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Effect of metakaolin on the mechanical properties of lateritic soil

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The effect of varying additions of metakaolin (MK) on the mechanical properties of lateritic soil to be utilised in the construction of pavement foundations was studied. The preliminary test results show that the soil is highly plastic and lacks sufficient mechanical ability to be used as a compacted subgrade/sub-base for flexible pavement foundation. Kaolin was calcinated to form MK, which was utilised at proportions of 3, 6, 9 and 12% by weight of the dry lateritic soil to stabilise it. California bearing ratio (CBR) and unconfined compressive strength (UCS) tests were conducted on the MK-treated lateritic soil to determine the suitability of the treated materials in the construction of compacted subgrade and/or sub-base layers of flexible pavement. The stabilisation test results show that MK has the potential to be utilised to improve the CBR and UCS of lateritic soil with a peak proportion of 6% MK by weight of dry soil, beyond which the soil experiences a decline in strength formation.

Keywords: consolidation/diffraction (X-ray)/laboratory tests/lateritic soil/metakaolin/pavement strength/stabilisation/sub-base/sustainable pavement

Introduction

Assessment of the geotechnical properties of lateritic soils (LSs), which are undoubtedly a fundamental soil type in terms of distribution and suitability for the civil engineering construction process, is essential since all civil engineering structures rest on them (Onyelowe *et al*., 2022). Significant research efforts have recently been made for sustainable sub-base and subgrade construction around smart application and utilisation of road construction materials for soil stabilisation to reduce the high cost and emission of greenhouse gases during pavement construction. Basically, undue collapse of national highway pavements, commonly occasioned by poor drainage leading to crack developments, as well as influenced by the joint action of traffic, environment and climate conditions, is primarily induced at the subgrade and sub-base layers (Abadin and Hayano, 2022). A highway pavement should perform optimally such that it reduces the stresses transmitted to the subgrade to a level that the soil will accept without significant deformation (Chindaprasirt *et al*., 2020; Maichin *et al*., 2021). An increase in soil strength, durability and stiffness and a reduction in soil plasticity and swelling or shrinkage potential are the benefits of soil stabilisation (Firoozi *et al*., 2017; Naeini *et al*., 2012). Soil stabilisation is the process of improving some soil properties using different techniques, such as mechanical or chemical ones, to produce an improved soil material with the desired engineering properties (Burra *et al*., 2021; Onyelowe *et al*., 2021a).

Soil stabilisation has had a long history, being earlier adopted in ancient Egypt and Mesopotamia, expanding to the use of lime by the Greeks and Romans, and today has globally included various agriculturally and industrially based wastes (Ardah *et al*., 2016; Firoozi *et al*., 2017; Jong *et al*., 2022; Liu *et al*., 2022). Be that as it may, conventional stabilisers such as lime and cement that are rich in calcium are usually not effective in regulating the shrink and swell behaviour of some soils due to the formation of ettringite, an expansive mineral (Khadka *et al*., 2020). The use of industrially based wastes such as metakaolin (MK; $Al_2O_3{\cdot}2SiO_2$), a product obtained after calcination of kaolin ($Al_2Si_2O_5(OH)_4$) in a furnace at a temperature of about 750–800°C, also provides a novel, smart and environment-friendly construction material and technique for sustainability (Jamal *et al*., 2016; Muhammad *et al*., 2020; Onyelowe *et al*., 2021b).

Recent developments in sustainable sub-base and subgrade construction have heightened the need for proper examination of the mechanical effects of the incorporation of various soil stabilisers into the LS matrix. Etim *et al*. (2022) successfully utilised lime and periwinkle shell ash (PSA) under laboratory conditions in stabilising LS with a focus on confirming its potential for use as pavement layer material. Their study evaluated index properties, maximum dry density (MDD), optimum moisture content (OMC), California bearing ratio (CBR) (soaked CBR (CBRS) and unsoaked CBR (CBRU)) and unconfined compressive strength (UCS) and reported an optimum performance at 8% lime and PSA inclusion. In a similar manner, Attah *et al*. (2021) optimised the CBR values of expansive soil treated with a cement kiln dust and MK blend based on the Scheffe optimisation method. Etim *et al*. (2021) maintained that the mechanical properties of cemented LS, particularly CBR and UCS, improve significantly with an increase in the micro-sized quarry dust stabiliser used.

