

The Impact of Biosolids on the Geotechnical Properties of Some Soils of the Niger Delta Sub-region, Nigeria

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Abstract: The production of biosolids (human wastes) in the Niger Delta of Nigeria has been taking place since man inhabited the sub-region. One of the negative impacts of *biosolids* is the changes to the geo-environmental conditions of the soils of the sub-region. Studies carried out on the effects of biosolids in the Niger Delta Sub-region over the last sixteen years indicate that the conventional geo-environmental engineering properties of the soils have been altered significantly. Biosolids have been found to affect both the grain size distribution patterns, the Atterberg Limits (Liquid Limits (LL), Plasticity indices (PI), California Bearing Ratios (CBRs), Proctor Compaction indices such as Maximum Dry Densities (MDD); Optimum Moisture Contents (OMC), Soil friction angles (ϕ) & cohesion values (c) and to an extent Ultimate Bearing Capacities (q_{ult} & q_{allow}). Biosolids applied on two types of tropical soils classified as slightly to medium plastic (lateritic (CL) and Sandy (SP) soils) batched and mixed at four different percentage levels of 5%, 10%, 15% and 20% by weight of sample indicated that % biosolids in the soils positively correlated with the Total Organic Contents (TOC) while inversely correlating with the Moisture content in the lateritic soils to a limiting value at 15%, while in the basically sandy soil it was at the 20% biosolids treatment. The infiltration rate increased to a peak at 13.5% biosolids content and thereafter decreased, while in the basically sandy soil, addition of biosolids caused the infiltration rate to fluctuate. It has also been observed that 100kN is the critical stress under which high volume reduction is recorded in all cases of biosolids treatments. The 5 to 10% biosolids treatment range experienced minimum volume change (Δv) compared to the 15 to 20% biosolids treatment range. The wide gap observed existing between 15 – 20% and 0 – 10% biosolids treatment ranges tends to suggest the existence of two groups of biosolids-treated lateritic soils namely: the Low and High Compressible Lateritic soils.

Keywords: Biosolids Pollution, Geo-environmental Engineering Properties, Pollution Indices

1. Introduction

Environmental pollution is generally a man-made phenomenon that is introduced into the primordial environment. These could be through crude oil exploration activities (from errors in drill fluid handling to intentional destruction of oil pipeline routes for purposes of stealing crude) to the dumping of human wastes on lands (a method usually adopted by the inhabitants of rural and sometimes, semi-urban areas).

Biosolids Pollution and relationships with engineering properties.

Results of tests conducted in both un-polluted and polluted soils from the sites studied are presented in this study.

2. Methods

In preparing the soils for the tests, percentages of biosolids taken were: 5%, 10% and 15%. These percentages were applied to both the Sandy soils Section 2.1 as well as the Lateritic soils in Section 2.2. as modified from some existing Land Application of biosolids codes [1, 2, 3a-3b].

2.1. Sandy Soils

The following tests were administered to the Sandy soils namely (i) Particle Size Distribution; (ii) Atterberg Limits tests; (iii) Shear Strength parameter tests (determinations of Coefficients friction angles $[\phi]$ and cohesion intercepts $[c]$), (iii) Soil Organic matter contents, (iv) Soil Infiltration parameters such as Soil permeability $[k]$, (v) Soil Moisture Content $[w]$, (vi) Soil Compaction parameters such as maximum Dry Density $[MDD]$ and Optimum Moisture Content $[OMC]$, (vii) Soil Compressibility expressed as Coefficient of Volume Change $[M_v]$ and (viii) Pollution Indices $[PI]$.

2.2. Lateritic Soils

In the same way as in 2.1 above, the following tests were administered to the Lateritic Soils at the study sites. These were: (i) Particle Size Distribution; (ii) Atterberg Limits tests; (iii) Shear Strength parameter tests- (determinations of Coefficients friction angles $[\phi]$ and Cohesion intercepts $[c]$), (iii) Soil

Organic matter contents, (iv) Soil Infiltration parameters such as Soil permeability $[k]$, (v) Soil Moisture Content $[w]$, (vi) Soil Compaction parameters such as maximum Dry Density $[MDD]$ and Optimum Moisture Content $[OMC]$, (vii) Soil Compressibility expressed as Coefficient of Volume Change $[M_v]$ and (viii) Pollution Indices $[PI]$.

3. Results

3.1. Particle Size Distribution

3.1.1. Particle Size Distribution in Sandy Soils

In basically sandy soils, the effect of treatment with 5% biosolids is relatively slight compared with higher levels of treatment when D_{10} is considered. Considering D_{30} , biosolids treatment produced an obvious alternation of aggregation and disaggregation at 5%, 10%, 15%, and 20% biosolids treatments. However, a consideration of D_{50} and D_{60} showed a marked effect of aggregation and disaggregation with increasing percentage of biosolids treatment.

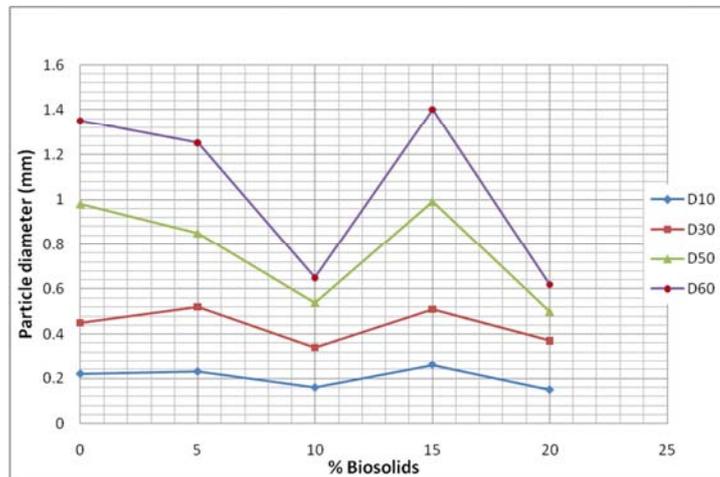


Figure 1. Effect of biosolids treatment on particle diameter indices of sandy soils.

3.1.2. Particle Size Distribution in Lateritic Soils

In lateritic soils, there is a slight variation in aggregation of particles with 0% to 10% biosolids treatment, while there is a sharp increase in aggregation at 15% biosolids treatment and a sharp decline in aggregation at 20% biosolids treatment.

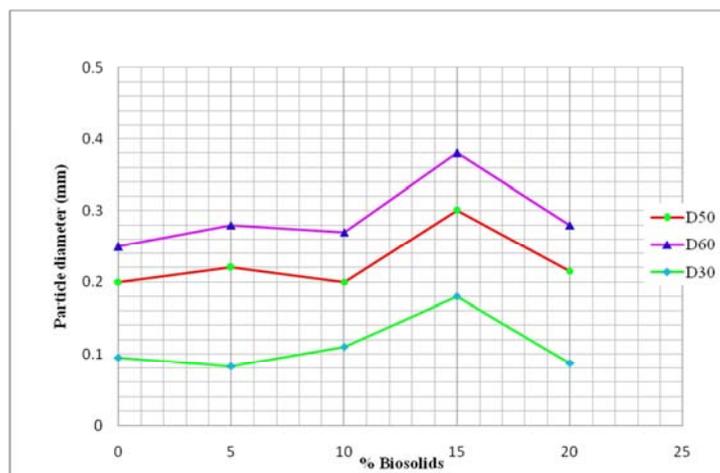


Figure 2. Effect of biosolids treatment on particle diameter indices of lateritic soils.

This observation in the lateritic soils indicates that 15% biosolids treatment will produce optimum level of aggregation in lateritic soil. Similarly, 15% biosolids treatment in the sandy soils produced an optimum aggregation in all the indices considered. Beyond 15%, higher levels of biosolids treatment should be performed to investigate what happens after 20% treatment, to clearly clarify the trend inherent in biosolids treatment in sandy soils.

These deductions from the observations both in the sandy as well as in the lateritic soils confirm the assertion that biosolids affect aggregate soil instability index [4]. It has also been observed that lower clay dispersibility associated with biosolid application keeps soil particles from detaching [5] Also, the fats, waxes, oil and resins contained in the biosolids, which act as binders keep the soil particles together. [6, 7].

