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Soil modification by addition of cactus mucilage

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Abstract. This research provides insight on the laboratory investigation of the engineering properties of a lateritic soil modified with the mucilage of *Opuntia ficus-indica* cladodes (MOFIC), which has a history of being used as an earthen plaster. The soil is classified, according to AASHTO classification system, as A-2-6(1). The Atterberg limits, compaction, permeability, California bearing ratio (CBR) and unconfined compressive strength of the soil were determined for each of 0, 4, 8 and 12% addition of the MOFIC, by dry weight of the soil. The plasticity index, optimum moisture content, swell potential, unconfined compressive strength and permeability decreased while the soaked and unsoaked CBR increased, with increasing MOFIC contents. The engineering properties of the natural soil, which only satisfies standard requirements for use as subgrade material, became improved by the application of MOFIC such that it meets the standard requirements for use as sub-base material for road construction. The effects of MOFIC on the engineering properties of the soil resulted from bioclogging and biocementation processes. MOFIC is recommended for use as a modifier of the engineering properties of soils, especially those with similar characteristics to that of the soil used in this study, to be used as a pavement layer material. It is more economical and environment-friendly than conventional soil stabilizers or modifiers.

Keywords: green technology; *Opuntia ficus-indica*; pavement material; soil stabilization; tropical soil

1. Introduction

Lateritic soils are the single most extensive kind of soil in tropical and sub-tropical regions. Their availability have made it economical to use them as pavement layer materials but some of them have poor engineering properties such as high plasticity, low strength and high permeability that makes them unsuitable for this purpose. This is because they do not satisfy existing standard requirements that stipulate acceptable plasticity and strength characteristics of soils to be used as as either subgrade, sub-base or base materials.

Cement and lime have been conventionally used to modify or stabilize the properties of lateritic soils but they are expensive, though they have been effective. Research efforts, such as Akinwumi *et al*. (2012), have been geared towards cheaper and environment-friendly alternatives. This research aims at investigating the effects of the application of the mucilage of *Opuntia ficus-indica* (MOFIC) on the plasticity, strength and permeability of a lateritic soil for use as a pavement layer material.

The Opuntia genus is the largest under the Cactaceae family. Opuntias adapt well to arid and

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semi-arid climatic conditions such as drought, unpredictable rainfall, and poor soils prone to erosion. *Opuntia ficus-indica* (OFI) is the most widespread Opuntia in the world, found on all continents except Antarctica (Inglese *et al*. 2002). It is common in the following countries or parts of these countries: Mexico, Argentina, Bolivia, Brazil, Canada, Chile, Cuba, Malta, Peru, the United States, Greece, Italy, Spain, Turkey, Algeria, Egypt, Eritrea, Ethiopia, Libya, Morocco, Namibia, South Africa, Tunisia, Israel, Lebanon, Saudi Arabia, Sri Lanka and Yemen. It is popularly referred to as cactus pear plant, Indian fig, nopal and nochtli. Cactus fruits and pads (cladodes) have been food for both man and animal (De Waal *et al*. 2006). The cladodes are known to have medicinal value, used in the production of jellies, jams, natural food colorants and cosmetics (Hernandez-Perez *et al*. 2009). Attempts have been made to use cactus fruits and cladodes (succulent leaves) also for engineering applications such as for reduction of turbidity (Pichler *et al*. 2012, Saenz *et al*. 2004) and arsenic contamination (Young *et al*. 2005) in drinking water, reduction of hardness in spring waters (Young 2006), steel corrosion inhibition (Torres-Acosta 2007, Torres-Acosta *et al*. 2012), aluminum corrosion inhibition (El-Etre 2003), use as additive to reduce the permeability of mortar (Chandra *et al*. 1998), use as a viscosity-enhancing admixture for cement mortar and concrete (Leon-Martinez *et al*. 2014) and for use as performance enhancement of lime-based mortar (Cardenas *et al*. 1998).