Muhammad *et al*. (2020) assessed the geotechnical properties of LS treated with MK and also determined its optimum quantity that could be used as road construction material for cost-effectiveness and environmental friendliness. However, apart from mineralogical composition and physical properties, their study was limited to mechanical properties such as CBR, UCS and durability. Similarly, Attah *et al*. (2019) observed that MK at different percentages improved the strength properties of the treated soil such as CBR and UCS. Foda *et al*. (2018) noted that mixing 10% MK increases the shear strength of soil and decreases the hydraulic conductivity (HC) compared with those of untreated soil. Additionally, Kavya and Soorya (2020) made a comparison of the reductions in permeability between plain cement grout and MK-added cement grout for all several water–binder ratios. They noted that at 10% MK addition, the coefficient of permeability reduces to 2.13×10^{-6} m/s for a water–binder ratio of 7:3 at 7 days of curing. To investigate the MK effect on the HC of cement-stabilised soils, Deng *et al*. (2015) used their developed flexible wall permeameter and reported that there was a good correlation between the HC, void ratio and median throat pore diameter for each kind of material used for construction.

Overall, the research to date has tended to focus on very few mechanical properties rather than a more detailed scope such as combined study of UCS, CBR, HC and consolidation (*C*), which promises to provide a better understanding of the global influence of the stabilising agent used. The current study investigated the effect of MK on the mechanical properties of LS for subgrade and sub-base construction.

Materials and methods

Preparation of materials

LS and kaolin were collected from Umuoke, Obowo, Imo State, Nigeria, with the coordinates 5.5619° north, 7.4050° east. This is within a geographical region where natural kaolin is found in abundance. The LS was processed and dried for use in laboratory experiments. The kaolin was calcinated in an oven at a temperature of 650°C to form MK and stored in an airtight container to avoid absorption of atmospheric moisture. Figures 1 and 2 show the kaolin and MK samples, respectively.

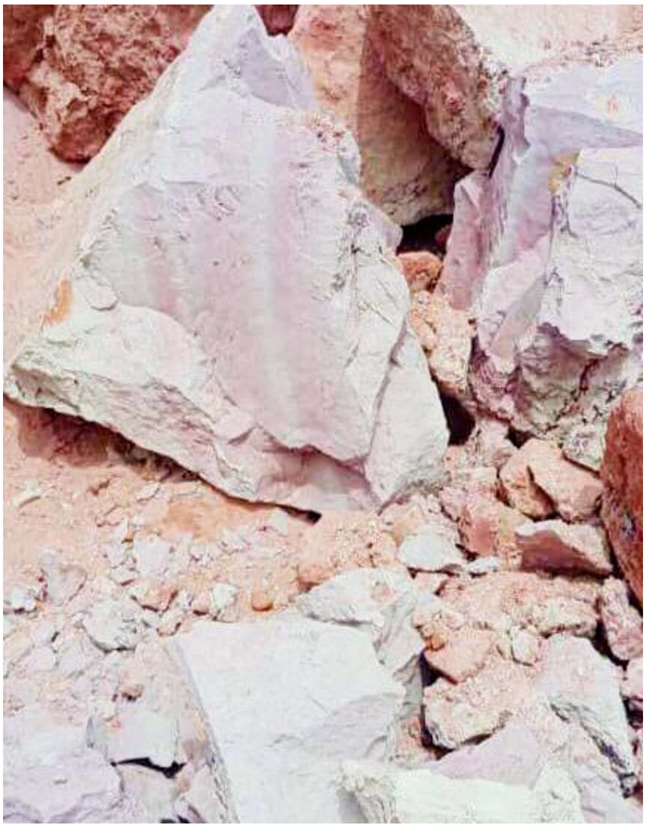

Figure 1. Natural kaolin site at Umuoke, Obowo, Nigeria, with the coordinates 5.5619° north, 7.4050° east

Figure 2. Processed MK sample at a calcination temperature of 650°C

Experimental methods

Basic experimental tests were conducted on the soils, which included particle size distribution analysis, compaction, Atterberg limit tests, CBR tests, UCS tests, one-dimensional (1D) consolidation tests, scanning electron microscopy (SEM) tests and X-ray fluorescence (XRF) tests (Figure 3). These tests were conducted in line with the requirements of BS 1377 (BSI, 2022). The MK was derived through a calcination process at a


(a) (b) (c)

Figure 3. Loading preparation and set-up for the 1D consolidation test: (a, b) soil sample in the consolidation cell, (c) loading regime

temperature of 650°C, which was characterised by loss of hydroxyl water from natural pozzolan known as kaolin, and the MK was further characterised based on the conditions of ASTM C 618 (ASTM, 2019) and BS 8615-1 (BSI, 2019) to determine its pozzolanic properties. The mechanical properties of the treated soil were studied by using CBR and UCS tests with MK mixed with the soil at proportions of 2, 4, 6, 8 and 10% by weight of the dry LS. The stabilisation of the LS was conducted in line with the requirements of the British standard BS 1924-2 (BSI, 2018).

