

Improvement of the Properties of Black Cotton Soils Using “Ionic Soil Stabilizer 2500.”

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This study was carried out to establish the effect of “Ionic Soil Stabilizer 2500” (ISS 2500) on black cotton soil. Samples were collected along Maiduguri–Gamboru Ngala road in North-East Nigeria. Initial results indicated that the black cotton soil is expansive with very high montmorillonite clay mineral content. The ISS stabilizer is 100% organic and is derived from combined organic sulphur and buffered acids that are combined as bi-sulphates. By its chemical composition, it (ISS) has an enormous ionic exchange capacity. The ISS stabilizer dosages of 1ml, 2ml, 3ml were mixed with 6000g weight of black cotton soil and tests were carried out to determine if improvement in properties would occur. For all the tests there were increases in properties to increase in ISS content. However, the plasticity index which was expected to decrease in view of the increases in the redox potential, and the electrical conductivity decreased instead. Also the acidic medium which prevailed increased with an increase in ISS content. Consequently, the CBR values increased marginally but below the specifications for oil-cement stabilization for both sub-base and road base materials. The ISS stabilizer is not effective in improving the properties of marginal black cotton soils to road base standards. Black cotton soils stabilized with ISS could be used as fill and sub-base materials in road construction. An optimum dosage of 1.5ml of ISS dosage could be used to stabilize sub base materials and 1ml of ISS dosage could be used in treating the black cotton soil to make it useful as a fill material in road construction.

Keywords: Black Cotton soil, California Bearing ratio, Chemical stabilizer, Expansive soil, Montmorillonite, Swell-Shrink.

1. INTRODUCTION

The behavior of expansive soils is uncertain when subjected to moisture changes. This present considerable challenges in their utilization for infrastructural development. The strength properties of these soils change according to the amount of water contained in the voids of the soils. The movement of water into and out of the soil voids induce severe swell-

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shrink behaviour causing stress levels which could be injurious to facilities placed on them. Highway facilities in particular stretches over considerable distances traversing diverse soil formations. The chances of encountering expansive soils are therefore high with highway facilities. Expansive soil behaviour is generally attributed to clay soils, and are characterized by excessive compression, dispersive behavior, collapsing behavior, low shear strength, high swell potential, and frost susceptibility (Abdullah and Al-Abadi, 2010). They are therefore not suitable for use without improvement of their properties.

The smectite (clay) group of soils is found in many parts of the world especially in arid and semi-arid parts of the world. In Nigeria they are available in the vast watersheds of the Chad Basin brought about by the accumulation of alluvial deposits over several decades. Due to the seasonal variation in the moisture content engineering infrastructure experience severe stresses which may eventually lead to failure. Road construction over an extensive area of black cotton soil such as that in the Chad basin generally poses operational, maintenance and construction challenges due to the high volume changes, severe cracking when dry, low bearing value when wet, lack of drainage and scarcity of suitable construction materials. Location of projects in this area therefore calls for careful evaluation of material properties to avert premature failure.

One difficulty encountered in the handling of clay soils in construction is the problem of pulverization. They are difficult to work with and stabilization methods inefficient in agglomerating the soil particles and reducing their void moisture content do not achieve substantial improvement in strength properties. Recently, proprietary chemical additives are being marketed in Nigeria as capable of achieving high strength gains in marginal cohesive soils. However, no known tests, field trials or laboratory programs have been carried out to determine the efficacy of these chemical stabilizers in the Nigerian environment. The aim of this paper therefore is to employ "ISS2500" chemical stabilizer to achieve the improvement of the strength of black cotton soil obtained from the failed sections of Maiduguri-Gamboru Ngalahighway in northeast Nigeria. This is with a view to comparing the results with cement stabilized soil mixes. The rest of the paper is organised as follows: The next section reviews the literature in the subject; section 3 presents the materials and methods of the research, while section 4 present details of the results. The discussion and conclusions are taken up in sections 5 and 6 respectively.

