STABILIZATION OF BLACK COTTON SOIL WITH LIME- IRON ORE TAILING BLEND

BY

ROLAND KUFRE ETIM

DEPARTMENT OF CIVIL ENGINEERING

AHMADU BELLO UNIVERSITY, ZARIA

NIGERIA

JUNE 2015

STABILIZATION OF BLACK COTTON SOIL WITH LIME- IRON ORE TAILING BLEND

BY

ROLAND KUFRE ETIM, B.ENG (FUTO) 2010

M.SC/ENG/585/2011-2012

A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES
AHMADU BELLO UNIVERSITY, ZARIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF

OF

MASTER OF SCIENCE DEGREE IN CIVIL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

JUNE, 2015.

DECLARATION

I hereby declare that this thesis titled “**Stabilization of Black Cotton Soil with Lime-Iron Ore Tailing Blend**” was carried out by me in the Department of Civil Engineering, Ahmadu Bello University, Zaria, under the supervision of Professor K. J. Osinubi and Dr. A.O. Eberemu. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

ROLAND KUFRE ETIM	________________	________________
(MSC/ENG/585/2011-2012)	Signature	Date

CERTIFICATION

The thesis titled **Stabilization of Black Cotton Soil with Lime - Iron Ore Tailing Blend** by **Roland Kufre Etim** meets the regulations governing the award of the degree of Master of Science of the Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

Prof. K. J. Osinubi ____________ ____________
Chairman, Supervisory Committee Signature Date

Dr. A. O. Eberemu ____________ ____________
Member, Supervisory Committee Signature Date

Dr. Y. D. Amartey ____________ ____________
Head of Department Signature Date

Prof. A. Z. Hassan ____________ ____________
Dean, School of Postgraduate Studies Signature Date

DEDICATION

This research work is dedicated to God Almighty and to the entire family of MWO G. E. Etim (rtd).

ACKNOWLEDGEMENTS

I acknowledge God Almighty for all His infinite mercies and His grace over my life; to Him is the glory and honour forevermore.

My gratitude goes to my supervisor, Engr. Prof. K. J. Osinubi for all his support, encouragement and guidance throughout the period of my programme. May God reward you abundantly. I am grateful to Dr. A. O. Eberemu. May God bless you for your time, kindness and encouragement throughout this research work. To the Head of Department and the entire members of staff, especially, Dr. T. S. Ijimdiya and Engr. J. Ochepo, I say a big thank you for your understanding and love.

I sincerely say a very big thank you to my dad and mum for their supports and understanding over the years, may the Lord reward you. To my brothers Nathaniel, Cyril and Williams, I love you all and to my late brother, Collins Etim, may your soul rest in peace. To my sisters Evelyn and Blessing, I love you all. To my friends, Mr. I. B. Anweting, Engr. Kenneth Andem, LT. Anwe, Mr. Micheal Isang and Idaresit Akpan, I appreciate you all for the love and support. To my cousins, nephews, niece and In-laws, I appreciate you all and to all members of Charismatic Renewal Mission Glory Centre Zaria and all lay readers of St. Martins De Porres Catholic Church, Nigeria Defense Academy, I love you all.

To the family of Engr. Mrs. A. R. Osim, a very big thank you and the memory will ever remain. To the families of Dr. G. Moses, and Dr.F.O.P Oriola and staff of Civil Engineering Department, Nigeria Defense Academy, I appreciate you all. To my colleagues you are all blessed.

