along with the MDD and vice versa (Muhammad et al., 2020; Abdulkarim et al., 2022).

Table 3. Trend of OMC with MDD for the treated soil

Additive (Lime + MK)	**0%**	**2%**	**4%**	**6%**
Optimum Moisture Content (%)	9.92	12.1	11.2	10.2
Maximum Dry Density (g/cm^3)	1.982	1.9	1.8	1.87

Result of particle size tests – Admixture effects on the particle size

The graph of the treated soil's particle size versus admixture is displayed in Figure 5. Fine, sand, and gravel percentages were 0.10 to 2.84%, 14.18 to 15.30%, and 82.98 to 84.60%, in that order. It is clear that as the admixture concentration grew, the percentage of fine particles climbed while the percentages of sand and gravel declined. The fineness of the lime and metakaolin were the cause of this increase in the percentage of fine.

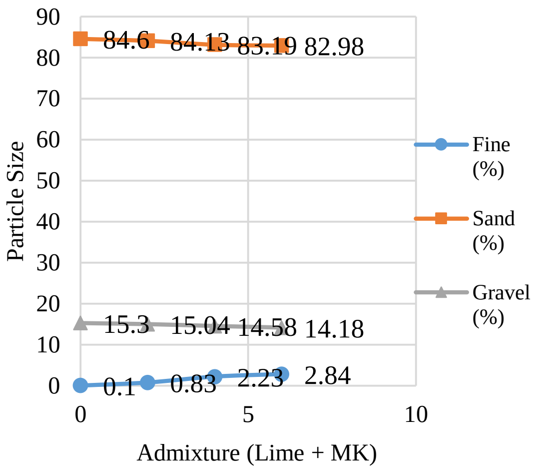

Fig. 5. Results of particle size against admixture for the treated soil

Result of specific gravity tests – Admixture effects on the specific gravity

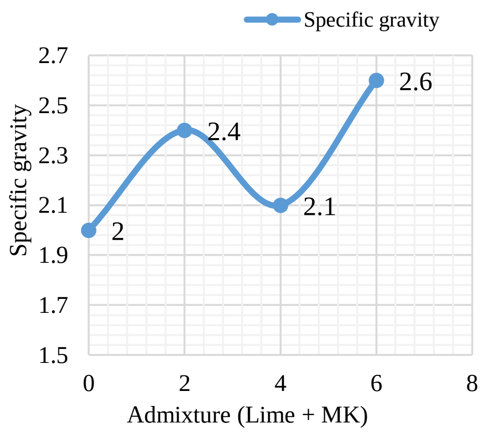

Fig. 6. Graph of specific gravity against admixture for the treated soil

Figure 6 displays a graph of the treated soil's specific gravity against the admixture. It is clear that the soil's specific gravity varied when metakaolin and lime were added in varying proportions. The specific gravity of the soil is influenced by the amount of sand present in it, as well as by the mineral composition and formation process. As illustrated in Figure 6, the specific gravities of the soil samples under investigation range from 2.0 to 2.6. A good lateritic material should have a specific gravity in the range of 2.50 to 2.75, according to Vincent et al. (2020). Even while the untreated soil's specific gravity first falls outside of this range, it eventually approaches it as the amount of admixture increases and reaches 6% lime + 6% MK. This may be due to the samples' high mineral content, as the addition of metakaolin and lime at 6% is thought to be of acceptable grade.

Implication of lime + metakaolin admixture on the lateritic soil

Only the subgrade course material requirements (LL < 80%, PI ≤ 55%, and MDD > 1760 kg/m^3) were satisfied by the untreated soil. The treated soil satisfied the standards for subbase and base course materials after being mixed with admixture, with the exception of the MDD view (i.e., LL < 35%, PI ≤ 12%, and MDD > 2000 kg/m^3). As the admixture's interaction progressed, it was able to decrease the soil's LL, PI, and MDD. This is beneficial for LL and PI, but not for MDD. The admixture's ability and sufficiency at 6% were demonstrated by the OMC, specific gravity, and particle sizes. As a result, it may be concluded that the admixture had a positive stabilizing effect on lateritic soil. After treatment, the soil classification, which indicated that it was good material, is remained A–2–6.

Conclusions

The geotechnical properties of lateritic soil in combination with metakaolin and lime have been investigated in compliance with the road construction norms of AASHTO MI145 (2018), ASTM D3282 (2015), and FMWH (2013). According to the results, LL, PI, MDD, OMC, fines, sand, and gravel were found to range in levels from 26 to 32%, 2 to 16%, 1850 to 1982 kg/m^3, 9.92 to 12.10%, 0.10 to 2,84%, 14.18 to 15.30%, 82.98 to 84.60%, and 2.00 to 2.60, respectively. The percentages of specific gravity and fine particles increased along with the admixture content (lime + metakaolin), while all other parameters decreased. The results portrayed that only the subgrade course material requirements (LL < 80%, PI ≤ 55%, and MDD > 1760 kg/m^3) were satisfied by the untreated soil. The treated soil satisfied the standards for subbase and base course materials after being mixed with admixture, with the exception of the MDD (i.e., LL < 35%, PI ≤ 12%, and MDD > 2000 kg/m^3). As the admixture's interaction progressed, it was able to decrease the soil's LL, PI, and MDD. This is beneficial for LL and PI, but not for MDD. The admixture's ability and sufficiency at 6% were demonstrated by the OMC, specific gravity, and particle sizes. Thus, it is concluded that the admixture had a positive stabilizing effect on the lateritic soil. After treatment, the soil classification, which indicated that it was good material, is still A–2–6. However, further research is required in other to find out how to raise the MDD of lateritic soil while increasing the admixture.

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