3.2. Atterberg limits

Atterberg Limits tests, as a convention are only carried out on cohesive soils and not on cohesionless sandy soils but in the presence of biosolids which form as binders, some Atterberg Limits tests were carried out on cohesionless soils.

3.2.1. Liquid Limits on Cohesive Soils

Liquid limits determined for the lateritic soils at different levels of biosolids application range from 35% at 0% application to 26.9% at 20% application. Figure 3 shows that increasing the percentage of biosolids in the lateritic soil decreases its Liquid Limit [8]. Similar tests with crude oils from the Nigerian Niger Delta Sub-region has also shown a similar relationship with the Liquid Limit of lateritic soils [9].

This situation is further confirmed by the linear model with negative slope fitted to the data,

$$y = -0.366x + 34.56 \quad (1)$$

$$R^2 = 0.955$$

where: x=percentage biosolids applied; y=liquid limit, in percentage; R=coefficient of correlation

The decrease in Liquid Limit observed with increase in % biosolids treatment of the lateritic soil, indicates that biosolids has the capacity to cause the soil to become viscous at lower moisture content than would be expected under normal conditions, and still retain some shear strength, since shear strength at the liquid limit is the same for all soils [10, 11a - 11b, 11c, 12, 13].

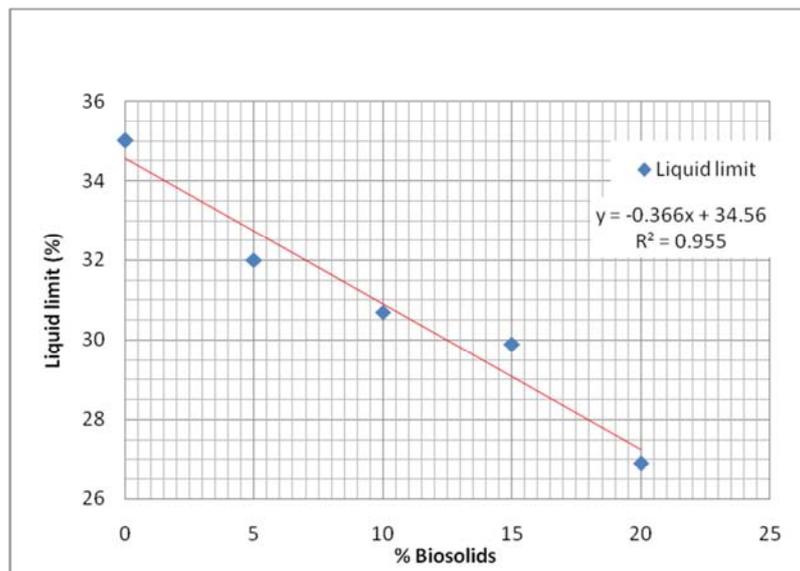


Figure 3. Relationship between % biosolids treatment and liquid limits of the lateritic soil.

3.2.2. Plastic Limits

Plastic limits determined for the Lateritic soil at the different levels of biosolids application range from 15% at 0% application to 13% at 20% application. In Figure 4, shows a slight decrease from 15% to 14.9% in plastic limit, as percentage biosolids increase from 0% to 5%, a sharp rise to 15.7% plastic limit was observed at 10% biosolids treatment. From 15.7% at 10% biosolids treatment, plastic limit value decreased steeply to 13% at 20% biosolids

treatment. It could be said that maximum plasticity index can be achieved with 10% biosolids treatment in the lateritic soils. This relationship is described with Eqn. (2).

$$y = -0.001x^3 + 0.025x^2 - 0.069x + 14.95 \quad (2)$$

$$R^2 = 0.968$$

where:

y=plasticity limit; x=percentage biosolids, and R=correlation coefficient

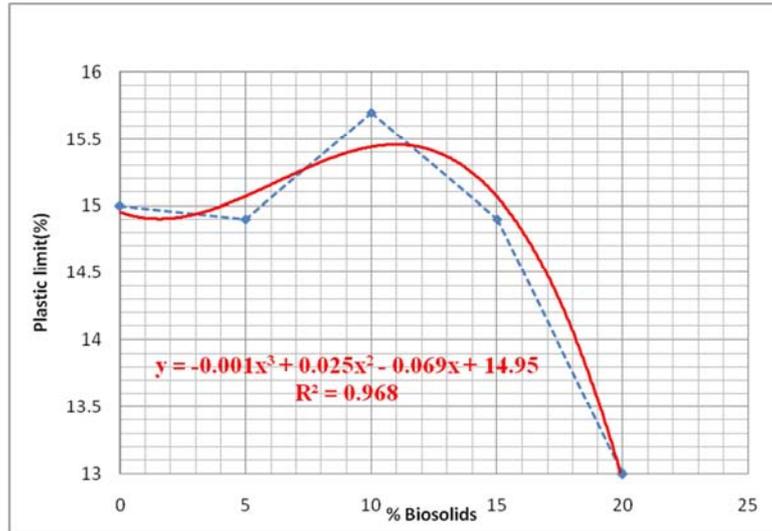


Figure 4. Relationship between % biosolids treatment and plastic limits of the lateritic soil.

3.2.3. Plasticity Index

Plasticity index values determined for the lateritic soil tested range from 20% to 13.9%. Figure 4 is the graph of plasticity index versus percentage biosolids. An inverse linear model is fitted to the data with the equation and correlation coefficient as given in Eqn. (3).

$$y = -0.286x + 19.06 \quad (3)$$

$R^2 = 0.873$
 where:
 y = plasticity index
 x = percentage biosolids, and

R = correlation coefficient

The plot of % biosolids versus plasticity index shows that both have positive correlation with each other (Figure 5). The equation of relationship with the correlation coefficient is given in Eqn. (5) below.

$$y = 0.776x - 7.78 \quad (4)$$

$R^2 = 0.901$
 where:
 y = plasticity index
 x = liquid limit, and
 R = correlation coefficient

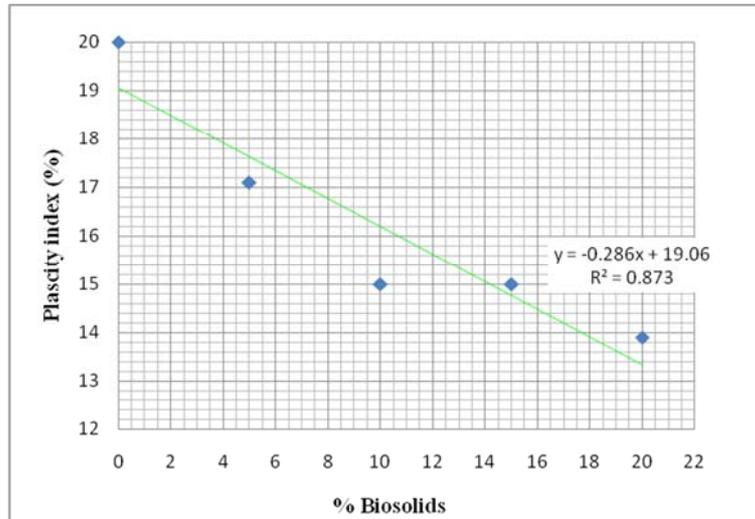


Figure 5. Relationship between % biosolids treatment and Plasticity index.

As shown in figure 6 below, the relationship between Plasticity Index and Liquid Limit for Biosolids polluted soils shows a straight line with an equation given by:

$$y = 0.776x - 7.781 \quad (5)$$

with a correlation coefficient (R^2) = 0.901.