Results and discussion

Characterisation of test materials

The LS preliminary studies showed that it is an A-2-7 class of soil according to the American Association of State Highway and Transportation Officials (Aashto) classification system and a poorly graded clayey silt according to the Unified Soil Classification System. The LS has a liquid limit (LL) of 42.5%, a plastic limit (PL) of 15.3%, an MDD of 1.77 g/cm^3, an OMC of 23.4% and a percentage passing through a 0.075 mm sieve of 30%. This means also that the soil has a plasticity index of 27.2%, which indicates that the soil possesses very high plasticity (>17% according to material requirements). Figures 4 and 5 and Table 1 show these preliminary properties of the soil. Figures 6 and 7 and Table 2 show the 1D consolidation graphical behaviour and numerical properties of the LS. The compression index and swelling index of the soil are observed to be 0.9123 1311 6 and 0.0452 5656 2, respectively, while the coefficient of compressibility and the coefficient of volume

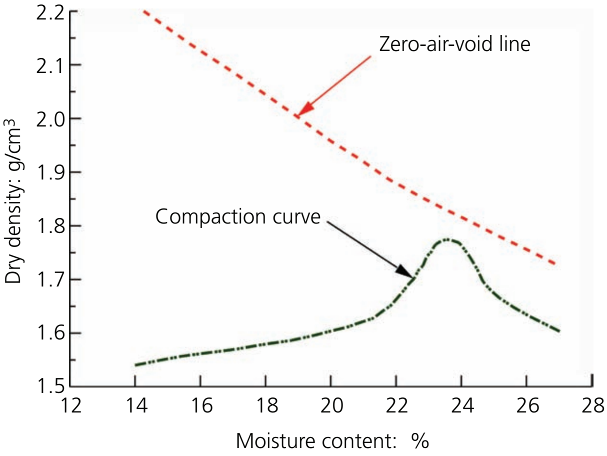

Figure 5. Compaction curve for the LS

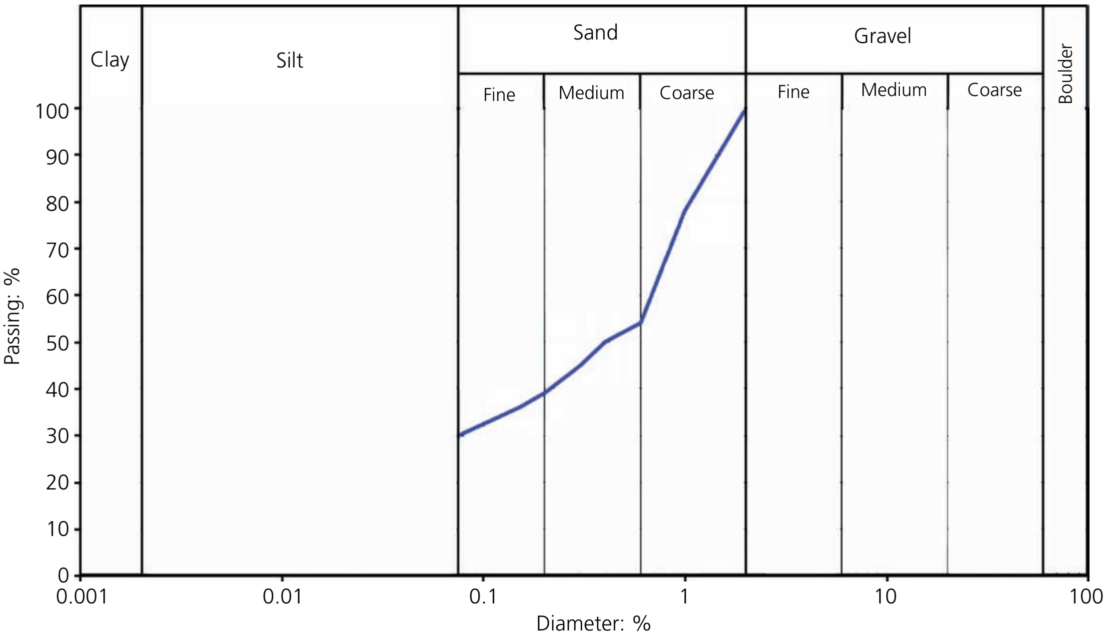

Figure 4. Particle size distribution curve for the LS

Table 1. Preliminary properties of the LS

Soil property	Passing 0.075 mm: %	MDD: g/cm^3	OMC: %	LL: %	PL: %	G_s	Clay: %	Silt: %	Type	Colour
Result	30	1.77	23.4	42.5	15.3	2.1	30	36.5	Clayey silt	Reddish

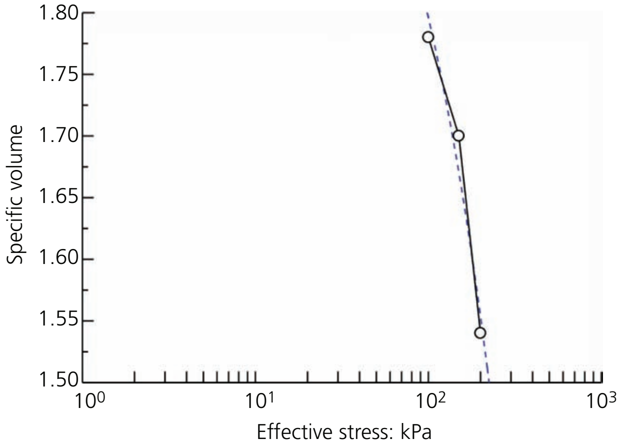

Figure 6. Compression curve for the LS

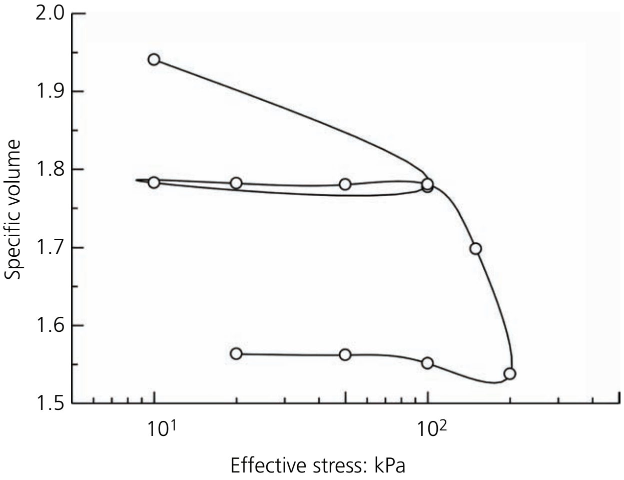

Figure 7. 1D consolidation curve for the LS

Table 2. Consolidation characteristics of the LS

Compression index, C_c	**Swelling index, C_s**	**Coefficient of compressibility, a_v: m^2/kN**	**Coefficient of volume change, m_v: m^2/kN**
0.9123 1311 6	0.0452 5656 2	0.0024	0.0008 4433 6