2. LITERATURE REVIEW.

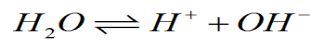
Black cotton soil is an expansive soil which swells or shrinks excessively due to changes in moisture content and has an appreciable plasticity in the clay fraction. It is dark gray to black in colour. Soils with a high content of clay usually over 50 percent, in which montmorillonite is the principal clay mineral are commonly expansive (Ayodele, 1979). The Lake Chad Basin is known to be the only location having extensive lacustrine deposits of black clay soils in Africa (Ola, 1978). Conditions which favour the formation of black cotton soils include evaporation exceeding precipitation, poor leaching, alkaline conditions, retention of magnesium and calcium in the soil. The parent material is basic igneous rocks such as basalt, made up of calcium-rich feldspars and dark minerals which are unsuitable and easily weathered (Balogun, 1985). Black cotton soils are loose or highly compressible, and have unsuitable consistency indices, low strength, and high permeability. These undesirable properties make them unsuitable for use in infrastructural development projects, hence they have to be stabilized. Unsaturated expansive clays are however used for beneficial purposes also. Containment of contaminants is an integral part of environmental protection strategy and unsaturated expansive clays are extensively used for engineered clay barriers and as buffer materials for waste disposal. This application of expansive soils is due to the possession of a remarkable swelling due to water intrusion and therefore restriction of the water and contaminant migration through them (Arya and Yasrobi, 2009).

Stabilization makes it possible for soils to support themselves and other imposed loads. In the case of black cotton soils, stabilization could be achieved by means of chemical additives. This is because pulverization is difficult to achieve with black cotton soils and chemical additives facilitates flocculation making densification possible; the main essence of stabilization. Stabilization of black cotton soils must improve the swell potential for strength gain to be attained. However, swell potential is associated with increased plasticity indices and higher cation exchange capacity (Fateme and Yasrobi, 2010) and (Guney et al., 2007). The cation exchange capacity (CEC) of montmorillonite (black cotton soil) is mainly due to the presence of sodium ions (Na^{+}), Potassium ions (K^{+}), Magnesium ions (Mg^{++}) and Calcium ions (Ca^{++}). This creates additional water affinity for clay soils leading to high swell potential. Hence the lower the CEC the more the strength gain (Zeynal and Resat, 2003). Most studies on montmorillonite clay focuses on the index, physical and chemical properties while strength properties often ignored. This is due to the low strength of clay soils which is increased when the index properties are improved.

Ionic Soil Stabilizer (ISS2500) is a water soluble chemical used in the construction of all types of road utilizing in-situ materials. It is 100% organic and is derived from combined organic sulphur and buffered acids that are combined as bi-sulphates (Road Materials Stabilizers, 1990). Stabilization with ISS2500 improves the physical and mechanical characteristics of marginal soils. Treatment with ISS releases the adsorbed water from the soil particles, minimizing the voids and allowing the particles to be compacted to much greater densities thereby increasing the shear strength and bearing capacity of the layer. The treatment is permanent and the compacted layer has a high density and high load bearing capacity and is unaffected by extreme climatic conditions (Road Material Stabilizers, 1990). ISS2500 could be applied to road base, sub-base and sub-grade materials. The fine particles of the marginal clays and silts, due to their mineralogical composition have an excess of negative ions (anions) and therefore attract positive ions (cations) of water, making this water adhere to them to form pellicular water (Road Material Stabilizers, 1990). ISS2500 has enormous cationic exchange capacity (Alhassan and Chukwuma, 2013). When small quantities of *ISS2500* are added to water, they activate the hydrogen ions (H^{+}) and hydroxyl ions (OH^{-}); ionizing the water which then vigorously exchanges its electrical charges with the soil particles forcing the pellicular water to break its electrochemical bond with the soil particles to become free water which can then drain from the soil through gravity or evaporation.

2.1 Mechanism of ISS Reaction

The water contained in the pores between the soil particles can be partly or entirely removed by seepage, evaporation or water extraction with suitable equipment. This film of water enveloping the particles, which ultimately governs the expansion and shrinkage of colloidal soil constituents, cannot be completely eliminated by purely mechanical methods. However, by means of temperature effects and the addition or removal of water with mechanical pressure, it is possible to vary the amount of water held in this manner. Such variations result to swelling or shrinkage. This provides an ideal point of operation for ISS. The ISS serves as a catalyst to dissociate the water molecules into hydroxyl (OH^{-}) and a hydrogen (H^{+}) ions. The hydroxyl ions in turn dissociates into oxygen and hydrogen, while the hydrogen atom of the hydroxyl is transformed into a hydronium ion as shown in Figure 1 and Figure 2. The latter can in the nascent state, accept or reject positive or negative charges, according to circumstances (Road Material Stabilizers, 1990).