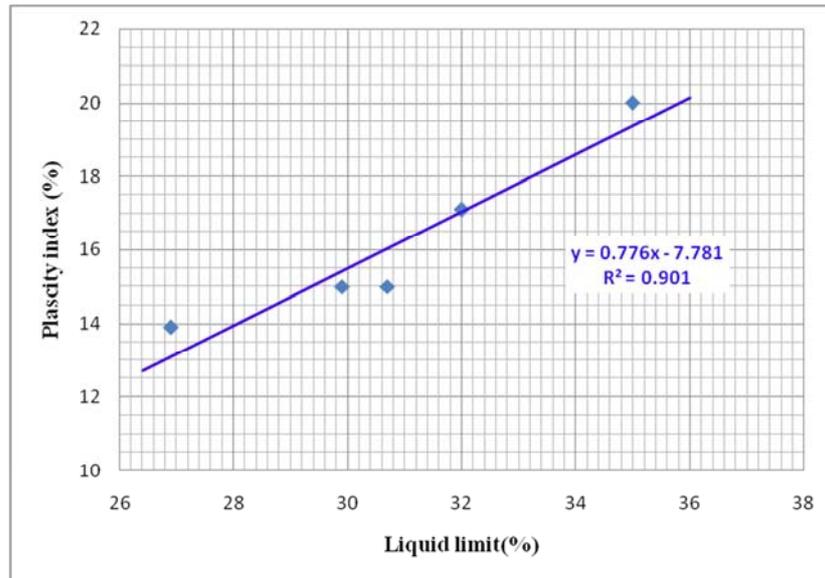


Figure 6. Relationship between Liquid limit and Plasticity index.

Liquid limit values plotted on the Plasticity Chart [14] classifies the soils tested as medium plasticity soils (Figure 7). Only the soil receiving 20% biosolids treatment was classified as high plasticity soil. It could then be said that the plasticity of lateritic soils can be affected by biosolids treatment, when the % of treatment is up to 20% and above.

The values obtained in this study are similar to those of the

low to medium plastic materials obtained in studies carried out on the argillaceous rocks of the Mamu Formation in the Enugu area of South-eastern Nigeria [15]. This can also be said of the lateritic soils tested in this study which plotted close to the boundary of low and medium plasticity (Figure 7).

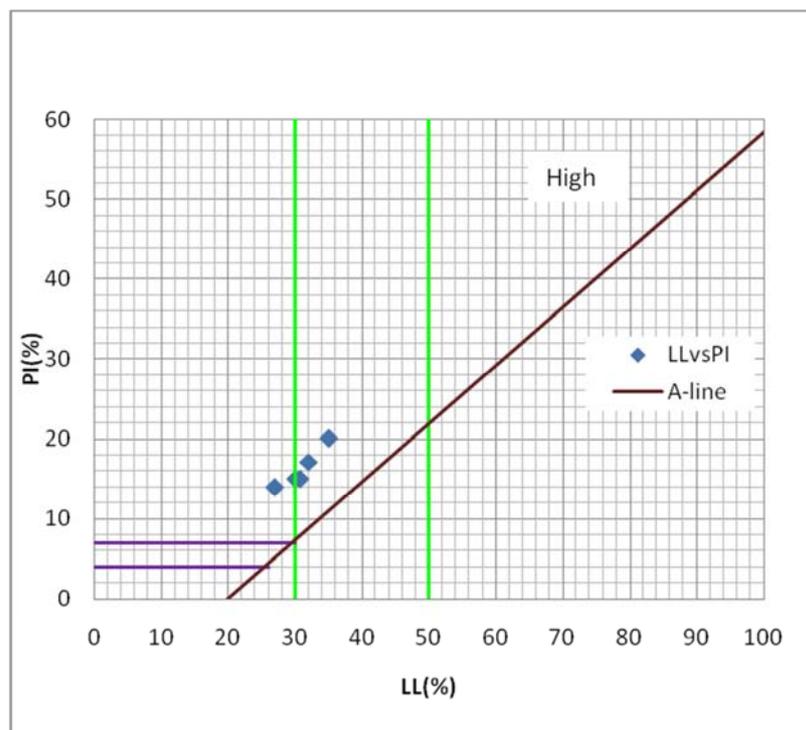


Figure 7. Plot of plasticity of the biosolids treated lateritic soil on Casagrande Chart.

3.3. Shear Strength Parameters of the Polluted Soils

3.3.1. Shear Strength Parameters of the Polluted Sandy Soil (SP)

Frictional angle, ϕ values determined are very low,

ranging from 3° to 4° , with the modal value as 3° and the cohesion, C ranges from 37.30kN/m^2 to 53.90kN/m^2 . Shear strength parameters, ϕ and C of the sandy soil are plotted against % biosolids (Figure 8). It is observed that biosolids

treatment did not have any significant effect on frictional angle, ϕ . The relationship between ϕ and % biosolids treatment can best be described using a polynomial equation. (Eqn. 6).

$$y=0.004x^3 - 0.16x^2 + 1.9x - 3 \quad (6)$$

$R^2=1$
 where:
 x=% biosolids treatment
 y=frictional angle, ϕ (deg)
 R=correlation coefficient

It is observed that biosolids treatment has a marked effect on the soil cohesion, (c). This situation was probably due to the biosolids behaving like clay particles. Biosolids treatment

obviously caused the cohesion to decrease from 50kN/m² at 5% biosolids treatment through 46.0kN/m² at 10% biosolids treatment to 37.3kN/m² at 15% biosolids treatment after which, further treatment caused an increase in cohesion to 53.9 kN/m² at 20% biosolids treatment. The relationship between cohesion and % biosolids treatment is expressed using the polynomial equation,

$$y=0.04x^3 - 1.294x^2 + 11.61x + 19.3 \quad (7)$$

$R^2=1$
 where:
 x=% biosolids treatment; y=cohesion, c (kN/m²) and
 R=correlation coefficient

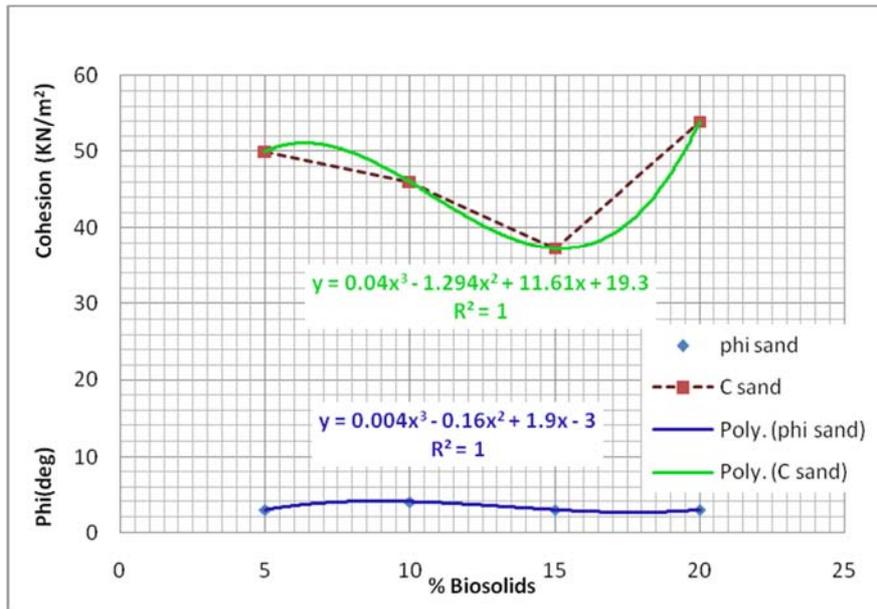


Figure 8. Plot showing the effect of biosolids treatment on the sandy soil shear strength parameters, ϕ and C.

3.3.2. Shear Strength Parameters of the Biosolids Polluted Lateritic Soil (CL)

Frictional angle, ϕ values determined though low, range from 5° to 12.8°, the mean is 8.54°. The cohesion, c values range from 54.9 kN/m² to 58.8 kN/m², with mode as 54.9 kN/m². Shear strength parameters, ϕ and c of the lateritic soil are plotted against % biosolids (Figure 9). It is observed that biosolids treatment did, relative to the sandy soil, have significant effect on frictional angle, ϕ (Figure 9).

Relationship between ϕ and % biosolids treatment can best be described using a polynomial equation (Eqn. 8)

$$y=0.007x^3 - 0.207x^2 + 0.985x + 11.46 \quad (8)$$

$R^2=0.955$
 where:
 x=% biosolids treatment
 y=frictional angle, ϕ (deg)
 R=correlation coefficient

It is also observed that biosolids treatment has a moderate effect on the soil cohesion, (c). The mean and modal values

of cohesion [c] are 56.1 kN/m² and 54.9 kN/m² respectively. Correlation between cohesion and biosolids treatment is good, and can be described with a polynomial equation of the nature given in (Eqn. 9),

$$y=-0.005x^3 + 0.133x^2 - 0.589x + 54.95 \quad (9)$$

$R^2=0.984$
 where:
 x=% biosolids treatment
 y=cohesion, c (kN/m²)
 R=correlation coefficient

Observation of Figure 9 shows that frictional angle decreases with biosolids treatment up to 15% of biosolids. At the same time, cohesion increased with biosolids treatment up to 15% of biosolids. Treating lateritic soils with biosolids improves its strength by the increasing of its cohesion component. At the same time, the strength is decreased by the reduction in the value of the frictional angle component up to 15% biosolids treatment where it starts to buildup. A careful tradeoff has to be made depending on the magnitude of Biosolids load involved.