ABSTRACT

A black cotton soil collected from Deba Local Government Area of Gombe state classified as A-7-6 (25) or CH in AASHTO and Unified Soil Classification System (USCS), respectively. It was treated with lime – iron ore tailing (IOT) blend in stepped concentration of 0, 2, 4, 6 and 8 % lime as well as 0, 2, 4, 6, 8, and 10 % IOT by dry weight of soil. Compaction was carried out using three energy levels namely, the British Standard light (BSL), West African Standard (WAS) and the British Standard heavy (BSH). Index, compaction, strength and durability tests as well as microanalysis of the natural and optimally stabilized specimens cured for 7 and 28 days were carried out. Liquid limit and plastic limit values decreased from 56.8 and 29.2 % for the natural black cotton soil to minimum values of 43.8 % at 8 % lime / 6 % IOT and 18 % at 8 % lime / 8 % IOT treatments, respectively. Plasticity index value decreased from 27.6 % for the natural soil to 24.3 % at 6 % lime / 10 % IOT treatment. The 7-day unconfined compressive strength (UCS) of the natural soil increased from 107.24, 326.25 and 408.35 kN/m^2 for BSL, WAS and BSH compactions to 1074.54, 1569.02 and 1688.76 kN/m^2 , respectively, for 8 % lime/ 8 % IOT treatment. The recorded UCS values of the treated specimens met the 1034.25 kN/m^2 criterion normally utilized/specified for adequate lime stabilization. The California bearing ratio (CBR) values (unsoaked condition) increased from 3, 4 and 8 % for the natural soil compacted with BSL, WAS and BSH energies, respectively, to 52, 79 and 88 %, respectively, when treated with 8 % lime/8 % IOT blend. For the 24-hour soaked condition the CBR values for BSL, WAS and BSH compactive effort recorded peak values of 41, 61 and 69 %, respectively, for 8 % lime/8 % IOT treatment. Only 67 % resistance to loss in strength (33 % loss in strength) at 8 % lime/6 %

IOT with BSH is close to the limiting value of 80 % resistance to loss in strength based on 4 days soaking. The 8 % lime/6 % IOT treatment of the soil can be used, at BSH compaction, for sub-base material because the soil was subjected to a harsher condition (of 7 days soaking).The scanning electron microscopy revealed that crystalline hydration products presumed to majorly contribute to strength gain were present in the optimally treated soil-lime-IOT mixture. The two-way statistical analysis of variance (ANOVA) without replication showed that the lime-IOT blend significantly improved properties of the soil.

TABLE OF CONTENTS

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: LITERATURE REVIEW

CHAPTER THREE: MATERIALS AND METHODS

CHAPTER FOUR: DISCUSSION OF RESULTS

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER ONE

INTRODUCTION

1.1 Preamble

Expansive soils are problematic and normally encountered in foundation engineering designs for highways, embankment, retaining walls backfills, etc. These soils are found in arid and semi arid regions of the tropical/temperate zones marked with dry and wet seasons; and with low rainfall, poor drainage and exceedingly great heat. The climatic condition is such that the annual evaporation exceeds precipitation (Chen, 1988; Nelson and Miller, 1992; Warren and Kirby, 2004). Expansive soils found in extensive deposits in the North Eastern part of Nigeria referred to as black cotton soils are characteristically dark grey to black soil with high content of clay, usually over 50 % in which montmorillonite is the principal clay mineral (Morin, 1971).

Black cotton soils are produced from the break-down of basic igneous rocks where seasonal variation of weather is extreme. The Nigerian black cotton soils are formed from the weathering of shaly and clayey sediments and basaltic rocks. They contain more of montmorillonite with subsequent manifestation of swell properties and expansive tendencies (Ola, 1983).

Expansive soils (also known as black cotton soil) is characterised by excessive volume changes and low bearing capacities when wet (Chen, 1988; Nelson and Miller, 1992; Warren and Kirby, 2004). These soils have high clay contents and are prone to expansion when wet and cracking or shrinkage when dry. Deposits of black cotton soil in the field show a general pattern of cracks during the dry season of the year. Cracks measuring 70 mm wide and over 1 m deep have been observed and may extend up to 3 m or more in case of high deposits (Adeniji, 1991). Therefore, in order to arrest the problems posed by deficient soils, it became necessary to improve their engineering properties by stabilization with chemicals. Various researchers (Ola, 1983; Balogun; 1991; Osinubi, 1995, 2006) have attempted to stabilize this soil.

Although poor and undesirable for engineering purposes, the properties of black cotton soil could be improved to meet standard specification by modification/stabilization processes. Stabilization of the soil with chemical additives is a common method of reducing the swell – shrink tendencies of the soil and also makes the soil less plastic (Ola, 1983; Balogun, 1991; Osinubi, 1995; 1999). Cement is one of the most effective in reducing the swelling properties of these soils (Osinubi et al., 2011).