(hydronium)

Fig. 1: Dissociation of ions equation.

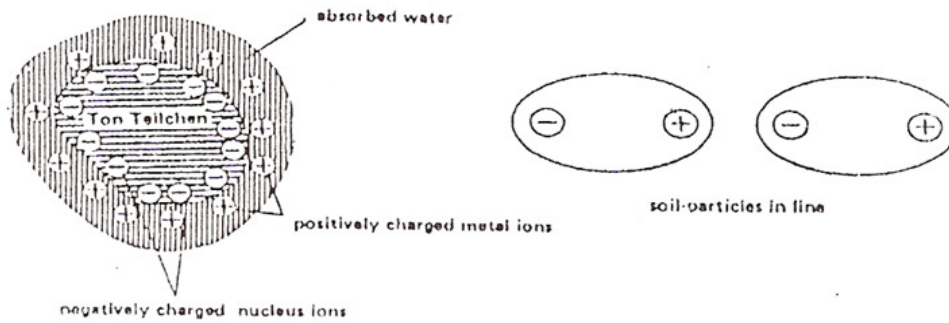


Fig. 2: Dissociation of ions.

Normally, the finest colloidal particles of soil are negatively charged. The enveloping film of absorbed water contains sufficient numbers of positively charged metal ions, such as sodium, potassium, aluminum and magnesium (Cation Exchange Capacity) which ensure charge equalization with respect to the electrically negative soil ion (Road Material Stabilizers, 1990). A soil particle comprising only chemically combined water cannot swell i.e., it cannot alter its structural density. Only the film of absorbed water adhering firmly to the particle surface can expand in volume as a result of further water absorption when the soil is wetted.

This effect is more prominent in fine-grained soils, such as clays. Since this absorbed water is held in a stable form on the clay particles, thickening of this water film will involve a displacement of the centers of the particles toward one another with the overall effect that the volume of the mass of soil increases (see Fig 3.). Therefore, in order to achieve the densest possible packing of the clay particles and to obviate the undesirable swelling and shrinking behaviour of such soil, it is necessary merely to reduce the thickness of the waterfilm (which, has already been pointed out, is held very firmly to the particles) or to break the film. The only possible way to do this economically and permanently is by ion exchange. Because of its electro kinetic properties, the ISS solution acts upon the positive and the negative charges of the soil particles. The effects of this action are threefold:

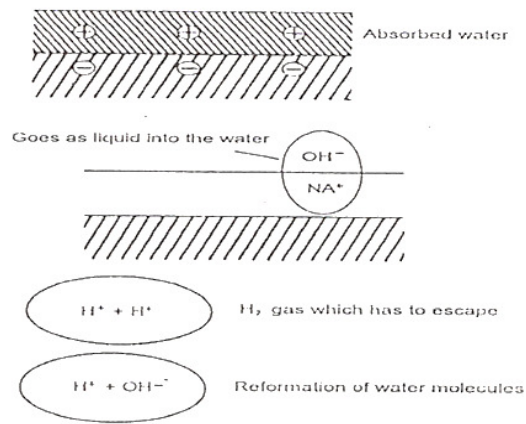


Fig. 3: Film of Absorbed Water Adhering to Soil Particles.

- i. The film of the absorbed water is greatly reduced and in fact entirely broken.
- ii. The soil particles acquire a tendency to agglomerate.
- iii. As a result of the relative movement, the surface area is reduced and less absorbed water can be held, so that this in turn reduces the swelling capacity.

Moreover, these three factors facilitate compaction of the soil or indeed make it in fact possible. In bringing about this phenomenon, the positive charges of the hydronium ion or of the negatively charged hydroxyl ion will normally combine with the positive charge to exert adequate pressure on the positively charged metal ions in the absorbed water film. As a result of this, the existing electrostatic potential barrier is broken. When this reaction occurs, the metal ions migrate into the free water which can be washed out or removed by evaporation. Thus the film of absorbed water enveloping the particles is reduced. The particles thereby lose their swelling capacity and the soil as a whole acquires a friable structure. This is an irreversible process. The hydrogen ions which are liberated in the dissociation of the water molecules can once again react with free hydroxyl ions and form water along the gaseous hydrogen. It is important to note that the moisture content of the soil affects the surface tension and is thus a factor affecting compaction (Road Material Stabilizers, 1990) as shown in Fig.4.