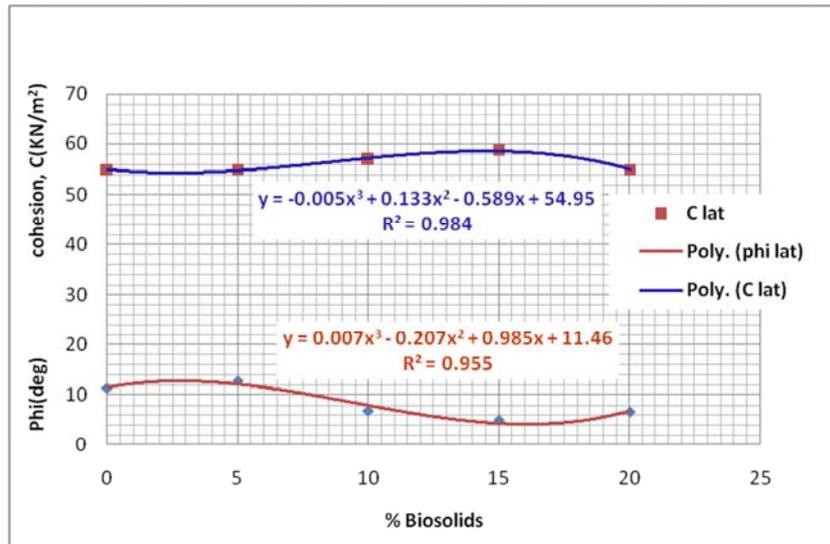


Figure 9. Plot showing relationship between biosolids treatment and lateritic soil shear strength parameters, ϕ and C.

3.4. Soil Organic Matter Content

Figure 10 shows the plot of biosolids versus the *Total Organic Content* [TOC] of the soils.

The polynomial equation given below as *Eqn. (14)* models the relationship between TOC and the amount of biosolids in the sandy soil tested with:

$$y = -0.000x^3 + 0.006x^2 + 0.005x + 0.033 \quad (10)$$

$$R^2 = 0.998.$$

Similarly, *Eqn. (11)* expresses the polynomial relationship between TOC and amount of biosolids contained in the lateritic soil tested.

$$y = 6E-05x^3 - 0.004x^2 + 0.098x + 0.036 \quad (11)$$

$$R^2 = 0.999$$

where:

y = total organic content (%)

x = % biosolids

R = correlation coefficient

Figure 10 further reveals that for a particular amount of biosolids introduced into the soil, *Total Organic Contents* determined in both the sandy and lateritic soils differ. The lateritic soil continues to show higher presence of organic matter than the sandy soil up to the theoretical value of 11.75% of biosolids, when the situation reverses. It seems that the biosolids component of the TOC in soil stability of both the sandy and lateritic soils should be between 10% and 15% limits.

The result of this test on both the sandy and lateritic soil confirms reports that biosolids application increases organic matter in the upper 3 cm of soil [16]. It also confirms a study that biosolids application increases organic matter content of a soil significantly after 3 years of biosolids application [4, 8, 16]. It can also be said from this test that, when biosolids are incorporated into the soil, soil total organic matter content increases in the manner described by Eqns. (10) and (11) above.

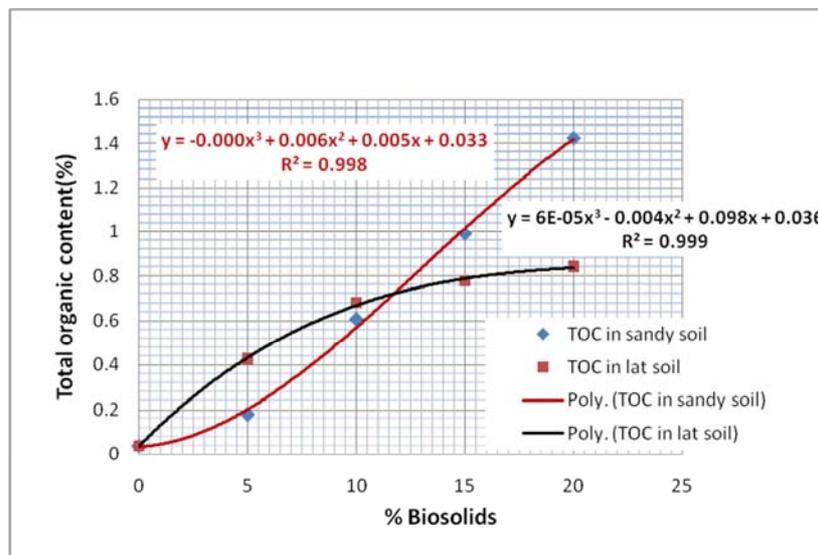


Figure 10. Plot showing effect of biosolids treatment on Total Organic Content (TOC) in Sandy and Lateritic Soils.

Figure 11 is the graph of *Total Organic Content vs Moisture Content*. In both types of soils, total organic content is inversely correlated with moisture content. This is expected because in a fixed volume of soil, addition of biosolids will reduce available moisture in the soil per unit biosolids. It has been observed that soil physical properties

affected by the biosolids addition were significantly correlated with organic matter content. The observation in this study agrees with those of that study. [4]

Eqns. (12) and (13) express this relationship between Total Organic Content [TOC] and Moisture Content in the sandy and lateritic soils, respectively.

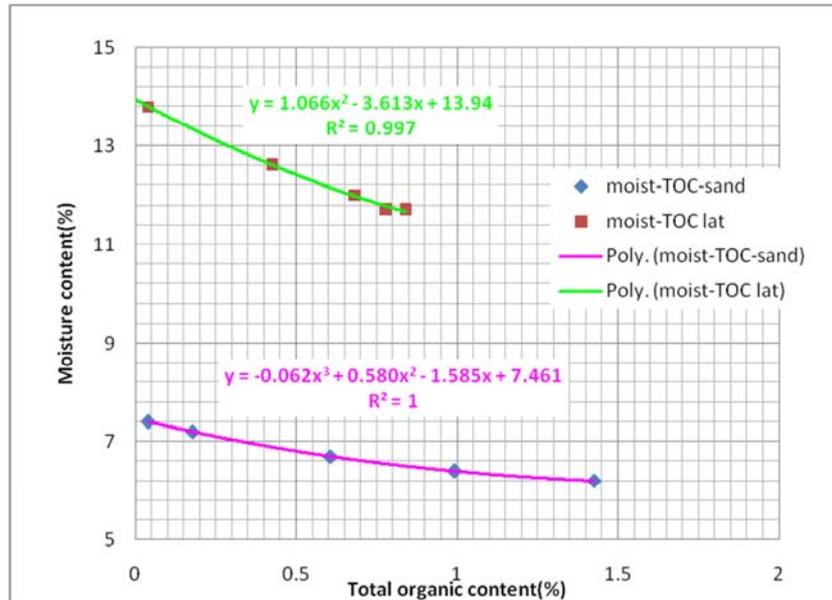


Figure 11. Variation of Moisture Content in the soils with total organic content.

3.5. Soil Infiltration

The infiltration (Permeability) rates obtained range from 16.1×10^{-8} cm/s to 22.1×10^{-8} cm/s in the Lateritic soils, and 55.4×10^{-8} cm/s to 88.5×10^{-8} cm/s in the Sandy soils.

The effect of biosolids treatment on the infiltration [Permeability] rates of the soils are shown in Figures 12 and 12b for the Lateritic and Sandy soils respectively.

In the *Lateritic soils*, Biosolids tend to *increase infiltration rate to about 13.5% of biosolids*, from where the infiltration rate starts decreasing.