Cactus cladodes, having the shape of a racket, serve as succulent leaves that store water for cactus plant. This characteristic makes the cactus plant thrive in arid and semi-arid areas. Mucilage (a hydrocolloid) is also stored within the tissues of cactus cladodes.

The MOFIC has been reported to contain arabinose, galactose, rhamnose, xylose, galacturonic acid, carbohydrates, Ca^{2+} and K^{+} (Sepulveda *et al*. 2007). The disposal of cactus cladodes constitutes environmental pollution resulting from its fermentation (Galati *et al*. 2002). Noting that MOFIC contains Ca^{2+}, the authors speculated that addition of the MOFIC has the potential of modifying the engineering properties of soils containing clay particles by facilitating the flocculation and agglomeration of these clay particles in a way similar to the modification of soil properties by the addition of lime.

This research effort is unique in that no research work has been reported in open literature that studied the effects of adding MOFIC on the geotechnical properties of a lateritic soil.

2. Materials and methods

2.1 Materials and preparation

Fresh mucilage in solution was produced by cutting OFI cladodes, collected from Ado-Ekiti, Southwest Nigeria, into small pieces and leaving it to be soaked in water for five days. Afterwards, gloopy (thick and sticky) juice was filtered and collected. The collected MOFIC contains 96.4% of water.

The solids content in the MOFIC is insignificant (approximately 0 mg/l). Contreras-Padilla *et al*. (2011) reported that the calcium content in OFI cladode powder increases with the age of the cactus and they found out that the calcium contents in 40 - 135 days old cactus cladodes ranged from 17.4–34.4 mg/g.

The soil sample used was collected, by method of bulk disturbed sampling, from Covenant University borrow pit (latitude 06°40′24″N and longitude 03°09′12″E) behind the university student hostels. They were collected at a depth of 0.5 m below the ground, after the removal of 0.2

m thick topsoil layer. Watertight bags were used to collect soil samples for natural moisture content determination. The samples were stored and air-dried in the Geotechnics laboratory of the Department of Civil Engineering, Covenant University, Ota. After each addition of the desired proportion of MOFIC to the soil, they were thoroughly mixed using a mechanical mixer and the mixture was placed in a container for 24 hours to allow for homogeneity of the mixture.

2.2 Methods

The geochemical characterization of the soil was determined using atomic absorption spectrophotometer. Natural moisture content, sieve analysis and Atterberg limits tests were performed on the natural soil sample. MOFIC was added to the soil in 4, 8 and 12%, by dry weight of the soil and thoroughly mixed to ensure homogeneity. Atterberg limits, compaction, California bearing ratio (CBR), unconfined compression and permeability tests were performed on each of the MOFIC-modified soil samples. For the natural soil and MOFIC-modified soil samples, the Atterberg limits, compaction, California bearing ratio (CBR), unconfined compression and permeability tests were performed in triplicate and their mean values were computed and presented. Graphical plots of each of these parameters were plotted against the MOFIC contents.

Sieve analysis was carried out on samples of soil retained on a sieve with 0.075 mm opening while hydrometer analysis, using sodium hexametaphosphate, was conducted on the soil sample passing the sieve. The index properties tests performed on each of the batches of the natural and modified soil samples were in accordance with BSI (1990a, b).

The modified proctor energy was used for preparing the specimen for compaction and CBR tests. The specimen diameter and height are 150 mm and 175 mm, respectively. While preparing the specimen, 4.5 kg rammer was used to provide 56 blows to each of 5 layers of compaction. Unsoaked CBR test specimens were cured for 7 days under controlled temperature (25 ± 2°C) and relative humidity (100%). For the determination of soaked CBR, specimens were cured for 6 days under the controlled temperature and the relative humidity before being immersed in water for 24 hours (Nigerian General Specification 1997). For the determination of the swell potential, soil samples compacted in the CBR mould and subjected to a preloading pressure were immersed in water for 24 hours, allowing them to swell. Periodical readings of displacement were taken. The swell potential of a specimen was determined by calculating the ratio of change in height of the specimen to its initial height.

