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Lateritic Soil Improvement Using Lime and MOFIC

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Abstract

This study investigates the effects of mucilage from *Opuntia ficus-indica* cladode (MOFIC), a bio-modifier, on Lime-stabilized Lateritic soil's durability and index features. Specifically, this research assessed the alterations to the Atterberg limits, compaction characteristics, California bearing ratio (CBR), index values and the unconfined compressive strength (UCS) properties of the soil samples and the stabilised samples through laboratory experiments. Lime + MOFIC was added to the soil at 0%, 2%, 4%, 8%, 12% and 16% wt (%) of soil. The result confirms alteration in the index and strength characteristics of the soil upon the addition of MOFIC to the Lime-treated Lateritic soil. The geotechnical characteristics of the soil improved from a subgrade soil to a subbase material upon the addition of 2% of LIME + MOFIC; with the presence of Lime + MOFIC at 2–4%, the bearing capacity of the soil improved from a subgrade material to a subbase material according to the Nigerian General Specification. The highest CBR value in Lime-stabilised was 56%, while the CBR value of Lime + MOFIC-stabilised soil was 70%. This represents a 20% increment in CBR. The presence of polysaccharides in MOFIC enhanced the soil binding attributes of the Lime and hence accelerated the strength properties of the soil. The promotion of green construction and reduction in environmental impacts of using Lime motivates the use of MOFIC in the study. Based on the result of the experimental research, MOFIC is thereby recommended as an eco-friendly alternative for enhancing engineering properties of pavements interlayers. The addition of MOFIC improved the index and strength properties of pavement interlayer material in road construction.

Keywords Pavement material · MOFIC · Lime · Soil stabilisation · Green construction

1 Introduction

In fulfilment of the requirements for sustainable practices in infrastructure development, the use of green materials is encouraged and explored in highway construction and structural applications [1, 2]. Lateritic soils are the most common foundation soil in many developing countries and in the world's tropical regions in different engineering and road designs [3]. However, it has been observed that most Lateritic soils in their natural unenhanced states are only suitable as subgrade [4] and usually require stabilisation to become a structural layer. Soil stabilisation is the procedure of modifying the geotechnical properties of natural soil to fulfill engineering standards [5]. Different types of traditional and non-traditional stabilisers in the form of additives have been utilised to enhance soils' engineering characteristics. Chemical reactions achieve stabilisation through cation exchange or pozzolanic interactions with the soil constituents in the presence of H_2O as chemical additives, such as Lime and Cement. Enhancement of geotechnical characteristics by Lime stabilisation of granular soils had been done by [6]. Quantifying structural contributions of Lime stabilisation in pavement design had been studied by [7] and stabilisation of expansive soils with Lime and fly ash by [8–12]. The enhanced attributes of Lime-treated materials include the long-term strength of the pavement layers [8] as well as increased resistance to frost; it also minimises the water absorption capacity of a treated layer of soil, thereby reducing its swelling potential [7].

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Strength properties and long-term performance of Lateritic soil material are routinely enhanced during engineering design and construction of the subbase or base layer quality through chemical stabilisation. Lime and cement are the major chemical alkaline supplements traditionally applied to soil stabilisation. Though these chemical reagents are effective in soil treatment, they are expensive due to the increasing production cost and high demand, resulting in higher costs of highway construction, particularly in growing economies [3]. Over the years, studies have proven the correlative performance and the effectiveness of cement and Lime in improving soil [13–15]. Recently, the research of [16] assessed the role of MOFIC in soil improvement, which showed a promising result.

In a bid to reduce cost and minimise the environmental impacts of using Lime in pavement construction, the use of Mucilage from *Opuntia ficus-indica* cladode (MOFIC) is a viable sustainable option. MUCILAGE are solvable but non-digestive complexes of the arabinose and xylose, which exist in some seeds and seaweeds. Due to their water-holding and viscous properties, these are utilized as thickening and stabilizing additives in food processing. Cactus mucilage is commonly known as cactus pear plant and nochtli. Cactus pads and fruits are edible for both humans and animal. According to several studies by researchers, cactus pods consist of numerous amino acids and sugars [17–19].

In the study conducted and reported in [20], different investigations have used cactus fruits and cladodes (succulent leaves) industrially, such as in limiting turbidity in H_2O, removal of arsenic contamination in consumable water, decrease in the hardness of spring H_2O [21, 22], prevention and inhibition of steel corrosion [23, 24], and aluminum corrosion [25]. MOFIC has been reported to contain arabinose, carbohydrates, galactose, xylose, rhamnose, galacturonic acid, Ca^{2+} and K^+ [26]. Despite the documented usefulness of cactus cladodes highlighted above, their disposal constitutes potential environmental pollution from fermentation [27]. Noting that MOFIC contains Ca^{2+} [20] proposed that the addition of MOFIC has the potential of modifying the engineering properties of soils containing clay particles by facilitating the agglomeration and coagulation of these clay particles akin to the modification of soil properties by the addition of Lime. Hence, this study focuses on the experimental study of Lime-stabilized Lateritic soil's index and strength properties using MOFIC.