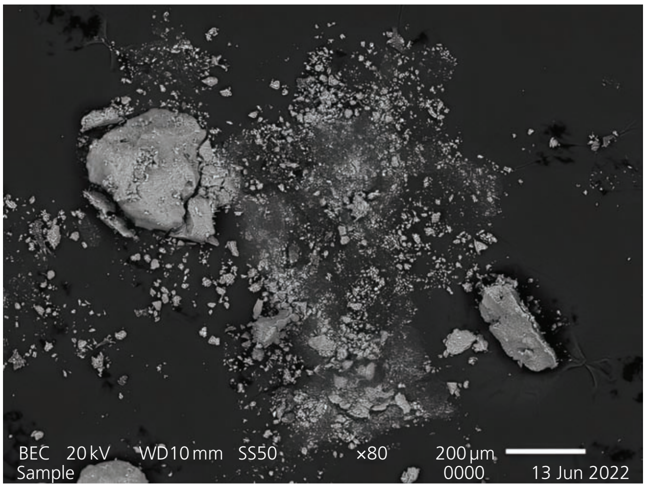

Figure 8. LS SEM

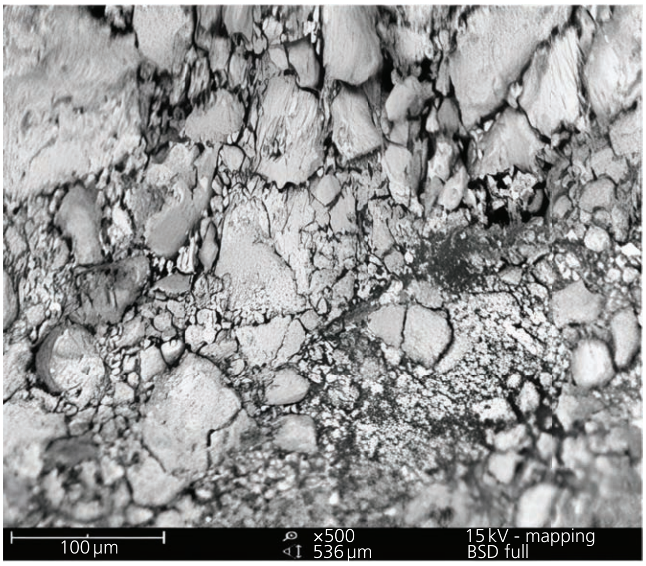

Figure 9. MK SEM at a calcination temperature of 650°C

change are observed to be 0.0024 and 0.0008 4433 6 m^2/kN, respectively. These show that the soil has a sufficient swelling capacity to resist axial loads under hydraulic conditions. Figures 8–10 show the surface configurations of the LS and the MK used as supplementary cement in this stabilisation protocol to stabilise the LS and a micrograph of the MK at 650°C, which shows that quartz is the dominating mineral and the almost insignificant presence of kaolin and anatase between 10 and 20° 2θ. The results indicate the microstructural and mineralogical properties exhibited by MK. The LS shows recognisable pores and particle inconsistency and requires improvement. The XRF results presented in Table 3 reveal that the pozzolanic three-

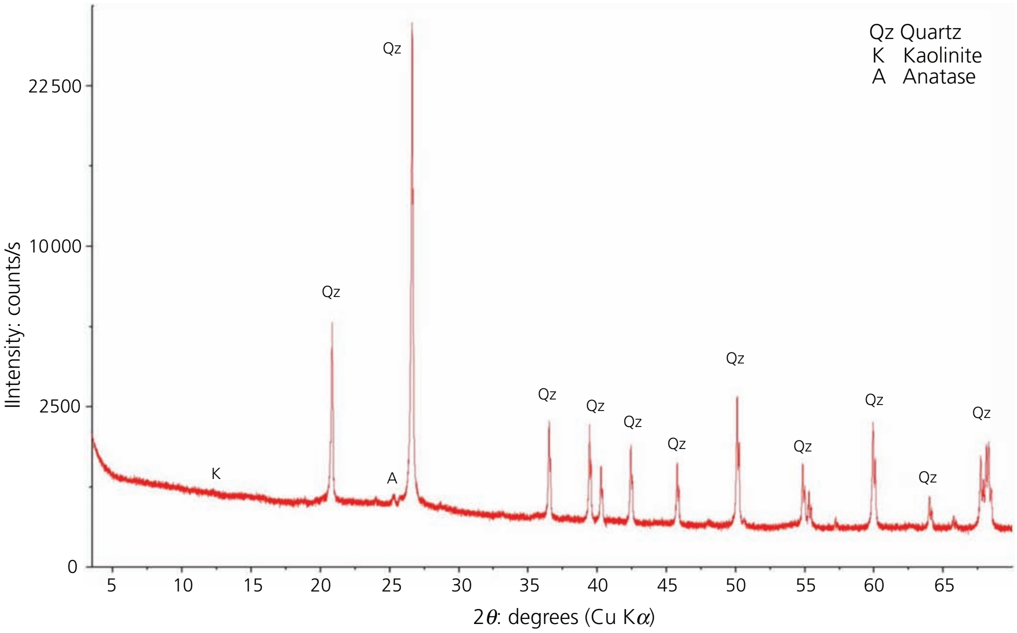

Figure 10. MK X-ray diffraction at a calcination temperature of 650°C

Table 3. Chemical oxide compositions of the test materials

	Compound: %									
	Aluminium oxide (Al_2O_3)	Silicon dioxide (SiO_2)	Iron (III) oxide (Fe_2O_3)	Carbon dioxide (CO_2)	Manganese (III) oxide (Mn_2O_3)	Potassium oxide (K_2O)	Sodium oxide (Na_2O)	Calcium oxide (CaO)	Titanium dioxide (TiO_2)	LOI
LS	29.45	26.42	31.50	7.05	2.1	1.5	—	0.56	1.42	—
MK	33.24	44.75	7.51	—	—	0.73	0.09	0.44	0.64	12.56