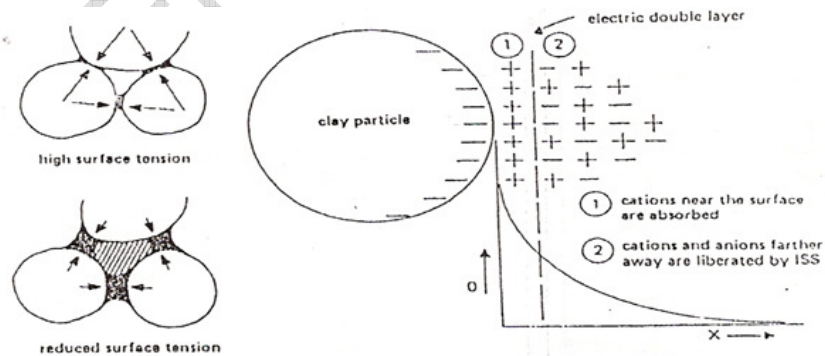


Fig.4: Ions exchange

It should furthermore be pointed out that dry soil is not suited for compaction because of the surface tension of the water contained in it. This is the reason why a certain total quantity of ISS solution is necessary for processing the area of ground in question. This is important, for if less than the total required quantity of solution is applied, its penetration into the ground

will be adversely affected. These two phenomena (gas and water formation and surface tension) can be reduced by an increase in moisture content.

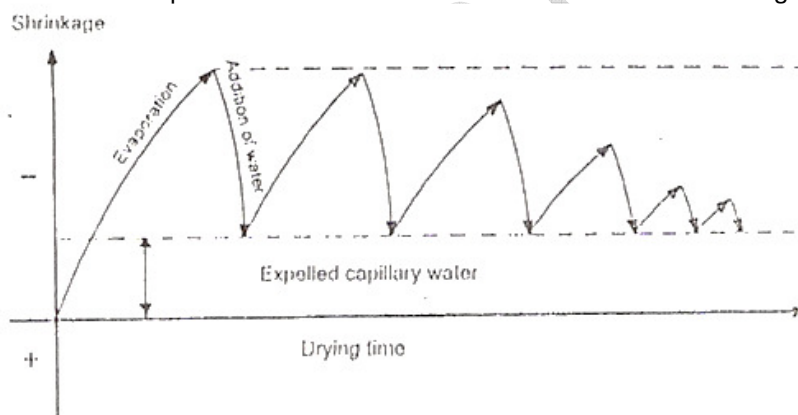
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If the forces involved are reduced as a result of increased moisture content, the ISS solution can penetrate more easily into the capillary structure of the soil and the ion exchange process can take place more rapidly. The water released in consequence can therefore either seep away or be expelled by the kneading action of, for instance, a sheep foot roller and then evaporate at the surface. ISS therefore creates favourable conditions for compaction by changing the zeta potential of the clay and silt particles. The zeta potential (electro kinetic potential) decreases with increasing concentration of the ions of opposite charges from the ISS solution. The cations and anions are liberated from the diffuse double layer, which reduces the swelling properties of the soil. The shrinkage time diagram in Fig.5 clearly shows a kind of sawtooth pattern with the teeth diminishing to zero in the course of time. It thus appears that, when water is added after shrinkage has occurred, the shrinkage decreases to an amount corresponding to the amount of capillary water that has emerged. If the soil is allowed to dry again so that water evaporates from it, the shrinkage that will then occur will never be quite as great as it was previously. This account for the fact that surfaces treated with ISS solution and left uncovered will always increase in stability over a prolonged period of time. The most notable properties of ISS and its effects on the soil therefore are:

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I. Reduction of the dipole moment which has a water repelling effect on the individual soil particles and at the same times reduces the swelling capacity.