1.1 Motivation and Significance of the Study

Frequent failure of pavements results in loss of lives and properties, particularly roads in Nigeria. This has created the urgent need to find a low-cost means of constructing long-lasting roads by improving the subgrade layers in the road pavements. This is because most of these soils do not satisfy the UCS value of 0.7–1.5 MPa and CBR value greater than 30% as existing in Nigerian standard requirements for pavement subbase construction. To this end, Cement and Lime have been conventionally utilized to enhance the geotechnical properties of Lateritic soils. The use of Cement and Lime in soil improvement is expensive, and it is not also environmentally friendly. Also, cement production represents a huge carbon footprint in many growing economies saddled with environmental impacts. Lime, one of the earliest chemical hydraulic binders, is used to stabilise soil materials, the burning of limestone in kilns produces it. In the process, it is a significant source of CO_2 discharge. Moreover, the high energy costs of Lime production and a limited supply of the binder make it a costly alternative in roadway construction. As non-renewable raw material and given the considerations above, there is a need for a cost-effective and green alternative to enhance or partially substitute traditional chemical binders. To promote sustainability and reduce construction cost, cactus mucilage (MOFIC) which is usually considered a weed with no economic value in Nigeria, is added as a partial substitute to Lime in soil stabilisation and it is investigated for associated strength improvement. The choice of MOFIC was adopted because it has pectin [26], which contains Ca^{2+} that interact with minerals in the soil [21]. The presence of Ca^{2+} may assist in improving the engineering properties of soils. This research aims to investigate the effects of applying the mucilage of prickly pear or *Opuntia ficus-indica* (MOFIC) on the index and strength characteristics of Lime-stabilised Lateritic soil for application as a pavement layer material. This is to reduce construction cost, improve soil strength, and encourage sustainability. The success of this study and implementation of the findings of this research could have great potential in growing the local economy, reducing the carbon footprint of Lime production, and improving the engineering properties and performance of stabilised Lateritic soil.

1.2 Overview of Mofic

The mucilage extracted from the cactus (Fig. 1) is generally identified as a water-solvable pectin-like polysaccharide. The most relevant and outstanding property of pectin in soil stabilisation is its capacity to transform into gels in the presence of Ca^{2+} ions [17]. The physical characterisations of calcium bonded gel depend on the formation of a three-dimensional cross-linked polymer molecular network [19], and the strength is influenced by factors, such as the molecular weight, degree of polymerisation, and calcium-binding power [24]. On the other hand, the recent study by on mucilage from *Opuntia ficus indicia* exhibits elastic attributes but not gelation [27]. This elastic property may help in the stabilisation process of soil.

Fig. 1 Cactus plant

The study by [28] on the chemical composition revealed that MOFIC contains arabinose, rhamnose, galactose and xylose. However, [29] showed that the pectin has neutral glucan, glycoproteins and an acidic polysaccharide. The presence of polysaccharide in the pectin is also buttressed by [30]. The author further showed that the polysaccharide contains 10% uronic acids, arabinose, galactose, rhamnose and xylose. In [31] revealed that MOFIC plants contain pectin and polysaccharides. However, [33, 34] avowed that the plant composition is made up of structured A-D-Galacturonic acid units attached to B-L-Rhamnose units. This, according to the authors, is also linked to 1/4 with connections on C-4, the connections identified as oligosaccharides. These findings, in addition to carbohydrates, Ca^{2+} and K^{+}, were asserted by [35, 36].

2 Methodology

2.1 Materials

Quick lime with a minimum chemical constituent of Ca, MgO, CO_2, and moisture [37] was applied for all stabilisation tests. *Opuntia ficus-indica* cladodes were sourced from Lagos, Nigeria, in the natural state to filter out the mucilage (MOFIC). The filtration process used was aqueous. The cladodes parts of the plant were sliced into thin parts (10–12 mm) placed in a holder and saturated in H_2O for 120 h to filter out and retrieve the viscous mucilage. The fluid was sieved carefully to extract all solid contents from the mixture. The fermented liquid (sieved) was greenish and very sticky. The procedure of the filtration process used in this study conformed to the process discussed in [21]. Portable tap water was used to extract the mucilage pectin and make samples for testing. The examination of the filtrate indicated 96.4% H_2O composition, 3.6% (36,000 mg/L) of mucilage pectin, and 0 mg/L of displaced solid content. The Lateritic soil was sourced from Ibadan, south-western Nigeria (Longitude 4° 21′ 0″ E and Latitude 6° 34′ 0″ N). Optical observation reveals that the soil has a reddish brown colouration. The soil sample was obtained at a depth of 0.5 m below the ground level and transported to the laboratory in sealed polythene bags (Fig. 2).