Unconfined compressive strength (UCS) test specimens (50 mm × 100 mm), prepared and extruded from a cylindrical mould, were cured in sealed plastic bags. The UCS for each batch was determined after 7 days of curing.

Constant head permeameter was used to determine the coefficient of permeability of the samples. The permeability tests were carried out in accordance with BSI (1990a).

3. Test results

3.1 Chemical composition of soil

Using atomic absorption spectrophotometer, the concentrations of oxides of silica (SiO_2), iron (Fe_2O_3) and aluminum (Al_2O_3) in the soil were determined in order to identify the extent of laterization of the soil sample. A ternary or tri-plot of this composition is shown in Fig. 1. The

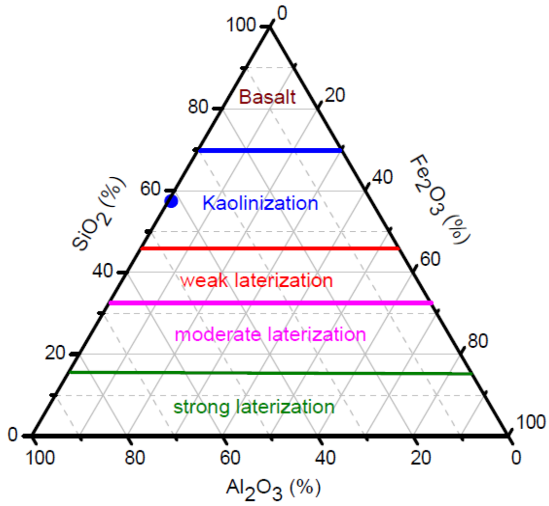

Fig. 1 Al_2O_3-SiO_2-Fe_2O_3 (wt, %) ternary plot for the soil sample

concentration of silica in the soil was found to be higher than that of each of the other oxides. Thereby, suggesting that this soil was formed from laterite on an acidic rock and containing some quartz. The soil also contained a higher concentration of aluminum oxide than that of iron oxide; suggesting that the soil is bauxitic. The ratio of silica-sesquioxides was determined to be 1.35, confirming that the soil is lateritic. According to the Schellmann (1986) classification scheme, this soil sample belongs to a kaolinized profile.

3.2 Natural soil

Table 1 summarily presents the results of tests for determining the gradation, classification, index and strength characteristics of the natural soil. It has a natural moisture content of 15.7% and is classified as A-2-6(1), according to the AASHTO soil classification system. A gradation curve showing the particle size distribution of the soil is shown in Fig. 2. Fig. 2 shows that the soil is granular and it has 29.1% of its particles passing through British Standard No. 200 sieve (0.075 mm). Consequently, this fraction considerably influences the behaviour or characteristics of the soil. The soil sample was in its plastic state at the time of its collection. Its plasticity index was found to be greater than 11% indicating that its fines are clayey. The activity of the soil was determined to be 1.08 and using the table for activity of clay-rich soils provided by Budhu (2011), this soil can be described as normal.

3.3 Effects of adding MOFIC to the natural soil

Fig. 3 shows how the liquid and plastic limits and the plasticity index of the lateritic soil sample vary with the MOFIC content in the soil. From Fig. 3, it can be seen that a negative correlation exists between the plasticity index of the soil and the addition of MOFIC to the soil. Addition of 12% MOFIC to the natural soil resulted in a decrease in its plasticity index by 77.5%. There is a strong correlation (r = −0.967) between the decrease in plasticity indices of the modified soil samples and their MOFIC contents. The reduction in the plasticity index of the soil by the addition of MOFIC reduced its moisture-holding capacity and made the soil more workable.