The situation observed in this study is fitted with a

polynomial model defined by Eqn. (12).

$$y = -0.004x^3 + 0.084x^2 + 0.094x + 15.84 \quad (12)$$

$$R^2 = 0.894$$

where:

x = % biosolids

y = permeability (cm/s), and

R = correlation coefficient

The Sandy soil (Figure 12), presents a different situation from what was described above.

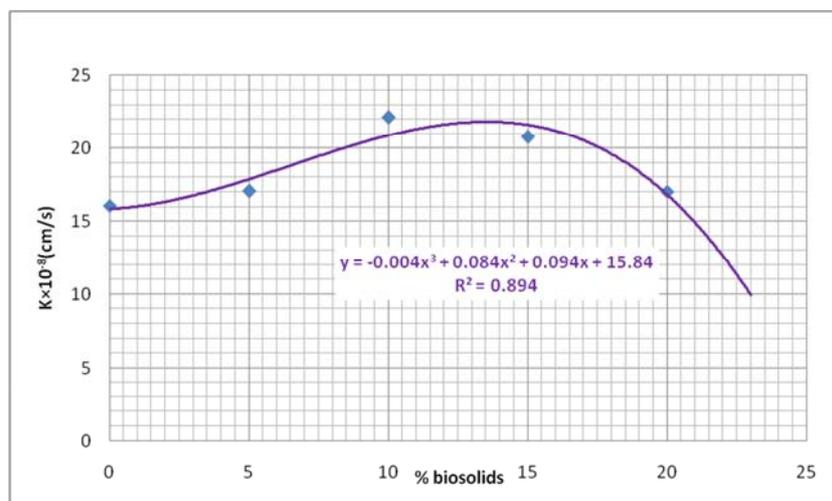


Figure 12. Variation of Permeability in lateritic soil at 0-25 kN/m² (as infiltration) with % biosolids.

In this case, the infiltration rate exhibits a periodic behavior. The reason for this has not been fully understood. It could be due to "excess" biosolids, which provide more space in the soil for soil moisture to trickle through. However, a polynomial equation with *periodicity 4* has been fitted to the data points to provide a model for the observation.

This polynomial equation is given below as Eqn. (13) below.

$$y=0.013x^4 - 0.515x^3 + 6.170x^2 - 22.38x + 71.05 \quad (13)$$

$$R^2=1$$

where:

x=% biosolids

y=permeability (cm/s), and

R=correlation coefficient

It has been observed that biosolids application increases soil infiltration capacity/rate (Permeability) in laterites to an extent, but as experienced in this study, Sandy soils behave quite differently [17, 7], [3a, 16].

3.6. Soil Moisture Content

The plots of the moisture content against the % biosolids applied to the soils are shown in Figure 13. The moisture

contents determined for the biosolids-treated Sandy soil range from 6.2 - 7.4%. In this Figure 13, it could be observed that moisture content is inversely correlated with percentage biosolids. Linear regression model (Eqn. 14) is thought the best model to describe this relationship between moisture content and % biosolids in the Sandy soil.

$$y=-0.064x + 7.42 \quad (14)$$

$$R^2=0.977$$

where:

x=% biosolids

y=moisture content (%) and

R=correlation coefficient

It could also be said there are two factors controlling moisture content in the soils, such as:

(i) Soil type and the other

(ii) The additive, in this case, biosolids.

Moisture content in the Lateritic soil seems to have a limiting value at 15% biosolids treatment, while in the Sandy soil, it is at the 20% biosolids treatment.

Figure 13 shows the graph of moisture contents from biosolids-treated Lateritic soil against moisture contents from biosolids-treated Sandy soil.

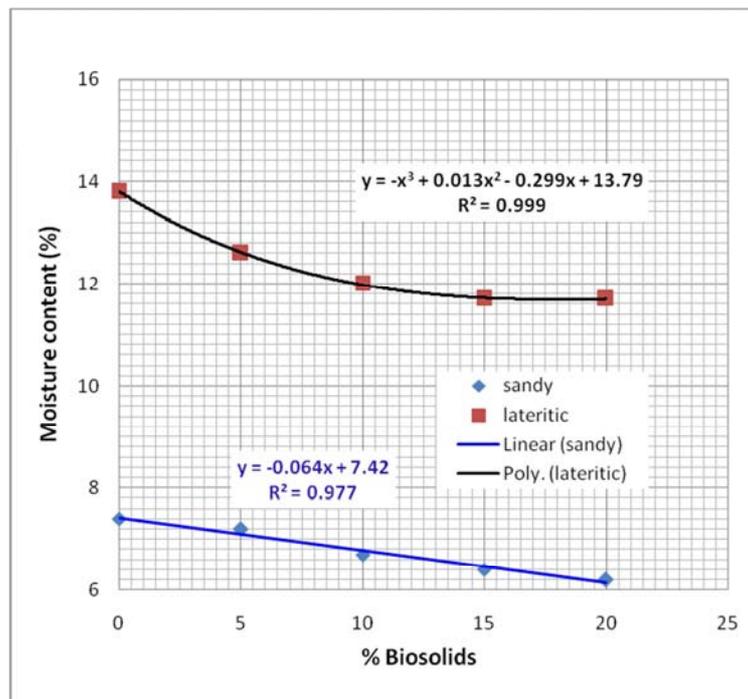


Figure 13. Variation of moisture content in the soils with biosolids treatment.

The figure revealed that the two sets of moisture content data can be related to each other in a positive linear relationship if the moisture contents from the untreated specimens are removed from the plot.

This shows that biosolids have improved the water holding capacity of the sandy soil. (Eqn. 15).

$$y=0.951x + 5.696 \quad (15)$$

$$R^2=0.951$$

where

x=moisture content of the sandy soil; y=moisture content of the lateritic soil and

R=correlation coefficient

Figure 14 is the graph of Total Organic Content [TOC] versus Moisture Content. In both types of soils, the Total Organic Content [TOC] is inversely correlated with Moisture content. This is expected because in a fixed volume of soil, addition of biosolids will reduce available moisture in the soil per unit biosolids. It is observed that soil physical properties affected by the biosolids addition were significantly correlated with organic matter content [4]. The observation in this study agrees with this. Eqns. (14) and (15) express the relationship between Total Organic Content (TOC) and Moisture Content (MC) in the Sandy and Lateritic soils respectively.

3.7. Soil Compaction

In soil Compaction exercise, two parameters usually evolve and these are (i) Maximum Dry Density [MDD] and

(ii) Optimum Moisture Content [OMC]

3.7.1. Maximum Dry Density [MDD]

The compaction Maximum Dry Densities [MDD] of the soils tested are shown in Figure 15. It is observed in the figure that biosolids treatment has influence on the maximum dry density of the soils tested. Increasing biosolids treatment increases MDD in the sandy soil. A good correlation is observed between MDD and % biosolids (Eqn. 16).

$$y=4E-05x^3 - 0.001x^2 + 0.010x + 1.640 \quad (16)$$

$$R^2=0.998$$

where:

x=% biosolids

y=maximum dry density, MDD (mg/cm³), and

R=correlation coefficient

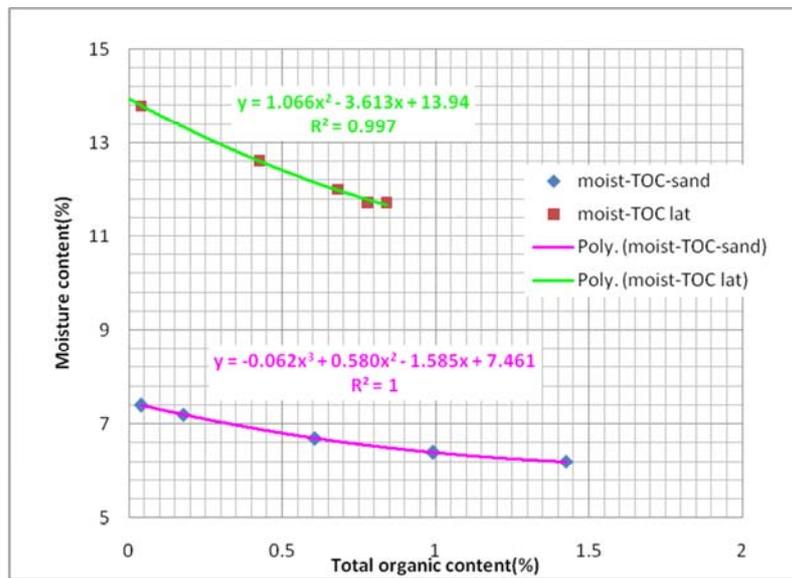


Figure 14. Variation of Moisture Content in the soils with Total Organic Content [TOC].