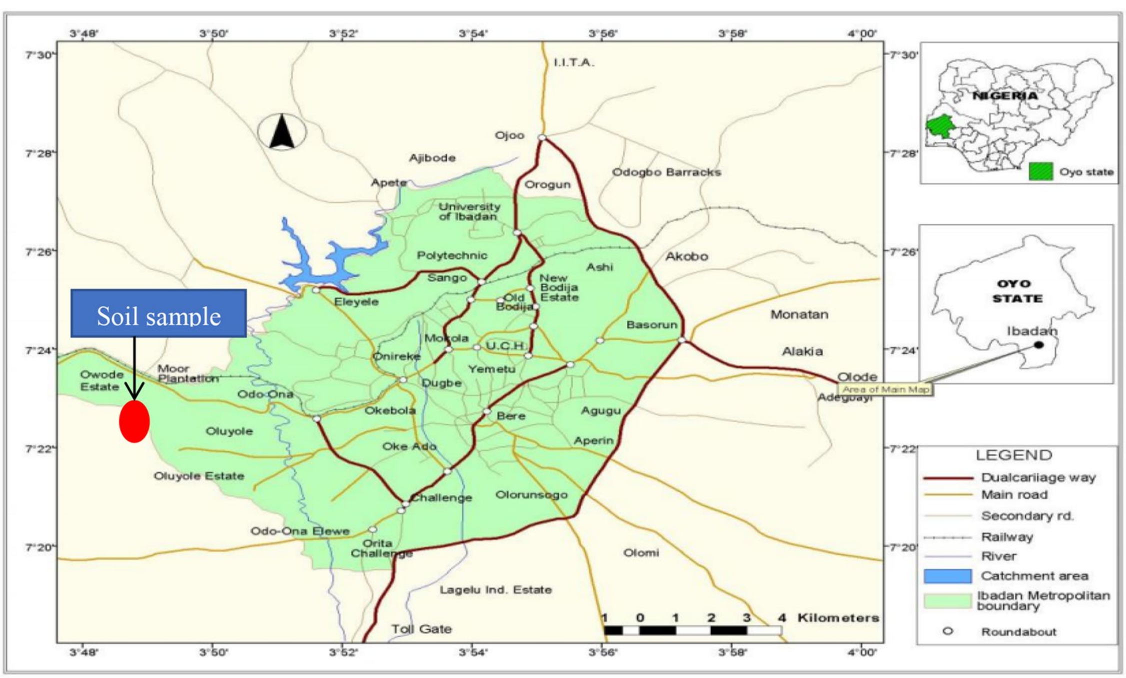

Fig. 2 Map of the study area where the soil sample was obtained

2.2 Experiments and Methods

Lateritic soil samples were obtained and evaluated to know their index characteristics, particle size distribution, soil category and compaction features. The standard Proctor compaction method was used. Adapted Proctor energy was applied for formulating the samples for compaction and CBR analysis. The sample dimensions are 150 mm and 175 mm. 4.5 kg rammer was applied to yield 56 blows to the five layers of compaction during specimen formulation. Unsaturated CBR test specimens were cured for 168 h in regulated conditions [temperature (23 ± 2 °C) and relative humidity (100%)]. Specimens were curated for 144 h under regulated conditions to determine soaked CBR prior to immersion in H_2O for 24 h. Regarding swell potential, soil specimens compacted in the CBR mould and under preloading pressure were placed in H_2O for 24 h, causing the sample to swell. Periodic examinations of displacement were recorded. The specimen swell potential was calculated from the ratio of variation in the specimen height to the initial height.

Unconfined compressive strength (UCS) test samples (5 cm × 10 cm), formulated and produced from a cylindrical mould, were cured in sealed plastic bags. The UCS for each batch was known following 168 h of curing by the protocols explained in [38]. Perkin Elmer Analyst 200 Atomic Absorption Spectrometer was applied in determining the percentage of oxide compositions in the Lateritic soil. The method used for this research was to differentiate the Lime and MOFIC constituent in equal quantities based on the air-dried weight of the Lateritic soil specimen. The stabilisation tests were conducted at 0%, 2%, 4%, 8%, 12% and 16% of (Lime + MOFIC) by dry weight treatment of the dry soil sample. The Lime was fixed at 2% benchmark while the MOFIC sample was varied. In essence, treatment of 2% of Lime + 0–16% MOFIC of the soil dry weight of Lateritic soil was adopted for this experimental research. This was to decrease the amount of Lime used in the stabilisation process and to investigate the consistency, and physical characteristics of the MOFIC-treated Lime-stabilised Lateritic soil. Atterberg limit tests, consisting of liquid and plastic limits, were obtained as specified by [39].

Air-dried Lateritic soils with Lime and MOFIC mixtures were compacted using standard compactive effort [40]. According to [41], 25 blows from the rammer released from an elevation of 300 mm above the soil were used as the compactive efforts. Additionally, to assess the strength index, (soaked and unsoaked CBR tests) were performed according to [37]. The soil samples for the tests were open dried for 24 h before analysis to simulate field conditions. UCS test was performed by British Standards Institute [40]. The soil samples are mixed and left for two hours before compaction using this method. It was compacted into 150 mm cubes, moist cure and soaked for 168 h.

3 Results and Discussion

3.1 Material Characterization of the Soil

The natural soil moisture content was obtained to be 4.8%. From grain size analysis data, the Lateritic soil is a coarse-grained material with percentages of gravel and sand fractions of 34.06 and 65.40, respectively. Based on the particle dimension analysis and distribution curve (Fig. 3), the percentages of fine, sand, gravel combined with coefficients of uniformity, Cu of 6.7 and curvature Cc of 1.1 are displayed in Table 1. If the soil is categorized only as a coarse-grained material, it is a well-graded sand with gravel by the Unified Soil Classification System (USCS) method [42]. Also, the soil particle sizes are mostly within the range of fine sand