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Fig.5: Shrinkage Time Diagram

II. The electro kinetic phenomenon causes the stabilization of the soil particles. As a result, the soil acquires a higher shearing strength and its compatibility is significantly improved. In general, the soil particles align themselves parallel to one another and because of the formation of an electrical cushioning, causes a sliding effect that takes place in the horizontal molecular structure.

III. Broadly speaking a soil of colloidal character can contain a fairly large amount of voids which are filled either with water or with air. During treatment with ISS, these voids must be filled with porewater derived from the static water. Only in this way can ion exchange by higher valency cations take place and dipole moment of the soil particles be reduced.

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When the reaction has occurred, less water can accumulate in the soil than was originally possible. As a result, the swelling capacity is reduced and the internal moisture of the soil is

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reduced. Subsequent additions of water cannot reverse this process and once the latter has been accomplished, the swelling capacity is destroyed and the shearing strength is increased. For the processing solution to function correctly, the minimum requirement is that the soil should have optimum water content. Slightly higher water content will intensify the reaction but on no account must the amount of water in the soil approach the saturation limit, for this will result in the reduction in penetration power and the effectiveness of the process. A further problem that can arise if the soil water content reaches saturation is that the surface of the ground becomes scaled off by the original swelling effect (Road Material Stabilizers,1990).

3 MATERIAL AND METHODS

The disturbed samples were collected from three different locations along Maiduguri–Gamboru Ngala road. The conditions of the road are shown in Fig. 6. The three locations belong to the same Sahel region of Nigeria which is a semi-arid region with long periods of dry weather and short spells of wet weather. These areas lie in the Chad basin that was formed in the late tertiary period of geological history and in which was deposited a series of clays and sands during the Paleocene and Pleistocene periods. The general topography is flat and the vegetation is of the savannah type with considerable tree growth diminishing towards Lake Chad. The soils consist of medium to fine sands, silty fine sands and clays with deposits of coarse to medium sands.

Soil sampling was carried out by removing the topsoil, digging test pits at three locations, between 400mm and 1500mm depth and collecting 12 soil samples from each pit, taking natural moisture content using the speedy tester, properly labeling and conveying to the laboratory for testing.



Fig.6: Condition of Dikwa-Gomboru Road.

3.1 Laboratory Test Program

A laboratory testing program was designed to determine the Geotechnical and physicochemical properties of the soil samples. The physical tests on the samples included basic geotechnical tests such as grain size distribution, soil classification, Atterberg limits, optimum moisture content, maximum dry density, specific gravity and CBR tests, all in conformity with the relevant Nigerian standards FMWH(1997). The tests on the soil samples

included pH, redox potential and electrical conductivity. The pH measurement was performed in accordance with standard test method (ASTMD:4972-95a Method A) using a Hanna bench-top pH meter. The particle charge test for the chemical stabilisers was carried out by introducing low direct current into the chemicals by immersing a cathode and an anode into it. Besides, the chemical content tests on the stabilizers were carried out by tritrimetry, gravimetry (density and weight) or calorimetry methods and the contents were reported mainly in mg/litre of the chemical, following the guidelines and standards for environmental pollution control in Nigeria (FEPA, 1991). The sample preparation processes were all in accordance with the Nigerian standard methods (FMWH., 1997).

3.2 Soil Stabilization Designs

Stabilization design was carried out to determine relative increases in strength achieved by the stabilized soils as the quantity of the proprietary ISS stabilizer was increased. The strength parameter measured is the California Bearing Ratio (CBR), tested after wrapping in a polythene bag and curing for seven (7) days. In carrying out the stabilization designs, pre-determined doses of the chemical were diluted with water to achieve the optimum moisture content. Also 6,000g of each soil sample was required to be compacted to the optimum moisture content (OMC) for the CBR test to be run on them. In determining the range of quantities of chemicals to dose to each 6,000g untreated soil, the claim of the marketers of ISS 2500 was used as a guide. Road Technologies (1990) claim that only 0.04liters of the ISS 2500 was needed to fully stabilize a square meter of soil, 100mm thick. Compaction test was conducted to determine the initial optimum moisture content (OMC) and maximum dry density (MDD) with zero Ionic Soil Stabilizer (ISS) additive. The average OMC obtained from this experiment was used to mix the soil samples with the addition of various quantities of ISS solution, while the MDD results from the preliminary compaction test were used in the determination of ISS dosage. Dosages of 0ml, 1ml, 2ml, and 3ml were used and mix with the samples accordingly. Samples of the soils are shown in Fig. 7.