For the lateritic soil, the effect of increasing biosolids content is the reverse of the effect in the sandy soil. Increasing biosolids content lowered MDD. Correlation between MDD and % biosolids, though high, is not as good as in the sandy soil.

The equation for the trend line in the lateritic soils is as Eqn. (17),

$$y=-5E-05x^3 + 0.001x^2 - 0.002x + 1.728 \quad (17)$$

$$R^2=0.904$$

where:

x=% biosolids

y=permeability (cm/s), and

R=correlation coefficient

3.7.2. Compaction Optimum Moisture Content (OMC)

The compaction Optimum Moisture Contents (OMC) of both the sandy and the lateritic soils are shown in Figures 15 & 16.

Increasing % biosolids treatment in the Sandy soil around

15% caused the OMC to increase. Further increase in % biosolids treatment around and beyond 20% has a lowering effect on OMC.

A polynomial trend-line fitted through the data points models this observation (Eqn. 18).

$$y=-0.000x^3 + 0.001x^2 + 0.080x + 13.03 \quad (18)$$

$$R^2=0.886$$

where:

x=% biosolids

y=optimum moisture content (%) and

R=correlation coefficient

With the Lateritic soil, 5% biosolids treatment caused an initial increase in OMC. Increasing biosolids treatment further up to and around 15% brought about a reduction in OMC of the soil (Figure 16). Further increase in biosolids treatment beyond 20%, caused a reversal of the trend.

Eqn. (19) has been used to describe this situation.

$$y=0.003x^3 - 0.089x^2 + 0.470x + 14.33 \quad (19)$$

$R^2=0.981$

where:

x =% biosolids

y =optimum moisture content (%) and

R =correlation coefficient

A closer look at the MDD and OMC plots in Figures 15 and 16, shows that increasing biosolids content in a sandy

soil will help in achieving higher MDD goals. In the lateritic soil however, increasing biosolids content beyond 15% may impede the achievement of higher MDD goals. In correspondence with the observation made on MDD trends, biosolids treatments beyond 15% may increase the OMC in lateritic soils, whereas the reverse is the case in sandy soils.

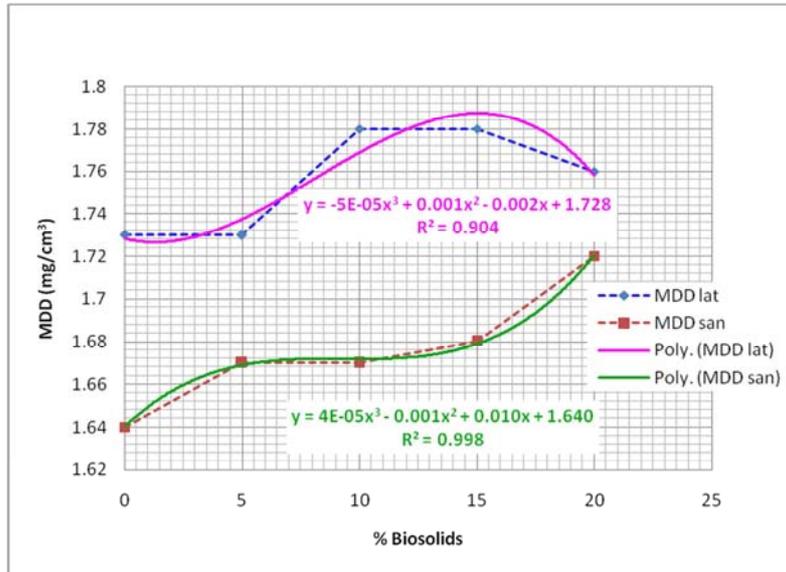


Figure 15. Effect of biosolids on the Maximum Dry Density, MDD of the soils tested.

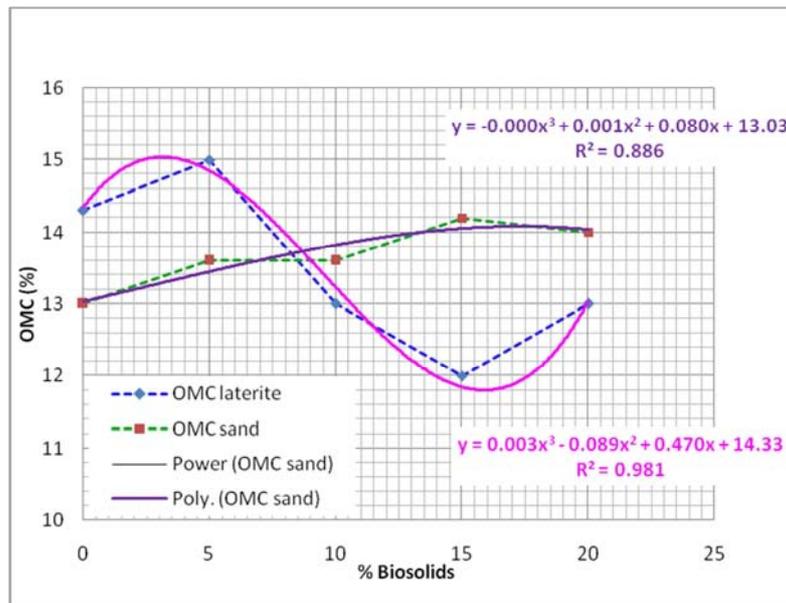


Figure 16. Effect of biosolids treatment on the optimum content, OMC of the soils tested.

3.8. Soil Compressibility

In compressibility of soils, one of the end results of compression is the reduction in the thickness of the soil column in the form of a Coefficient of Volume Change M_v depending on the degree of compression and the type of Soils under consideration, whether Cohesionless soils such as Sandy materials or Cohesive soils such as Lateritic Soils.

(i) Effect of Biosolids on M_v in Sandy Soils

The results of the Coefficient of Volume Change, M_v at the different % of the biosolids-treated Sandy soil under different stress levels are presented and shown in Figure 17. The behaviour of M_v under the different stress ranges, with increasing % biosolids treatment is periodic, though with varying “frequency” and “wavelength”.

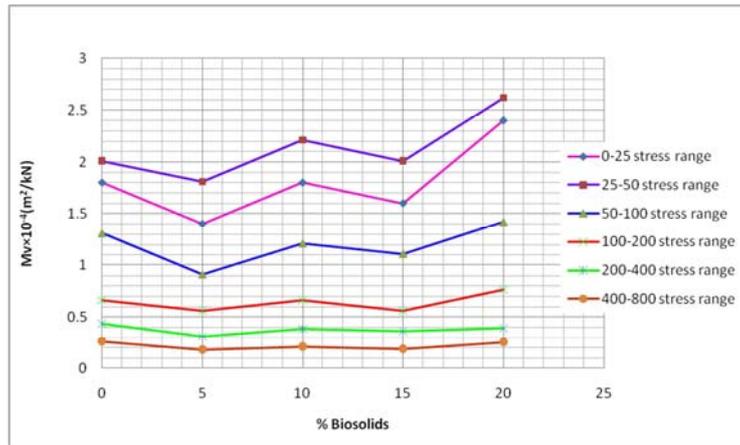


Figure 17. Plot of the Coefficient of Volume change, (M_v) of the Sandy Soil against Biosolids Treatment.

The effect of biosolids treatment at the lower stress (ranges) is more pronounced than at higher stresses (Figure 18). 100 kN could be said to be the critical load under which, high volume reduction is recorded in all cases of biosolids treatment. However, with 20% biosolids in the soil, volume increase expressed as high M_v value is observed.

It is proffered here that the periodic behaviour of M_v under

the different stress ranges was due to the existence of “excess” biosolids. It is also suggested here that the right amount of biosolids should be applied in the soil in order to avoid having excess that would constitute compressibility problem. Under any loading condition, 5% and especially 15% biosolids are recommended.