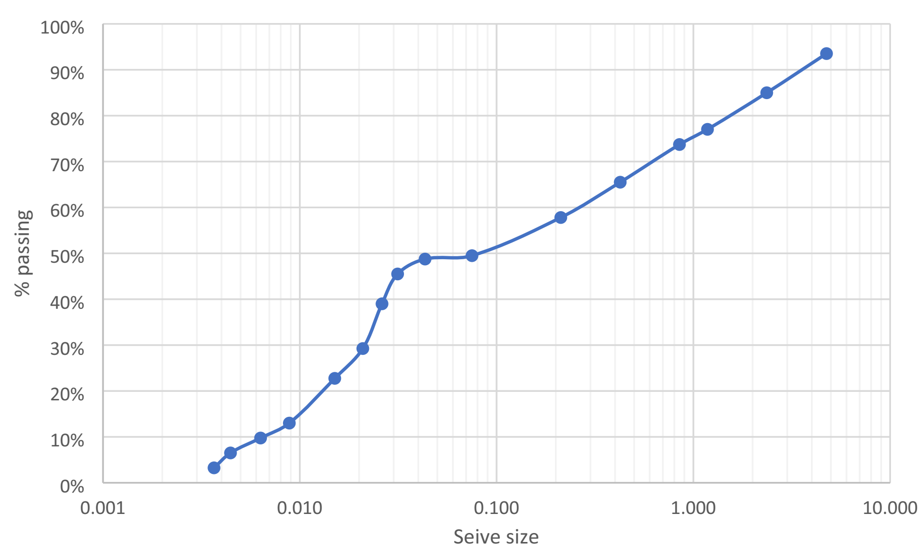

Fig. 3 Sieve evaluation of the soil sample

Table 1 Material characterization and engineering characteristics of the soil sample

Gradation	Gravel (> 0.475 cm), %	34.06%
	Sand (0.075–4.75 mm), % 58.4	65.40%
	Silt and clay (< 0.075 mm), %	0.52%
	The coefficient of curvature, Cu	1.1
	The coefficient of uniformity, Cc	6.7
	AASHTO soil classification	A-2-6(0)
	Unified soil classification	Silty Sand
Index Properties	Natural moisture content (%)	4.84
	The specific gravity of the soil particles	2.77*
	Liquid limit (%)	32
	Plastic limit (%)	15
	Plasticity index (%)	17
	Maximum dry density, MDD (g/cm3)	2.04
	Optimum moisture content, OMC (%)	12.4
	Color	Reddish Brown
Strength Index	Soaked CBR (%)	21
	Unsoaked CBR (%)	23

*Estimate value based on degree of saturation at the optimum water content of at least 90%

and fine gravel. Hence, the soil classification in accordance with the American Association of State Highway and Transportation Officials (AASHTO) is A-2-6 (0).

The soil samples used for Atterberg limit, compaction, CBR, and UCS tests in the laboratory were prepared according to specification [43, 44]. Both the soil classification results and CBR values are summarised in Table 1. Though this soil is mainly coarse-grained, factoring in Atterberg limits data, particularly the plasticity index PI, which is greater than 7%, plots in CL above the “A” line in the plasticity chart, the Lateritic soil is categorised as silty sandy soil with gravel. Given the particle grain dimension evaluation, Atterberg limit and CBR values, the soil sample was determined to be good enough as a subgrade material as the CBR value was not greater than 30% according to [38].

In accordance with the Nigerian specification standards for roads and bridges, this Lateritic soil, which has a liquid limit of 32% and a plasticity index of 17%, meets the criteria for a subgrade material without requiring additional amendments. With the addition of up to 4% of (Lime + MOFIC) content, the liquid limit increased slightly, but with further addition of the Lime + MOFIC above 4% and up to 16% content, the liquid limit decreased accordingly (Fig. 4). Similarly, the plastic limit increased with the additive of up to 4% (Lime + MOFIC), and after that, it remained slightly constant from 4 to 16%. The plasticity index remained constant with the addition of up to 8% of (Lime + MOFIC) content but then decreased with the surge of Lime + MOFIC content from 8 to 16%. These changes in the Atterberg limits of the stabilised soil samples, according to [30], followed no well-defined trend because, in the stabilisation of Lateritic soils with Lime, the changes recorded in the Atterberg limits were usually due to the mineralogy of the soils.

The various additions of Lime + MOFIC improved the soil sample from a subgrade material to a subbase material. The addition of Lime steadily dilutes the silica, Al and Fe oxides (SiO_2, Al_2O_3, Fe_2O_3), constituting the Lateritic soil in the presence of H_2O, producing hydrates of calcium silicate (CSH) and calcium aluminate (CAH). Also, the presence of Ca^{2+} in the pectin (the main constituent of MOFIC) in the soil further improved the cementation process, which altered the soil's consistency and plasticity index [31], see Fig. 4. The comparative assessment of the atterberg limits of the two stabilisers revealed that Lime + MOFIC showed a better Atterberg limits result than using Lime in soil modification.