Table 1 Geotechnical properties of the natural soil

	Properties	Quantity / Description
Gradation / Classification	Gravel (> 4.75 mm), %	12.5
	Sand (0.075–4.75 mm), %	58.4
	Silt and Clay (< 0.075 mm), %	29.1
	AASHTO Soil Classification System	A-2-6 (1)
	Unified Soil Classification System	SC - Clayey Sand
Physical	Colour	Brown
	Natural Moisture Content (%)	15.7
	Specific Gravity	2.54
	Liquid Limit (%)	29.0
	Plastic Limit (%)	10.8
	Plasticity Index (%)	18.2
	Linear Shrinkage (%)	4.0
	Maximum Dry Unit weight (kN/m^3)	17.5
	Optimum Moisture Content (%)	14.7
	Permeability (cm/s)	8.58×10^{-5}
	Swell Potential (%)	0.287
Strength	Unsoaked CBR (%)	56
	Soaked CBR (%)	29
	Unconfined Compressive Strength (kN/m^2)	1304

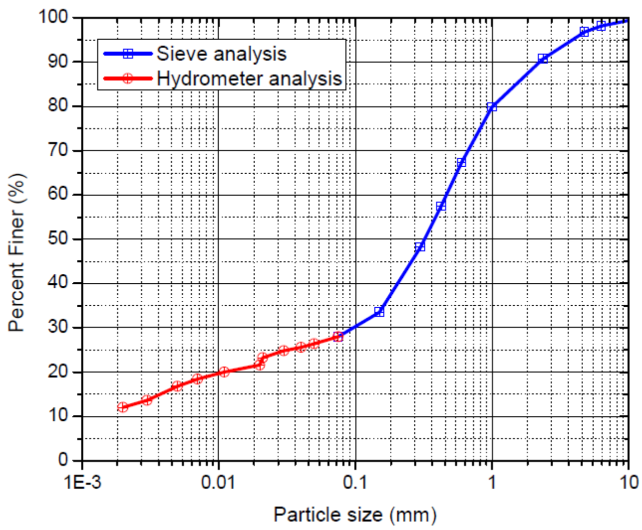

Fig. 2 Particle size distribution of natural soil

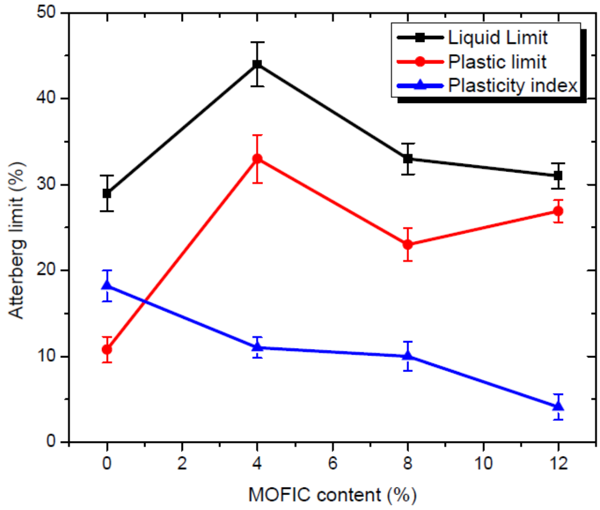

Fig. 3 Variation of Atterberg limits with MOFIC content

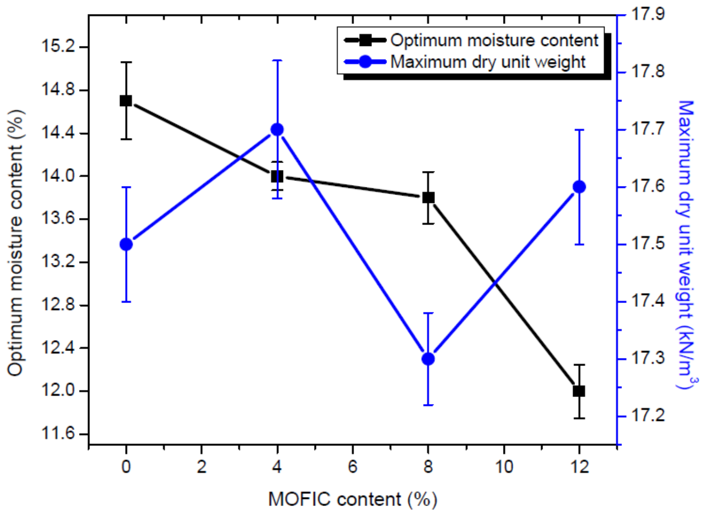

Fig. 4 Variation of compaction characteristics with MOFIC content

Series of dry unit weight against moisture content were plotted from the results of compaction tests for 0%, 4%, 8% and 12% MOFIC contents in the soil. The points of maximum dry unit weight and optimum moisture content (OMC) were taken from these plots and used to produce the plots of OMC against MOFIC content and maximum dry unit weight against MOFIC