Lime is an additive which has been recognized to bring several beneficial changes in the engineering properties of fine-grained soils. Calcium oxide (CaO), commonly known as quicklime, is a widely used chemical compound. It is a white, caustic and alkaline crystalline solid at room temperature. As a commercial product, lime often also contains magnesium oxide, silicon oxide and smaller amounts of aluminium oxide and iron oxide. Lime in the form of quicklime (calcium oxide – CaO), hydrated lime (calcium hydroxide – $Ca(OH)_2$), or lime slurry can be used to treat soils. Quicklime is manufactured by chemically transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide. Hydrated lime is created when quicklime chemically reacts with water. It is hydrated lime that reacts with clay particles and permanently transforms them into a strong cementitious matrix. Most lime used for soil treatment is “high calcium” lime, which contains no more than 5 percent magnesium oxide or hydroxide. Lime, either alone or in combination with other materials, can be used to treat a range of soil types. The mineralogical properties of the soils will determine their degree of reactivity with lime and the ultimate strength that the stabilized layers will develop. Lime has a number of effects when added into soil which can be generally categorized as soil drying, soil modification, and soil stabilization (Bhuyan, 2010).

Iron ore tailing is an industrial by-product of the mining of Iron ores. This waste product is produced in large quantities in many part of the world, Nigeria inclusive. The Itakpe iron ore deposit has a reserve of about 182.5 to 200 million tonnes with an average iron ore content of 36% (Soframine 1987, Adepoju and Olaleye 2001). Large quantities of tailings are obtained as waste product of the beneficiated iron ore (Ajaka 2009, Adepoju and Olaleye 2001). This tailing is often dumped around the industries concerned where they form “molehills” and consequently leaches residual chemical into the environment thereby causing pollutions and contamination of the surrounding environment. This study matches the compelling need for safe disposal of this environmentally debilitating waste material for the society, and the engineer’s need for better and cost effective construction materials (Collins and Ciesiellski, 1993).

1.2 Statement of the Problem

Expansive soils occupy about 3 % of the world land area, mainly found in Africa, Asia, Australia, and West Indies and in vast areas of Russia (Klinkenberg and Higgins, 1972). In Nigeria this soil covers an area of some 104,000 km^2 in the Northern eastern fringe (Ola. 1983) of the country including major roads linking the country with neighbouring West African countries like Niger, Chad Republic and Cameroun. When the roads are not motorable, this poses a danger to the economy of the region.

The rapid growth in development has resulted in demand for stronger and more durable roads and buildings all over the world. Consequently, engineers are forced to be more careful in the utilization of construction materials. A number of factors such as increase in construction volume, more severe loading conditions and growing shortage of suitable materials as well as poor site conditions and high cost of additives (cement, lime, etc) have greatly increased the need for modification and stabilization of soils using agricultural and industrial waste. The modification/stabilization of soils is recognized by engineers as an important process of improving the performance of problematic soils and makes marginal soils perform better as civil engineering materials (Amadi, 2010). But the over dependence on the use of industrially manufactured soil improving additives (cement, lime etc), have kept the cost of construction of stabilized road financially high. This has continued to deter the underdeveloped and poor nations of the world from providing accessible roads for their rural dwellers constituting a higher percentage of their population of which mostly depend on agriculture.

The effort by researchers (Mohammedbhai and Baguant, 1990; Osinubi, 1995; 1998a, 1999; 2000a, b; Cokca, 2001; Medjo and Riskowski, 2004; Stephen, 2006; Moses, 2006; Akinmade, 2008; Ochepo, 2008) to obtain cheaper additives which can be used to substitute these expensive industrially manufactured soil improving additives (cement, lime, bitumen, etc.) led to the consideration of agricultural waste resources such as rice husk ash (RHA), bagasse ash (BA) and locust bean waste ash (LBWA). Thus, the use of cheap admixtures to replace or supplement cement or lime stabilized soils especially wastes from agricultural or industrial products will ultimately reduce the cost of construction works where expansive soils are found. This study matches the need for safe and environmental disposal of waste, for the society, and the engineer’s need for better and cost effective construction materials (Collins and Ciesiellski, 1993; Phanikumar and Sharma 2004; Malhotra and Mehta 1996; Cokca 2001).

The Itakpe iron ore deposit in Nigeria which has a total estimated reserve of about 182.5 million metric tonnes consists mainly of quartzite with magnetite and hematite Soframine (1987). The deposit has been developed to supply iron ore concentrates to Ajaokuta steel plant and the Delta steel plant, Aladja, in Nigeria. Itakpe iron ore processing plant produces a waste material of about 64 % of its capacity (Ajaka, 2009).