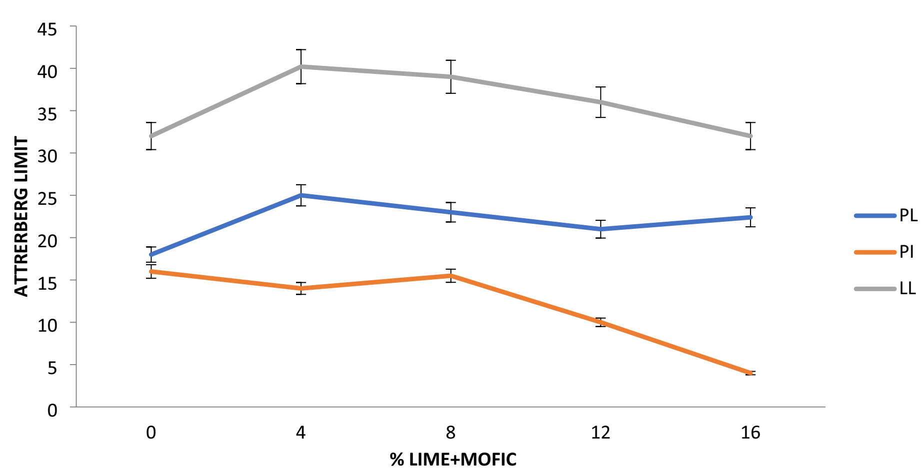

Fig. 4 Atterberg limits of Lime + MOFIC-stabilised soil

3.2 Compaction

The natural soil has a maximum dry density of 2.04 g/cm^3 at an optimum moisture content of 12.4%. For the natural soil, compaction greater or equal to 95% of the maximum dry density using Standard Proctor effort occurs within the range of moisture content of 9% at the dry of the optimum to 14% at the wet of the side of the optimum (narrow range of only 5%). Treated soil samples produced compaction curves that shift downwards (reduction in MDD values) and to the right (increase in OMC values) as the Lime + MOFIC content increases. The shift in the location of OMC from the natural soil involves the availability of more Ca^{2+} from the Lime and MOFIC, requiring a higher amount of water in the hydration process to form CSH and CAH. Figure 5 presents the compaction curves for the natural Lateritic soil and the Lime + MOFIC-treated soil samples. The reduction in the maximum dry density as the Lime + MOFIC content increases is due in part to the increase in the OMC as the specific gravity of the treated samples is less than the value for the soil. The increase in OMC as the chemical additive content increases is explained as following the increase in CaO content requires an increase in water to form $Ca(OH)_2$ [45]. At the same time, the reduction in the MMD is related to cementation of particles that cause repulsive contact force in the soil offering greater resistance among the particles resulting in a loose structure and an expected lower density for a given compactive effort [25, 46, 47]. The shift also results in more spread in the moisture contents to the dry and wet to the optimum for Lime + MOFIC-stabilised soil than the narrow range observed in the case of the natural soil. Figure 4 presents the variation in MDD and OMC values for the Lime + MOFIC (0–16%)-stabilized soil (Fig. 4). Strong correlations were found for both MDD and OMC values versus the Lime + MOFIC contents of the treated samples. The plasticity limit value increases slightly with an increase in Lime + MOFIC content, similar to the trend exhibited by OMC values, while the PI value decreases (Fig. 6).

3.3 Comparative assessment of Lime and Lime + MOFIC-stabilised soil sample

Based on the observed index properties, especially the Atterberg limits and compaction test results of Lime + MOFIC-treated soil samples, soaked, and unsoaked CBR samples of soil were prepared and tested for Lime + MOFIC contents of 2%, 4%, 8%, 12% and 16%. Figure 7 represents the CBR (soaked and unsoaked) for the Lime-stabilised sample, while Fig. 8 presents the results of CBR (soaked and unsoaked) for the range of Lime + MOFIC contents tested. With the addition of Lime + MOFIC, the soaked CBR values increased remarkably for the range of Lime + MOFIC contents tested in this study when compared with the natural soil and Lime-stabilised samples (Figs. 7, 8). The unsoaked CBR value of the untreated natural soil sample was 23% which improved

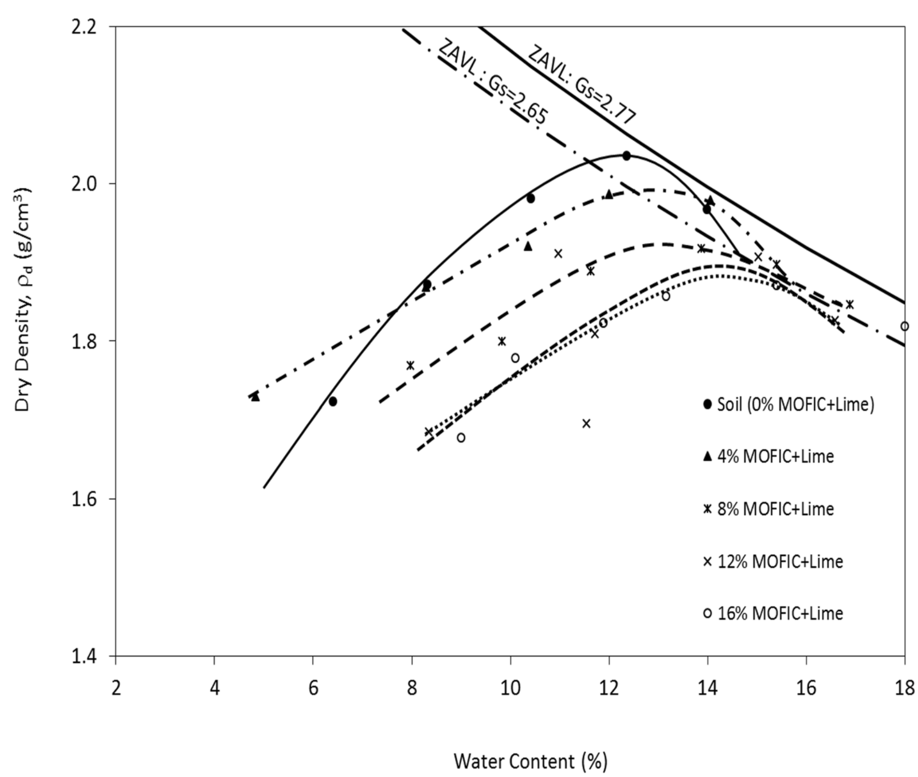

Fig. 5 Compaction curves of natural soil and Lime + MOFIC-stabilised soil samples