content (Fig. 4). A negative correlation exists between the OMC and the addition of MOFIC to the soil. The variation of OMC and maximum dry unit weight of the soil with MOFIC content is shown in Fig. 4. Addition of 12% MOFIC to the soil resulted in a decrease in its OMC by 18.4%. There is a strong correlation ($r = -0.932$) between the decrease in OMC of the modified-soil samples and their MOFIC contents. There is no correlation ($r = -0.076$) between the maximum dry unit weights of the modified soil samples and their MOFIC contents.

The decrease in OMC of the soil as its MOFIC content increases can be attributed to the agglomeration of the clay particles of the soil, facilitated by the adhesive property of the MOFIC, and described using Fig. 5. Fig. 5 is the plasticity chart showing how the plot of the plasticity characteristics of the natural soil shifted with increasing MOFIC content. It shows that the fines of the natural soil falls within the area on the Unified soil classification (USC) system chart categorized as clay of low plasticity (CL) and within the area on the AASHTO classification system chart categorized as A-2-6. As the MOFIC content in the soil increases, the plots on the

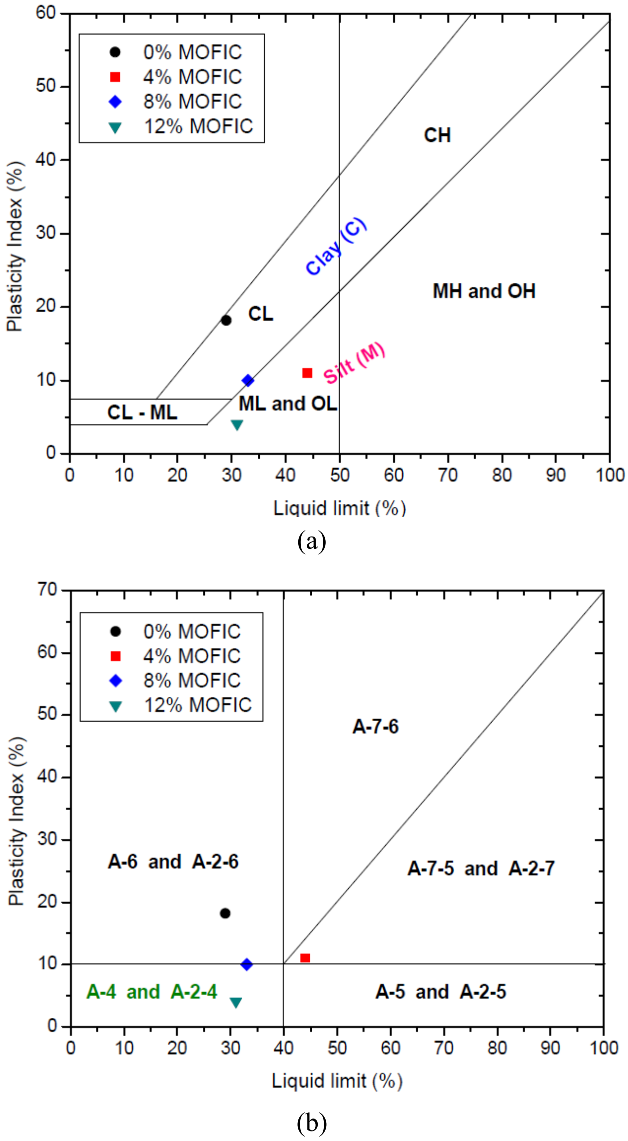

Fig. 5 Plasticity chart showing plots for the natural and MOFIC-modified soil samples using: (a) USC; and (b) AASHTO systems