Fig. 7.: Samples of the Black Cotton Soils



Fig. 8.0: Compaction test in progress

4 RESULTS.

The results of the physico-chemical tests are shown in Table 1.0. The soils are cohesive in nature with over 60% passing the number 200 sieve size. The average natural moisture content of the soil 8.6% suggesting that the soil may have undergone several cycles of shrink-swell. The category of the soil according AASHTO classification is A-7-6[2] indicating that the soil could be lacking in some qualities to be suitable for use as a road building material. The soil in its natural form is basic in pH value and has poor conductivity but has a substantial electrical conductivity.

Table 1.0: Physico-chemical Characteristics of the Soils.

Properties/Samples	SAMPLES			
Stabilizer Content	0%	1%	2%	3%
Description	Dark gray to black clay			
Gravel	0.00	-	-	-
Coarse sand	0.00	-	-	-
Fine sand	35.44	-	-	-
Silt/clay	64.56	-	-	-
Specific Gravity	2.25	-	-	-
Nat. Moisture Content, %	8.60	-	-	-
Optimum Moisture Content, %	12.17	-	-	-
Maximum Dry Density [Mg/m ³]	1.79	1.86	1.80	1.80
Soaked CBR, % (7days)	37.47	41.40	46.77	50.27
% Passing BS sieve No 19mm	100	-	-	-
% Passing BS sieve No 7	100	-	-	-
% Passing BS sieve No 36	100	-	-	-
% Passing BS sieve No200	63.21	-	-	-
Liquid Limit, %	40.62	41.32	44.06	44.37
Plastic Limit, %	23.26	24.62	22.33	24.16
Plasticity Index, %	17.36	16.70	21.73	20.21
Linear Shrinkage	14.30	12.97	12.73	12.63
pH	9.88	5.70	4.48	4.12
Redox Potential	15	115	189	211
Electrical Conductivity	119.30	168.50	367.50	912.00
AASHTO	A-7-6[2]			

The behaviour of the Atterberg parameters with respect to increment in percentage ISS content is shown in Fig. 9 for both liquid limit and plastic limit. In the case of liquid limit there are increases in the liquid limit as the stabilizer content increases. Similarly, the plastic limit increases with increase in stabilizer content except for 3ml stabilizer content at which the plastic liquid drops below the zero stabilizer content. The plasticity index and shrinkage limit changes with an increase in stabilizer content are shown in Fig.10. The plasticity index(PI) variation with an increase in stabilizer content indicate increases in PI with a corresponding increase in stabilizer content, all the increments being higher than the zero stabilizer content. The shrinkage limit decreases as the stabilizer content is increased.