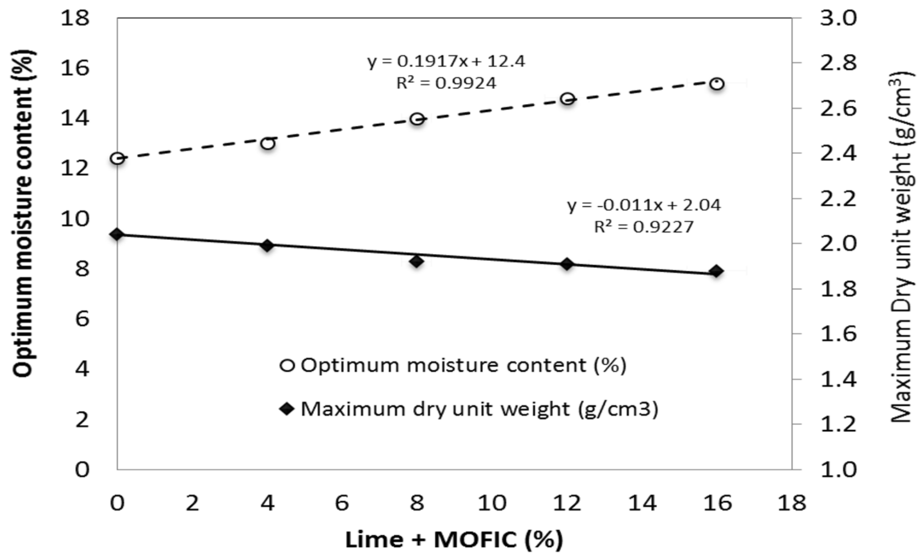

Fig. 6 Variation in MDD (g/cm^3) and OMC (%) of Lime + MOFIC

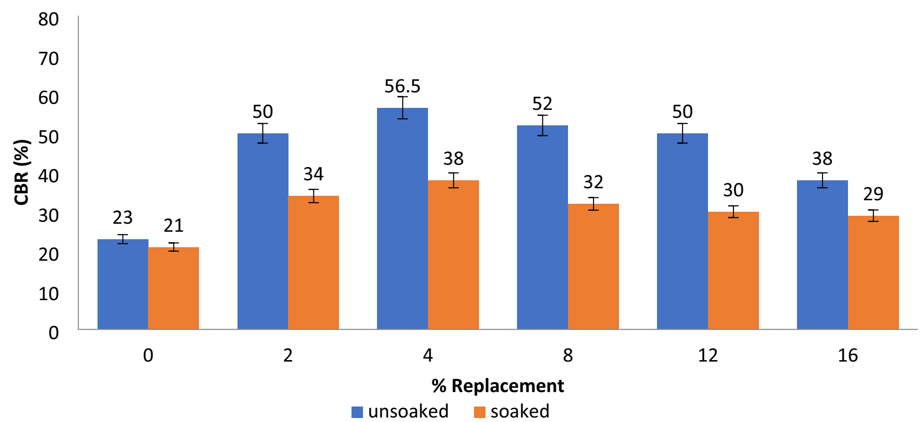

Fig. 7 Soaked and unsoaked CBR data of Lime-stabilised Lateritic soil samples

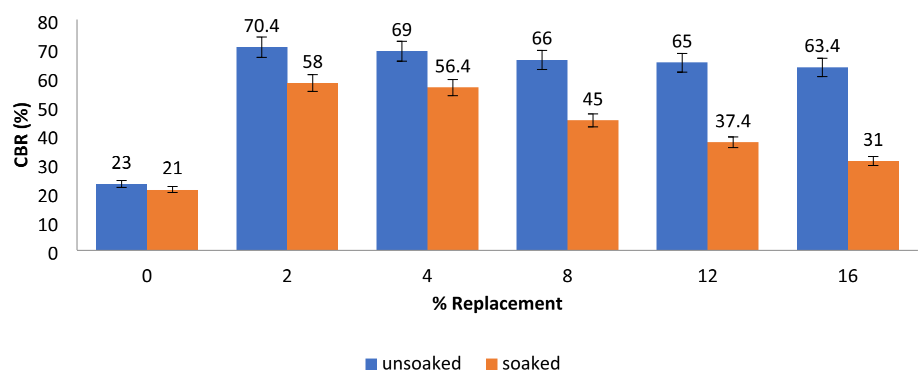

Fig. 8 Soaked and unsoaked CBR data of the Lime + MOFIC-stabilised Lateritic soil samples

to 70.4% at 2% (Lime + MOFIC), further addition of (Lime + MOFIC) reduced the CBR of the sample with the value at 4%, 8%, 12% and 16% addition resulting in 69%, 66%, 65% and 63.4% CBR values, respectively. However, unsoaked CBR value of 70.4% corresponding to approximately 176% increase over the unsoaked CBR values of the natural untreated soil was obtained for 2% Lime + MOFIC content. Based on CBR tests, optimum stiffness values of the Lime and Lime + MOFIC-treated Lateritic soil samples occur at 4% and 2%, respectively. For the soaked samples, additional Lime or Lime + MOFIC content above the maximum values causes an initial gradual decrease in CBR values followed by a dramatic drop in values such that the soaked CBR values of soil treated with Lime and

Lime + MOFIC contents of 16% reduced to 38 and 29 for both soaked and unsoaked CBR.