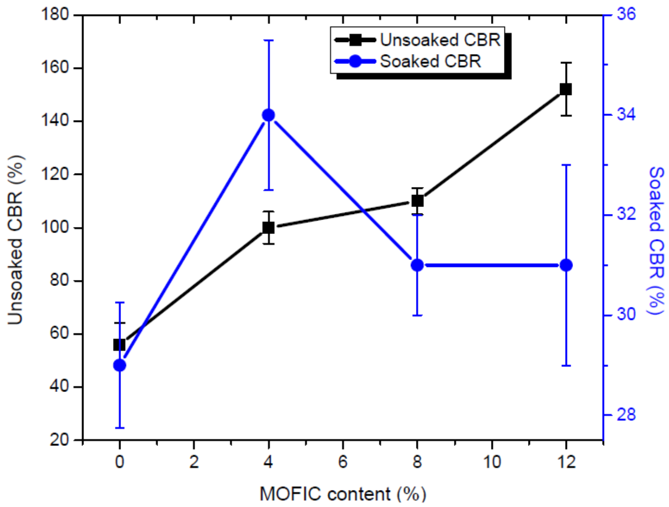

Fig. 6 Variation of CBR with MOFIC content

plasticity charts for the MOFIC-modified soil samples progressively shifted towards the portion of the USC system chart classified as silt of low plasticity (ML) and towards the portion of the AASHTO system chart classified as A-2-4. This indicates that some of the clay particles of the natural soil got clumped-together after the application of MOFIC and began to behave like silt-sized particles. The coarser a soil becomes, the lesser the moisture content it requires to reach optimum (Akinwumi 2012, 2014a, b).

There exist a positive correlation between the unsoaked CBR of the soil and the MOFIC content in the soil, as observed in Fig. 6 that shows the variation of unsoaked and soaked CBR of the modified soil samples with their MOFIC contents. Addition of 12% MOFIC to the soil increased its unsoaked CBR value by 171.4%.

The increase in unsoaked CBR as the MOFIC content in the soil increases is strongly correlated, $r = 0.976$. However, there is no correlation between the soaked CBR of the soil and the MOFIC content in the soil, $r = 0.188$.

The decrease in the plasticity index and the increase in the CBR values of the soil as its MOFIC content increases may be better appreciated when we compare the results for the natural soil and modified soil with standard requirements for soils to be used as pavement layer materials. The natural soil that only met the requirements of TRL (1993) and Nigerian General Specification (1997) for use as a subgrade material became suitable for use as sub-base materials, after the application of MOFIC to the soil.

Variation of the swell potential of the soil with its MOFIC content is shown in Fig. 7. There exist a negative correlation between the swell potential and the MOFIC content in the soil. The decrease in swell potential as the MOFIC content in the modified soil increases is strongly correlated, $r = -0.844$. The swell potential of the natural soil is low and became slightly and further reduced with increase in its MOFIC content, as seen in Fig. 7. The low swell potential suggests that kaolinite is the predominant clay mineral in the soil and this suggestion is corroborated by Fig. 1, which indicates that the soil was taken from a kaolinized profile. Kaolinites are known to be non-swell (Voottipruex and Jamsawang 2014, Calik and Sadoglu 2014, Akinwumi *et al*. 2014) and stable.

The unconfined compressive strength (UCS) of the natural soil and those of the MOFIC-modified soil samples are shown in Fig. 8. The decrease in the UCS as the MOFIC content in the soil increases is strongly correlated, $r = -0.621$.