LOI, loss on ignition

chemical capacity (i.e., the three dominating chemical oxides that constitute the pozzolanic ability of alternative binders) of MK improved from 67% as kaolin to 85.5% as MK at 650°C, meeting the requirement (>70%) for pozzolans being used as supplementary cementitious materials (SCMs) in infrastructural development (ASTM, 2019; BSI, 2019).

CBR of MK-treated LS

Figures 11 and 12 as well as Table 4 show the MK-treated LS CBR behaviour under unsoaked and soaked conditions subjected to 2.5 and 5.00 mm penetrations. In Figure 11, which shows the 7-day soaked condition of the MK-treated LS, there was a steady increase in the CBR of both the 2.5 and 5.00 mm penetrations with the addition of between 2 and 6% by weight of MK. However, this trend changed with the addition of beyond 6% by weight of MK. At the peak MK proportion, CBRs recorded were 17 and 28%, respectively, for the two penetration capacities. These satisfy the CBR values of 10–25% specified for treated subgrade soils by the Aashto standard, the Nigerian highway design manual by the Federal Ministry of Works and Housing (FMWH, 1997) and other highway and research specifications (Ojuri, 2016; TRRL, 1977).

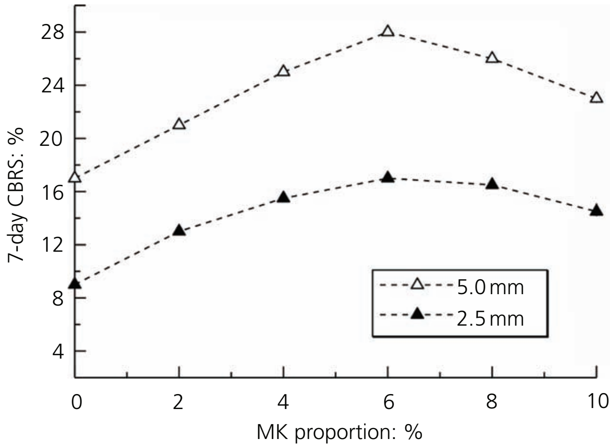

Figure 11. CBRS of MK-treated LS

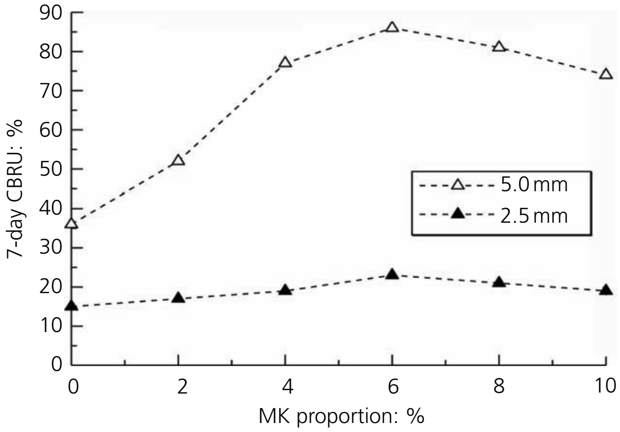

Figure 12. CBRU of MK-treated LS

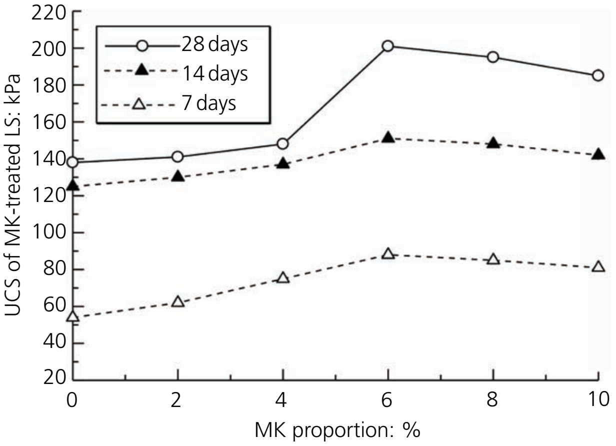

Figure 13. UCS of MK-treated LS

Table 4. CBR of MK-treated LS

Sample mix	7-day CBRS: %		CBRU: %	
	2.5 mm	5.0 mm	2.5 mm	5.0 mm
LS	9	17	15	36
LS + 2% MK	13	21	17	52
LS + 4% MK	15.5	25	19	77
LS + 6% MK	17	28	23	86
LS + 8% MK	16.5	26	21	81
LS + 10% MK	14.5	23	19	74