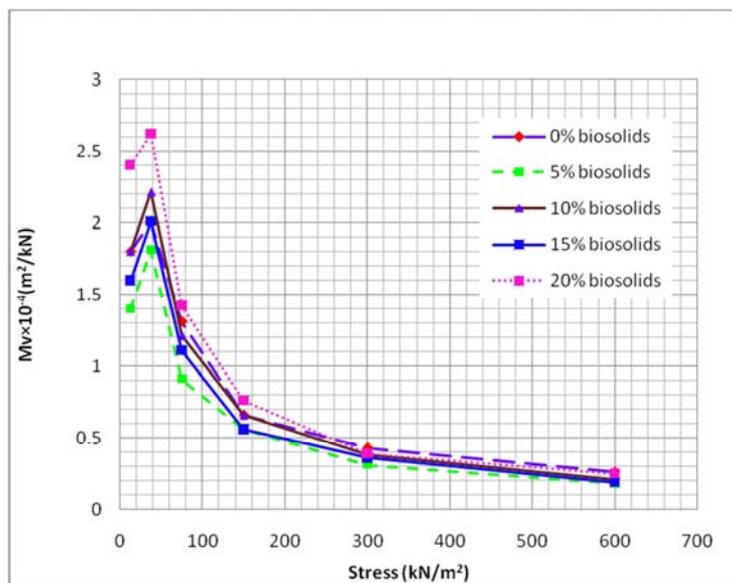


Figure 18. Plot of the coefficient of volume change, M_v of the sandy soil against stress.

(ii) Effect of Stress on Biosolids-treated Sandy Soil

Figure 18 reveals that at all the different levels of biosolids treatment, application of the initial stresses (between 0-50 kN) was accompanied with large amount of volume reduction of the material under test. It is significant that 5% and 15% level of treatment were the least compressible.

The rate of reduction in volume continued to decline steadily to a steady state level.

It is observed that at all the stress levels, the 5% and 15% biosolids treatment continue to experience minimum volume change. It is also observed that 20%, 10%, and 0% biosolids treatment, in that order, experienced higher volume change. These observations could equally be due to excess biosolids

in the mixture as suggested previously.

(iii) Effect of Biosolids on M_v in Lateritic Soil

The results of the Coefficient of Volume Change, M_v of the biosolids-treated lateritic soil under different stress ranges are presented and shown in Figure 19. Compressibility in the lateritic soil can, as in the sandy soil, be divided into two types, based on stress application and on biosolids treatment. Generally, compressibility increased with increase in % biosolids. In the lateritic soil, the periodic behaviour of M_v with increasing % biosolids treatment is not as prominent as in the sandy soil.

At the lower stress (regime) the effect of increasing % biosolids in the soil, produced larger volume changes under the same stress than under high stress regimes (Figure 19). It

is observed that 100 kN is still the critical load under which, high volume reduction takes place. However, with 20% biosolids in the soil, volume increase expressed as high M_v value is observed.

Generally, the lateritic soil undergoes more volume change

than the sandy soil for the same stress applied and % biosolids treatment (Figure 19). This shows that soil type remains the dominant factor in the determination of soil compressibility. The effect of biosolids treatment becomes relevant as a “soil modifier” within the particular soil type.

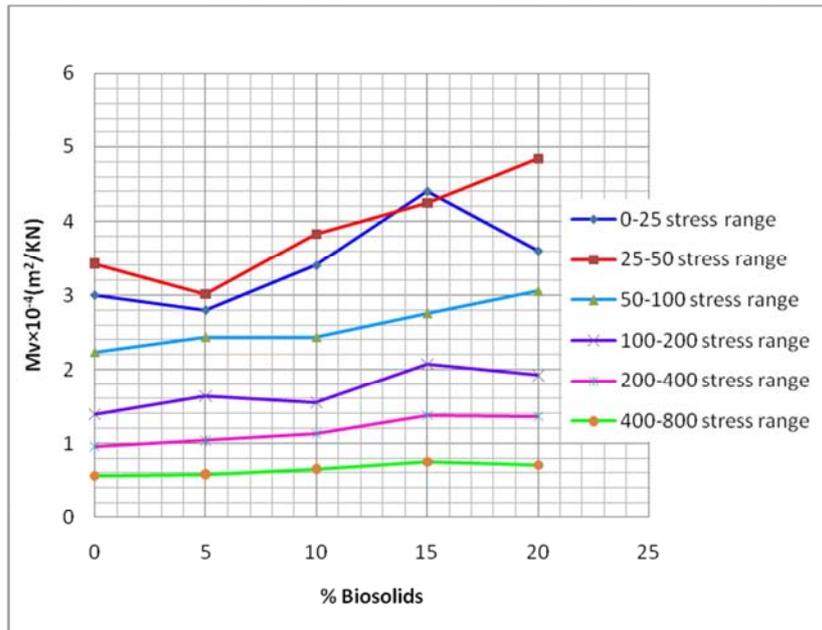


Figure 19. Plot of the coefficient of volume change, M_v , of the lateritic soil against biosolids treatment.

(iv) Effect of Stress on Biosolids-treated Lateritic Soil

The effect of stress on the compressibility of the lateritic soil is presented and shown in Figure 20. It is observed that at the different levels of biosolids treatment, application of the initial stress (between 0-50 kN) is accompanied with large amount of volume reduction of the material under test. As against the situation in the sandy soil, 0% and 5% are the least compressible. Figure 20 further revealed that in the

lateritic soil, % biosolids plays an important role in the determination of the degree of compressibility under any stress level, since the more the % biosolids in the soil, the higher the coefficient of compressibility. 15% and 20% treatments with biosolids are likely to induce large volume changes under any stress application. Appreciable gap exists between 15%-20% and 0% - 10% biosolids treatments as shown on Figure 20.

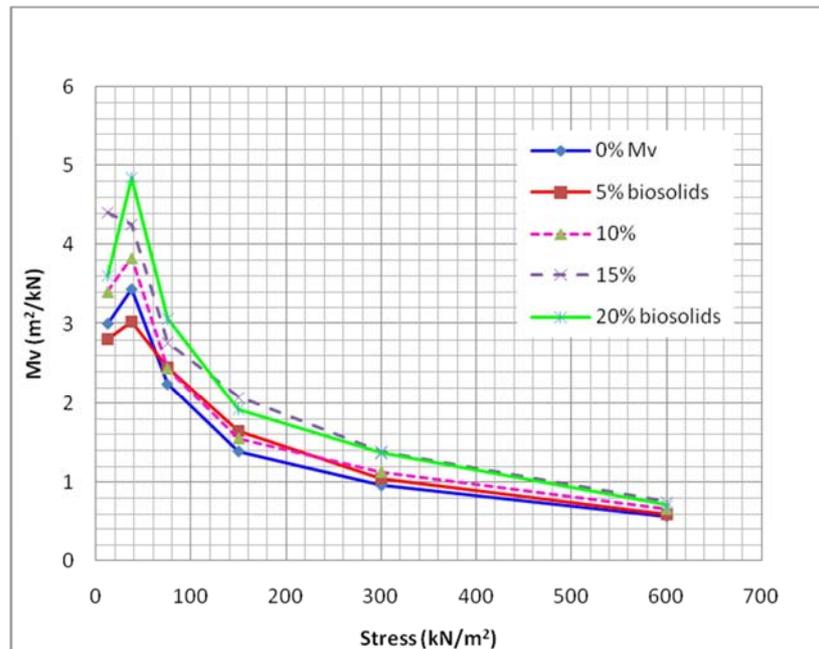


Figure 20. Plot of the Coefficient of Volume Change (M_v) of the lateritic soil against stress.

Based on this observation, it could be said that two possible groups of biosolids-treated lateritic soil are identifiable: the low compressible and the high compressible lateritic soils.

3.8.3. Pollution Indices [PI]

The concept of *Pollution Index* [PI] is the ratio of Polluted to Unpolluted of a particular parameter, ie.,

$$M_v \text{ (polluted)} / M_v \text{ (unpolluted)} = \text{Pollution Index of } M_v = M_v \text{ [PI] Eqn. (24)}$$

Table 1 shows the computed Pollution Indices for M_v at different % of Biosolids pollution of lateritic Soils.