The decrease in the UCS with increasing MOFIC content in the soil may have resulted from the loss of some of its cohesion. The clay fraction in the soil is responsible for its cohesion but as stated earlier, some of it becomes clumped together and behaves like silt-sized particles due to the application of MOFIC to the soil. Consequently, the contribution of these clumped particles to cohesion becomes lost and thereby leading to a decrease in the UCS of the MOFIC-modified soil.

There is a negative correlation between the permeability of the soil and its MOFIC content, as

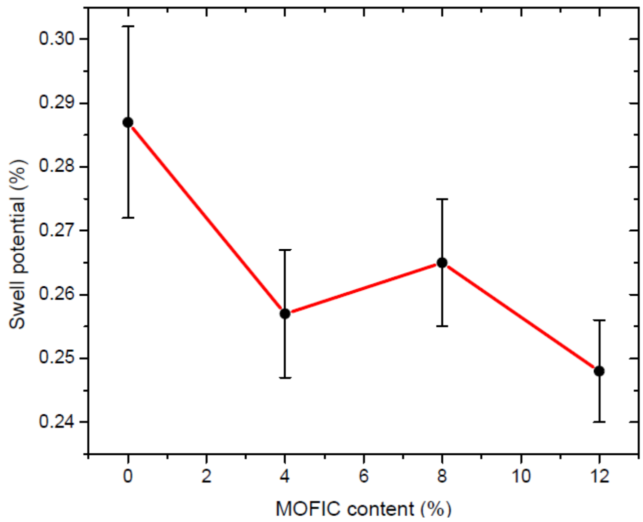

Fig. 7 Variation of swell potential with MOFIC content

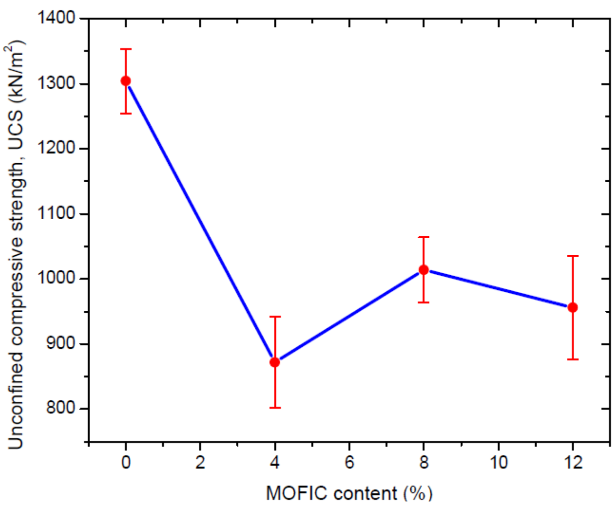

Fig. 8 Variation of UCS with MOFIC content

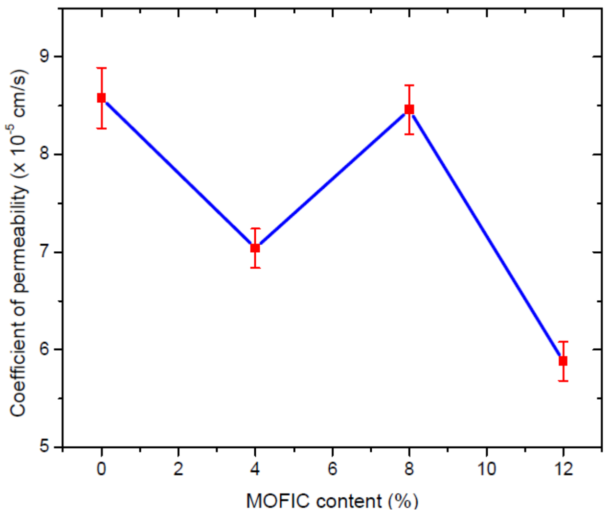

Fig. 9 Variation of permeability with MOFIC content

presented in Fig. 9. The decrease in the coefficient of permeability as the MOFIC content in the soil increases is strongly correlated, $r = -0.673$.