Table 5. UCS of MK-treated LS

Sample mix	UCS: kN/m^2		
	7 days	21 days	28 days
LS	54	125	138
LS + 2% MK	62	130	141
LS + 4% MK	75	137	148
LS + 6% MK	88	151	201
LS + 8% MK	85	148	195
LS + 10 MK	81	142	185

Under unsoaked conditions, which involved curing for 28 days, the CBRs recorded were 23 and 86% for the two penetration capacities with the addition of peak 6% by weight of MK. These also satisfy the CBR values of 10–25% for subgrade and 30–80% for sub-base that are specified for soils by the Aashto standard, the Nigerian highway design manual by the FMWH (1997) and other relevant standards and also compare with Ojuri's finding (Aashto, 2021; Ojuri, 2016; Stameq, 2012; TRRL, 1977). There was a decline in strength beyond 6% MK. Between 2 and 6% MK addition, the soil had a consistent hydration reaction with the pozzolanic compounds (aluminosilicates) of the admixed MK and maintained strength improvement. However, beyond that, there was reduced cation-exchange capacity, which resulted in a decline. Also, the reactivity potential of the MK was reduced due to carbonation. It can also be inferred that there was more densification between 2 and 6% addition of MK, but beyond this mark, due to increased fineness, the density dropped, leading to a loss in capacity to withstand penetration. Meanwhile, the increase in the bearing capacity recorded in the laboratory exercise indicates the potential of MK obtained at a temperature of 650°C to be utilised within the limit of 6% in the stabilisation of LS under any hydraulic conditions.

UCS of MK-treated LS

The MK-treated soil was cured for 7, 14 and 28 days to record its UCS under loading. It can be observed in Figure 13 and Table 5 that the same trend at the maximum addition of 6% by weight of MK in the LS repeated. A gain in strength was recorded between 2 and 6%, and there was a drop in strength gains beyond 6%. This was due to increased fine material of MK in the treated mix beyond 6%, which resulted in a loss of density and ability to withstand compression. The maximum strengths recorded for 7-, 14- and 28-day cured treated LS are 88, 151 and 201 kN/m^2, respectively. Meanwhile, appropriate design standards (Aashto, 2021; FMWH, 1997; Stameq, 2011; TRRL, 1977) stipulate between 50 and 250 kN/m^2 as the minimum range requirement for a treated soil to be used as subgrades and sub-bases and 350 kN/m^2 as the minimum for base materials. It follows that at 7, 14 and 28 days of curing of the MK-treated LS, the reconstituted soil met the requirements to be utilised as a compacted subgrade. This was met at the addition of peak percentage of 6% by weight of MK.

Conclusions

The stabilisation of LS with MK was studied under laboratory conditions by studying the mechanical properties of LS, which are CBR, under soaked and unsoaked conditions, and UCS, with curing for 7, 14 and 28 days. The following can be concluded from the exercise.

- The soil showed insufficient mechanical abilities to be used as a subgrade and a sub-base of flexible pavements; hence, it needed improvement.

- The CBR and UCS showed a consistent increase in strength with the addition of between 2 and 6% by weight of MK but showed a decline beyond the 6% mark.
- The CBR showed maximum values of 17 and 28% under soaked conditions and 23 and 86% under unsoaked conditions at 2.5 and 5.0 mm penetrations, respectively. This indicates the ability of LS mixed with 6% MK to be utilised as both subgrade and sub-base materials under unsoaked conditions.
- The UCS showed maximum values of 88, 151 and 201 kN/m^2 for 7-, 14- and 28-day curing periods, respectively. This shows that at 28 days, the treated soil developed sufficient strength to be used as subgrade material.
- Generally, MK is a potential SCM for the stabilisation of soils for use as pavement foundation and also for use as liner material.

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