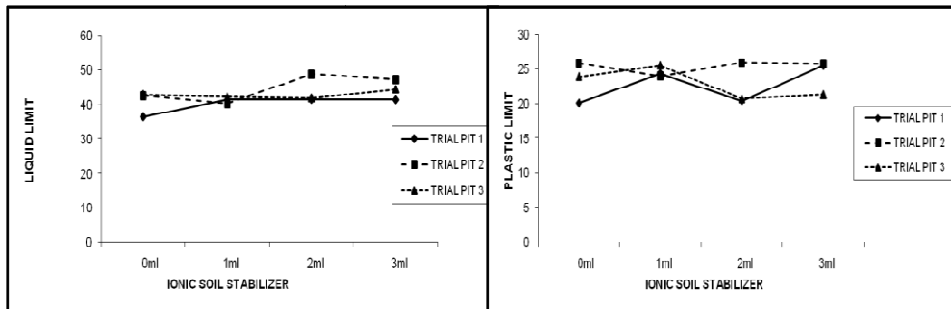


Fig. 9.0: Liquid and Plastic limit Properties with Stabilizer content

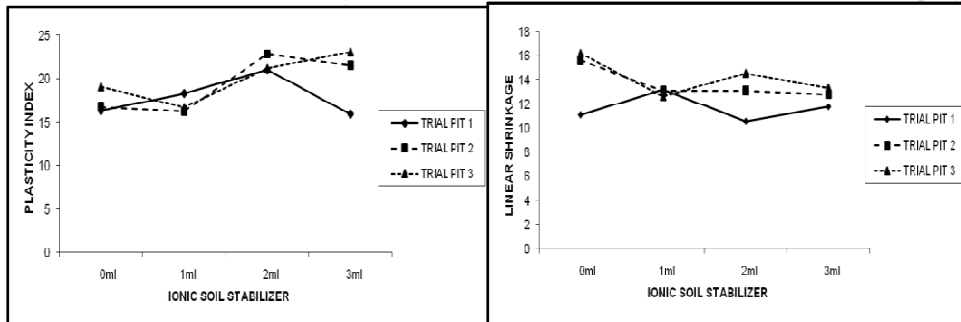


Fig. 10: Plasticity Index and Linear Shrinkage Properties with Stabilizer Content

The pH-value trend with stabilizer content as well as the redox potential of the soil samples are shown in Fig.11. The pH decreased as the stabilizer content increased whereas the reverse is the case for redox potential. This means the samples are becoming easily ionised in acidic medium. It was observed from the pH results that black cotton soil is alkaline in nature (Table 1) with average pH value of 9.88. Soil with a high pH value is deficient in cations (Ele, 1992) and this enhances the water molecules to be held by the soil particles in natural states. The pH value of black cotton soil turns acidic as ISS is added and increases in acidity as the the ISS content is increased.

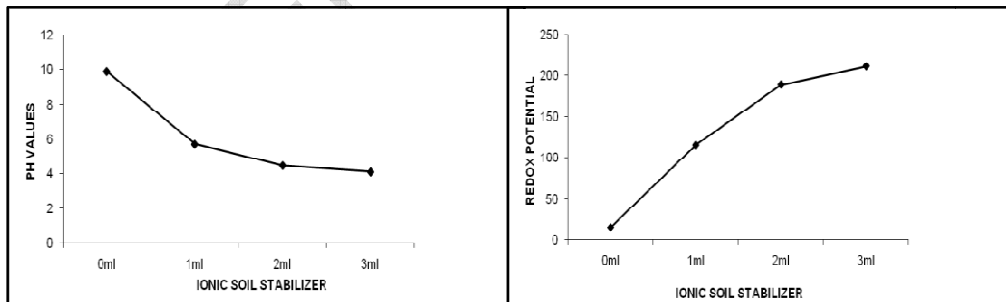


Fig.11: pH-Value and Redox Potential

Electrical Conductivity increases for every addition of ISS as depicted in Fig.12. Electrical conductivity is a measurement of the dissolved materials in an aqueous solution or the measure of the swiftness of movement of electrons. The ISS system of stabilization has to do with ionizing and exchange of electrical charges. The fine particles of black cotton soils due to their mineralogical composition have an excess of negative ions (anions) and therefore attract positive ions (cations) of water, making this water adhere to them to form

pellicle water. But it was observed from the results of the redox potential and electrical conductivity that ISS has an enormous potential ionic exchange capacity Alhassan and Chukwuma (2013). When small quantities of ISS were added to water they activate the ions H^+ and $(OH)^-$ - ionizing the water which then vigorously exchanges its electrical charges with the soil particles as evident in the increment of redox potential and electrical conductivity with the addition of ISS.

The effect of the stabilizer on maximum dry density (MDD) and CBR is shown in Fig.13. The maximum dry density increases suddenly upon addition of ISS stabilizer and decreases gradually to a lower value at 3ml ISS content addition. However, the MDD increment at 3ml ISS content are higher than the corresponding value at zero ISS content. Addition of 1, 2 and 3ml of ISS increased the CBR values by 11%, 25% and 34% respectively. Within the ISS content utilized, none of it was able to achieve 80% CBR which is the specification for base course materials.