Using the results of the mean specific gravities and mean dry unit weights of the natural soil and those of the MOFIC-modified soil samples, their void ratios and porosities were calculated. The results obtained (Fig. 10) indicate that the void ratio and porosity both progressively decreased with increasing MOFIC content in the soil. This decrease in void ratio and porosity may be due to the clogging of the pores within the soil that resulted from the formation of a chemical bond between pectin in the mucilage and water molecules having some clay particles. This may be responsible for the decrease in the permeability of the soil as its MOFIC content increases.

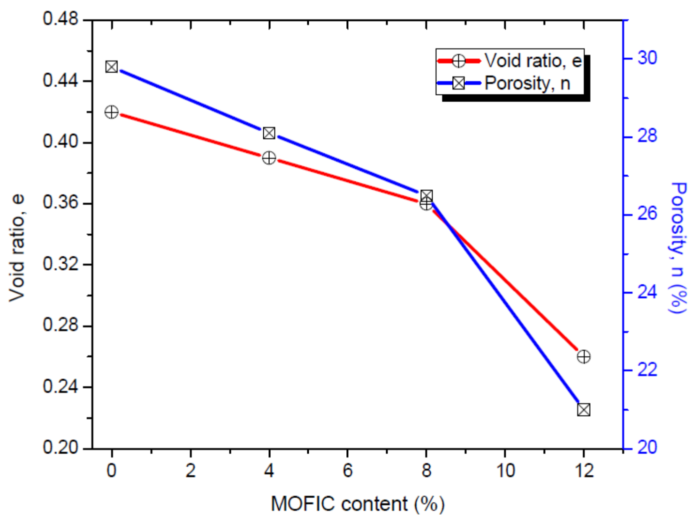

Fig. 10 Variation of void ratio and porosity with MOFIC content

4. Discussion

The addition of MOFIC to the soil facilitated fermenting bacteria to produce polysaccharides referred to as exopolysaccharides. Polysaccharides were classified by Tisdall and Oades (1982) as being a transient soil-binding agent. They bind smaller fractions of the soil particles to form sizes larger than 0.25 mm and they can easily and rapidly get decomposed by microorganisms (Graber *et al*. 2006). Also, the major component of MOFIC is pectin, which is usually covered by a layer of calcium ions (McCann and Roberts 1991). The calcium ions in the MOFIC reacts with the silica and water in the soil to form calcium silicate hydrates (a cementitious compound), which is responsible for binding the small particles of the soil together. These aggregations of small particles are responsible for the reduction in plasticity index and swell potential; and the increase in the bearing capacity of the MOFIC-modified soil.

Based on these characteristics, MOFIC may be a cheap, effective and sustainable additive to earth building materials (Akinwumi 2014c). However, the transient nature of the binder may have contributed to the reduction in the UCS of the modified soil.

The permeability of the MOFIC-modified soil became reduced by the production of these pore-filling materials (pore-clogging exopolysaccharides) that resulted in the reduction of the porosity and consequently, the reduction in the permeability of the modified soil (Ivanov and Chu 2008).

5. Conclusions

This study shows that MOFIC has beneficially improved the plasticity, swell behaviour and bearing capacity of the lateritic soil. It also reduced the ease with which water flows through the soil.

Addition of a MOFIC content of 12% to the soil reduced its plasticity index by 77.5%, its swell potential by 13.6% and its permeability by 31.4%. It also increased the unsoaked and soaked CBR of the soil by 171.4% and 6.9%, respectively. The natural soil, which only met the requirements of TRL (1993) and Nigerian General Specification (1997) for use as a subgrade material, became suitable for use as a sub-base material, after the application of 12% MOFIC content.

The effects of MOFIC on the geotechnical engineering properties of the soil were brought about by bioclogging and biocementation processes. The application of MOFIC to modify soils with similar geotechnical engineering properties as those of the soil used in this study is recommended as an economical and sustainable additive to these soils for use as pavement layer material or earth building material. However, the modified soil condition must be such that will not favour the production of exopolysaccharide-degrading microorganisms.

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