This drastic decrease in the soaked CBR values of the samples treated with high Lime and Lime + MOFIC contents may be attributed to the dissolution of the unreacted Lime and MOFIC in the samples when soaked. According to the analysis conducted in [48], given that the presence of polysaccharides in MOFIC has transient soil binding attributes based on the micro-organism present in it [49], it may account for the high gain in the strength index/stiffness at 2% addition of Lime + MOFIC (Fig. 8). The results of MOFIC in the geotechnical characteristics of the soil occurred from the bio-clogging process and the presence of calcium ions which react with the silica and water in the soil to form calcium silicate hydrates that bind the small particles of the soil together [21]. These aggregations of small particles are accountable for the decrease in plasticity index and the improved strength. With the presence of MOFIC when stabilized at 2% or 4% of Lime + MOFIC (Fig. 8), the stiffness of the soil increased when compared with Lime stabilization only. It improved from a subgrade material to attain the geotechnical properties of a subbase material according to the unsoaked CBR, it improved from 23% to 70.4% according to [35].

3.4 Unconfined Compressive Strength of the Stabilized Soil

The unconfined compressive strength of the Lime-stabilised sample increased as the percentage of Lime increased (Fig. 9). This implied that the resistance to failure of the samples improved with increasing Lime content. Accordingly, the addition of Lime + MOFIC also improved the resistance of the soil (Fig. 10) more than when treated with only Lime. Contrary to the observed trend for the CBR values, the UCS value for the Lime + MOFIC-treated soil samples heightens with the additive's constituent increase. The UCS showed an increase in the UCS values ranging from 15.6 to 25% for Lime + MOFIC-stabilised soil samples against the Lime-stabilised samples. When soil samples treated with the same Lime and Lime + MOFIC constituent are compared, 2% Lime + MOFIC content resulted in 25% strength gain, the highest UCS percentage increase among the range of additives content studied. This is remarkable giving that for every 2% Lime + MOFIC content (which

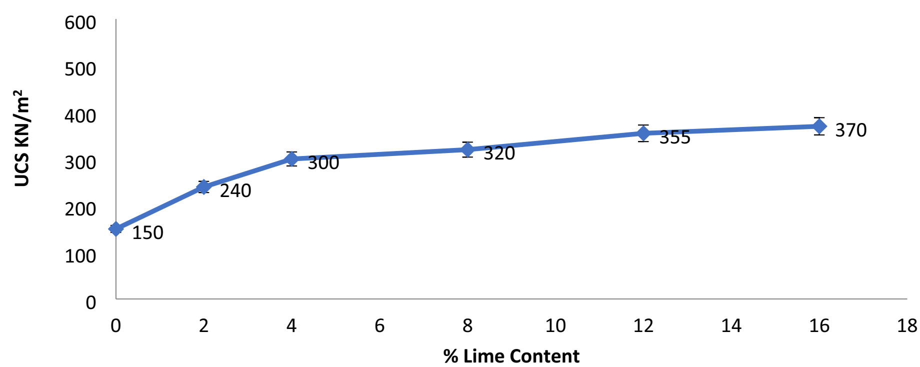

Fig. 9 Unconfined compressive strength (kN/m^2) versus Lime content (%)

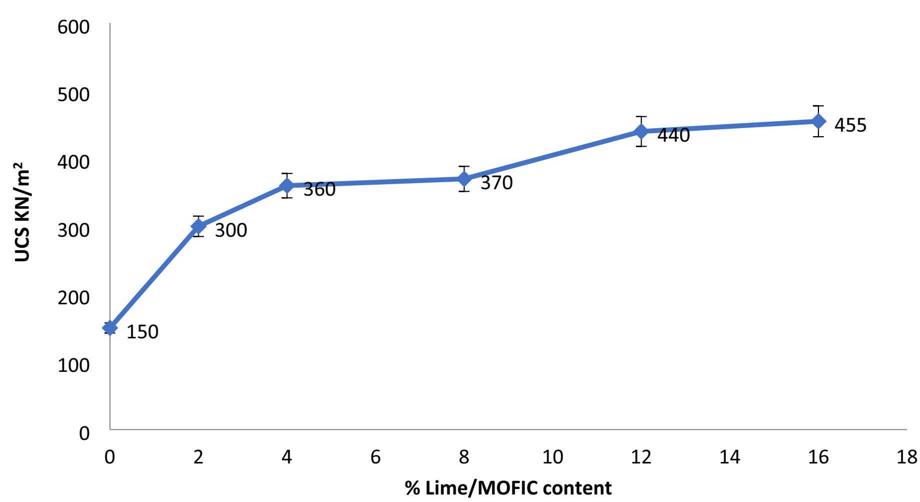

Fig. 10 Unconfined compressive strength (kN/m^2) versus Lime + MOFIC content (%)

represents 1% Lime and 1% MOFIC content by dry weight of the soil) is equivalent to adding 0.036% of pectin in solution to treated 1% Lime-stabilised Lateritic soil. The use of MOFIC significantly improved Lime-treated Lateritic soil's performance while dramatically reducing the quantity of Lime.