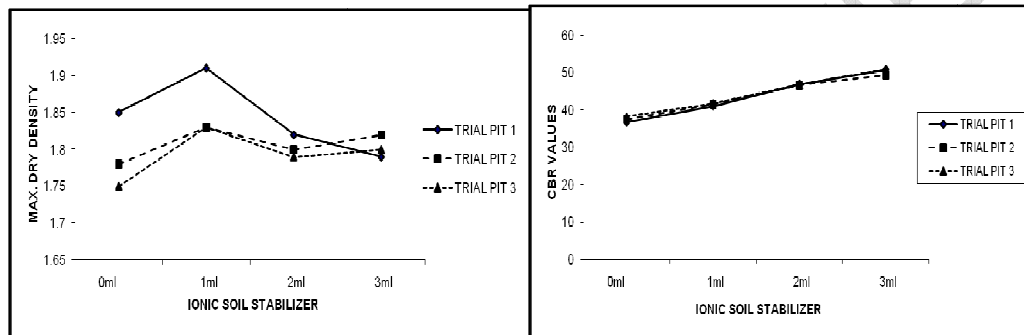


Fig.13: Maximum Dry Density and CBR against ISS Content.

5.0 DISCUSSION

The results of the tests clearly indicate that the black cotton soil is a marginal soil; lacking in some properties to make it useful in for direct use in road construction. The ISS stabilizer improves the Atterberg properties of black cotton soil as well as the MDD and CBR. For any clay material to be improved, there must be decreases in the liquid limit or plasticity index, and must have a high cation exchange capacity. Previous studies by Alhassan and Chukwuma (2013) at the same location clearly indicate that the black cotton soil is dominated by the smectite group especially montmorillonite and has a high cation exchange capacity rich in Sodium, Potassium, Magnesium and Calcium ions. The increase in the redox potential and the electrical conductivity with an increase in ISS content shows that ionisation is enhanced but does not translate into a consistent reduction in plasticity index. This means that the pellicle water is not sufficiently removed or has not had sufficient time to evaporate. Hence the erratic behaviour of the plasticity index as the ISS content increases.

The initial reaction of MDD to the addition of ISS is to cause a sudden increase in MDD. However, further additions of ISS only marginally increase the MDD above the zero ISS content MDD value. In one particular sample the MDD at 3ml ISS content was lower than the MDD at zero ISS content. The CBR performance with ISS content is consistently higher at higher ISS content. However, all the values are below the specification required for use of the material as road base material. Furthermore, improvement of the black cotton soil obtainable with respect ISS stabilizer is below the requirement for soil-cement stabilization in accordance with the Nigerian general specifications for roads and bridges.

6. CONCLUSIONS

The ISS stabilizer mixed with black cotton soil turns the alkaline soil into an acidic medium thereby increases the chances of ionization of the water in the voids of the soils and enhances the cation exchange with cations contained in the soil.

The improvement of the properties of the black cotton soil falls below the specifications required of a material for road base construction. CBR increased by 9.5% for 1ml ISS content, by 24.8% for 2ml ISS content and by 34.2 with the addition of ISS dosage of 3ml. The CBR at zero ISS content was 37.7%. The plasticity index at zero ISS content was 17.36% and increased to 20.21% at 3ml ISS content.

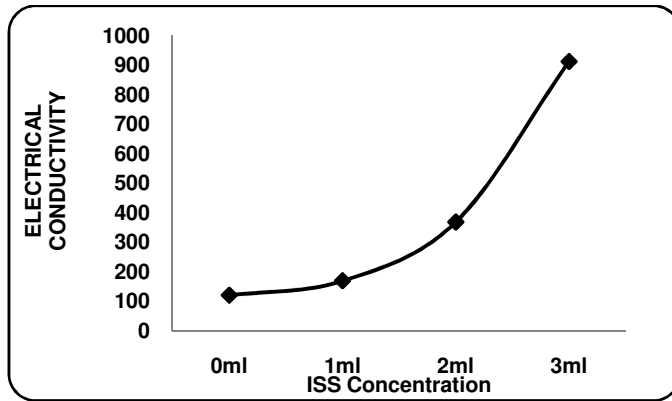
Both the increases in redox potential and electrical conductivity recorded was expected to cause greater ionization and cation exchange capacity but did not translate into consistent increased of the properties of the black cotton soil.

Stabilized black cotton soil with ISS could be used for fill and subbase materials in road construction. An optimum dosage of 1.5ml of ISS dosage could be used to stabilize the sub base material. 1ml of ISS dosage could be used in treating the black cotton soil to make it useful for fill materials in road construction.

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435 Fig.12: Electrical Conductivity against ISS Content.
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