Table 1. Pollution Indices of Coefficient of Volume Compressibility [M_v] at various Stress levels and % Biosolids for tropical Laterites.

Stress Level (kPa)	% Biosolids			
	5%	10%	15%	20%
5.00	0.93	1.13	1.46	1.20
50.00	0.88	1.118	1.24	1.40
100.00	1.10	1.10	1.315	1.44
200.00	1.16	1.16	1.50	1.46
300.00	1.11	1.22	1.47	1.55
400.00	1.125	1.188	1.50	1.50
500.00	1.125	1.13	1.538	1.428
600.00	1.00	1.00	1.33	1.33

4. Discussion

Normally, sands and gravels are Non-Plastic and as such are Cohesionless and very permeable, in most cases. However, the addition of Biosolids to these cohesionless materials makes these hitherto cohesionless materials become cohesive.

Hence the Sands and gravels with Biosolids in this study have been observed to have some cohesion values (c) that have brought about their characteristic behavior patterns that have been observed in Figures 1, 8, 10, 11, 13, 14, 15, 16, 17 and 18. [18-26]. In earlier studies, it was also observed that just like Biosolids, Crude Oil Pollutants within the Nigerian Niger Delta Sub-region were also found to affect the Cohesion and Friction values of both Sandy as well as Lateritic soils [27, 28].

5. Conclusions and Recommendations

This paper has demonstrated the various effects of biosolids pollution on the geotechnical properties of soils from certain parts of the Niger Delta sub-region of Nigeria. The findings from the study indicate the following:-

- a) That biosolids have a complex effect on particle size distribution that is not yet fully understood. *There is a slight aggregation of particle size distribution of soils between 0% to 10% of Biosolids treatment and a sharp increase in aggregation at between 15% and 20% of Biosolids treatment. Thereafter there is a sharp decline in aggregation as typified by the Non-plastic Sandy and lateritic soils tested. This has been shown in Figures 1*

and 2 in this paper.

- b) That generally and in a definite manner, there exist equations that quantify the magnitudes of the effect of application, addition and / or presence of biosolids on the environment viz-a-vis, geotechnical properties of the affected soils. For instance, the Liquid Limits for Lateritic soils at different levels of Biosolids applications range from 35% at 0% application to 26.9% at 20% application with the linear model $y = -0.366x + 34.56$ (Eqn. 1) and Figures 1 and 2.

- c) The relationship between % biosolids treatment and Plastic Limits of Laterite soils is polynomial and expressed in the form shown in Figure 4 and in Eqn. 2 below:

$$y = -0.001x^3 + 0.025x^2 - 0.069x + 14.95 \quad (20)$$

$$R^2 = 0.968$$

where:

y=plasticity limit;

x=percentage biosolids, and

R^2 =correlation coefficient

- d) The relationship between % Biosolids treatment and Plasticity Index (PI)% is:

$$y = 0.776x - 7.781 \quad (21)$$

with a correlation coefficient (R^2)=0.901

- e) The Shear Strength Parameters [c and ϕ] of Polluted Sandy Soils (SP) can best be described using a polynomial equation as in Eqn. (6) and in Figure 8.

$$y = 0.004x^3 - 0.16x^2 + 1.9x - 3 \quad (22)$$

$$R^2 = 1$$

where:

x=% biosolids treatment

y=frictional angle ϕ (deg);

c=cohesion (kN/ m²)

R^2 =correlation coefficient.

In the same way, the relationship between Cohesion and % Biosolids treatment is expressed using the polynomial equation in Eqn. (7) and Figure 8:

$$y = 0.04x^3 - 1.294x^2 + 11.61x + 19.3 \quad (23)$$

where:

x=% biosolids treatment;

y=cohesion, C (kN/m²) and

$R^2 = 1$ =correlation coefficient.

- f) The Shear Strength Parameters [c and ϕ] of Polluted Lateritic Soils (CL) can best be described using a polynomial equation as in Eqn. (8) and in Figure 9.

$$y = 0.007x^3 - 0.207x^2 + 0.985x + 11.46 \quad (24)$$

where:

x=% biosolids treatment

y=frictional angle ϕ (deg);

R^2 =Correlation coefficient=0.955

In the same way, the relationship between Cohesion and %

Biosolids treatment of Polluted can be expressed as:

$$y = -0.005x^3 + 0.133x^2 - 0.589x + 54.95 \quad (25)$$

where:

x=% biosolids treatment;

y=cohesion, C (kN/m²) and

R²=1=correlation coefficient=0.984

g) That for a particular amount of biosolids introduced into the soil, *Total Organic Content (TOC)* determined in the soils differs, with *Lateritic soils* having *higher % of TOC* than *Sandy soils*.

h) The relationship between Biosolids content and the Total Organic Content (TOC) in Sandy Soils is given by the Equation (10) as:

$$y = -0.000x^3 + 0.006x^2 + 0.005x + 0.033 \quad (26)$$

where R²=0.998.

Similarly, the relationship between Biosolids % and Total Organic Content (TOC) in Lateritic Soils is given by the Equation (11) as:

$$y = 6E-05x^3 - 0.004x^2 + 0.098x + 0.036 \quad (27)$$

where R²=0.999

These two scenario are illustrated in Figure 10

i) The relationship between %Biosolids Content in both Lateritic Soils and Sandy Soils and the Soil Moisture Contents shows that:

a. In Lateritic Soils, the Relationship is inversely related with % Biosolids as:

$$y = -0.064x + 7.42 \quad (28)$$

where

R²=0.977, with a limiting Moisture Content at 15% Biosolids content.

b. In Sandy Soils, the Relationship is inversely related with % Biosolids as:

$$y = -0.951x + 5.696 \quad (29)$$

where

R²=0.951, with a limiting Moisture Content at 20% Biosolids content.

In both cases,

x=Moisture Content of the Sandy soil,

y=Moisture Content of the Lateritic Soil

c. Stability favored strength of both sandy and lateritic soils is *between 10% and 20%* application ratios.

j) That there are two factors controlling soil moisture. One is *soil type* and the other is *soil additives such as biosolids*. In the *lateritic soil*, *15% is the limiting value*, whereas it is *20% for the sandy soils*.

k) That soil infiltration rate [or Permeability] has been shown to *be increased with biosolids addition of up to about 13% biosolids*. However, biosolids addition in sandy soils induces a periodic behaviour.

l) In clayey soils, the addition of biosolids will enhance

the soil texture. This is particularly desirable in agriculture and in soil engineering.

- m) That the effect of biosolids treatment of soils depends on the type of soil and increases *Maximum Dry Density (MDD) of Sandy soil*, while the reverse is the case in the *Lateritic soil*.
- n) That the studies also show that increasing % biosolids in the sandy soil increases *Optimum Moisture Content (OMC)*, but beyond 15% biosolids brings about reduction in OMC. However, in the lateritic soils, % biosolids up to and around 15% brings about a reduction in OMC.
- o) That 100 kN/m² stress is the critical stress level under which, high volume reduction is recorded in all cases of biosolids treatment.
- p) That the periodic behaviour of M_v under the different stress ranges was due to the existence of excess biosolids and that at all the stress levels, the 5% and 15% biosolids treatment continue to experience minimum volume change.
- q) That the Coefficient of Compressibility [C_v] in the lateritic soil can, as in the sandy soil, be divided into two types [namely *Low and High*], based on stress application and on biosolids treatment.
- r) That Pollution Indices [PI] exist as a result of biosolids pollutions. These are either *reduction or enhancement factors* on geotechnical engineering properties of soils.

6. Recommendations

This paper recognizes the high potentials of biosolids as soil modifiers, and so recommends them as such. Though Biosolids pollutions are man-made occurrences that should be avoided as much as possible, biosolids in crops production and harvesting, should be encouraged since they will also provide effective ways of disposing of environmental pollutants. They will also prove to be cheap sources of soil modifiers. The effect of clay types on the effectiveness of biosolids as soil modifiers needs to be further investigated in order to:

- (i) Try to identify the type (s) of clays that constitute the Lateritic soil, so as to determine the influence of clay types on the effect of biosolids in the soil.
- (ii) To try to fully understand the *phenomenon of periodicity* as evident in the relationships *between M_v and % biosolids; permeability and % biosolids, and soil gradation (D-indices) and % biosolids*.

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