An ANOVA test was performed to establish whether Atterberg limit parameters strongly influence the enhanced UCS value of Lime-treated Lateritic soil. *F* value of 17.259 which signifies the model is statistically significant while the values of "Prob > *F*" less than 0.0500 indicate that the model terms/parameters are statistically significant. In this case, A, B and C translate to LL. PL and UCS are significant model terms, as shown in Table 2.

$$UCS = 223.54 + 11.3LL - 24.6PI \quad (1)$$

The model result revealed that a unit increase in LL would lead to an 11.30 KN/m^2 increase in the UCS, while a unit increase in PI will reduce the UCS by 24.60kN/m^2 (Eq. 1). The model result showed that as the plasticity index reduces, the unconfined compressive strength of the soil increases. However, if all the input parameters are not considered, the UCS will have a 233.53 KN/m^2 strength value. This was buttressed by the R^2 value, which establishes the robustness of the model. Giving that the deformation of a pavement layer under traffic load depends on the pavement material stiffness, comparative analysis of soaked CBR values of Lime only and Lime + MOFIC treatment results 70.6% stiffness gain when treated with 2% Lime + MOFIC content, 48.4% and 40.6% gain with 4% and 8% Lime + MOFIC contents, and 25% and 6.9% gain with 12% and 16% Lime + MOFIC contents. Similarly, for the resistance to failure as measured with UCS tests, the comparative analysis of UCS values of Lime only and Lime + MOFIC treatment results in a 25%, 20% and 15.6%, and 23.9% and 23.0% strength gain when treated with 2%, 4% and 8%, and 12% and 16% Lime + MOFIC content, respectively. Considering the gains in stiffness and strength value due to MOFIC addition over Lime-stabilised Lateritic soil samples, 2% Lime + MOFIC treatment results in high stiffness and strength gains, 4% and 12% Lime + MOFIC treatment lead to moderate stiffness, and strength gains, 8% Lime + MOFIC treatment gives rise to moderate stiffness and strength gains, while 16% Lime + MOFIC treatment produces too low stiffness and high strength gains.

Table 3 Model parameters

Standard deviation	33.59	R-squared	0.96
Mean	343.33	Adj R-squared	0.90
CV	9.78	Pred R-squared	0.78

4 Conclusion

This study evaluated Lime-stabilized soil's strength properties with MOFIC a green product that serves as a viscosity-enhancing admixture. The results showed the following:

i. Improved workability, stiffness and strength suggest the use of MOFIC could be a cost-effective methodology to improve the structural performance of subbase layers.
ii. As a viscosity-enhancing green product obtained from natural agricultural plants available locally, this material provides environmental benefits and meets the green construction requirements.
iii. The addition of Lime and pectin (a major constituent of MOFIC) to the soil progressively dissolves the silica, aluminum and iron oxides (SiO_2, Al_2O_3, Fe_2O_3) in the clay materials and, in the presence of water, produces a reaction giving rise to hydrates of calcium silicate (CSH) and calcium aluminate (CAH).
iv. The presence of Ca^{2+} in the MOFIC further improved the cementation process, which may be accountable for the change in the plasticity index, by aggregations of small particles.
v. Treatment of the Lateritic soil with Lime + MOFIC at 2% caused 70.6% stiffness and 25% strength gains

Table 2 ANOVA for response surface quadratic model

Source	Sum of squares	*DF*	Mean square	*F* Value	Prob > *F*	
Model	58,426.52	3	19,475.50	17.25	0.04	significant
A	41,376.12	1	41,376.12	36.66	0.02	
B	32,768.90	1	32,768.90	29.04	0.03	
C	57,280.23	1	57,280.23	50.76	0.01	
Residual	2256.80	2	1128.40			
Cor Total	60,683.33	5				

The "Pred R-Squared" of 0.7857 is in good agreement with the "Adj R-Squared" of 0.907 as laid out in Table 3. "Adequate Precision" evaluates the importance of the predicted parameters, which are LL, Pl and UCS. The standard deviation with the Adj R-Squared indicates that the data are sufficiently evenly distributed around the mean to compare to samples treated with the 2% Lime only which are equivalent to high stiffness and strength gains based on values recorded in this study.

vi. Samples treated with 4% Lime + MOFIC, the gains in stiffness and strength are 48.4% and 20% over samples treated with 4% Lime only, which is classified as moderate stiffness and high strength gains for this study.

vii. The optimum treatment content ranges from 2 to 4%, as samples treated with higher percentages of Lime + MOFIC result in lower stiffness and strength gains.

viii. The introduction of low MOFIC content as an additive to enhance Lime-stabilised Lateritic soil samples reduces cost, minimises environmental impact and significantly increases the stiffness and the strength values of the treated soil, thereby improving the structural capacity of stabilised subgrade material.

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Declarations

Conflict of interest Authors declare no conflict of interest.

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