The Itakpe iron ore deposit has a reserve of about 200 million tonnes with an average iron ore content of 36 %. This has to be beneficiated at a rate of 8 million tons per year to produce 64 % Fe concentrate as sinter material for the Ajaokuta blast furnace and 68% Fe concentrate as pellet feed for the direct reduction plant at Aladja, all in Nigeria. At this production rate, large quantities of tailings are obtained as waste product of the beneficiated iron ore (Adepoju and Olaleye, 2001). This tailing is often dumped around the industries concerned where they form “molehills” and consequently leaches residual chemical into the environment thereby causing pollutions and contamination of the surrounding environment. Protection of environment from debilitating industrial waste is a major concern to stakeholders in the sector especially with the increasing rate of mining activities all over the world Nigeria inclusive.

1.3 Justification for the Study

Stabilization is one of the effective methods to improve the engineering properties of soils. Researches have been carried out on black cotton soil using stabilizers such as lime, cement and bitumen to improve the strength properties in the past (Ola, 1983; Bairwa et al., 2013). Conventionally, lime, Portland cement and bitumen have been used to appreciably improve the index properties of most soils to make them meet the requirement of construction works. The efficacy of lime and Portland cement stabilization of problem soils have been highlighted by researchers (Ola 1978; Umar and Osinubi, 2003; Umar and Elinwa, 2005; Matawal and Tomarin, 1996) and hydrated lime and quicklime have been found to be the most effective agents in reducing the swelling properties of expansive soils.

The cost of incorporating these additives is high and to reduce cost of construction of stabilized roads, a practical alternative is to mix the lime-soil blend with requisite quantity of a pozzolanic admixture such as iron ore tailing (IOT). Interest in the use of IOT is principally for its disposal problem. Therefore to reduce the amount of lime to be used, there is need to assess the effect of IOT on lime stabilized soil.

Mine tailings is an industrial by-product which is produced in huge quantity from mining industries after extraction of minerals from pyritic ores and poses grave disposal problems. It also creates environmental hazard. In recent years there is an increase in trend to utilize the mine tailings for geotechnical applications, provided they are treated with some admixtures (Ramesh *et al.,* 2012). Mine tailings can be effectively utilized for civil engineering constructions which will minimize the disposal problems and reduce the environmental hazards [Pebble Project, 2005].

Preliminary study on the improvement of black cotton soil with iron ore tailing has shown that it can only be used as an admixture with lime or cement. Therefore, improvement of the properties of black cotton soil with iron ore tailings admixed with lime and the determination of the optimum quantity to be used, if found economical and suitable, will provide a lot of road making material. Also the environment problems associated with the waste will be minimized. Ishola (2014) and Samadou (2014) reported that iron ore tailing can only be used as an admixture for modification and stabilization with either lime or cement respectively. Therefore, the potential of the use of the waste as admixture in lime stabilization of black cotton soil was the focus of the study. Thus the dual purpose of soil improvement and safe disposal of industrial waste can be achieved.

1.4 Aim and Objectives

The study was aimed at the evaluation of the properties of black cotton soil when stabilized with lime – iron ore tailing (IOT) blend.

The specific objectives of the study include:

i. Determination of the properties of the natural and treated black cotton soils

ii. Evaluation of the effect of IOT (0, 2, 4, 6, 8 and 10 % by dry weight of the soil) on the index and strength properties of black cotton soil stabilized with lime (0, 2, 4, 6, and 8 % by dry weight of the soil) using three compactive efforts (British Standard light BSL, West African Standard, WAS and British Standard heavy, BSH).

iii. Determination of cation exchange capacity of the treated soil

iv. Determination of strength characteristics (unconfined compressive strength, UCS and California bearing ratio, CBR under soaked and unsoaked conditions) of black cotton soil-lime-IOT mixtures

v. Determination of durability of the treated soil by immersion in water..

vi. Determination of the optimum blend of lime and IOT needed for the stabilization of black cotton soil.

vi.i Microanalysis of optimally treated black cotton soil samples using scanning electron microscope.

viii. Statistical analysis of tests results using two – way analysis of variance (ANOVA).

ix. Batch equilibrium study of the leaching potential of iron ore stabilized soil on the environment.

1.5 Scope of the Research

The research was limited to determining the engineering properties of stabilized black cotton soil when used as highway pavement material Compaction test was carried out using the energies of British Standard light (BSL), West African Standard (WAS) or ‘Intermediate’ and British Standard heavy (BSH). All tests were carried out in accordance with BS 1924(1990) and BS 1377(1990).

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil Stabilization

Soil stabilization is aimed at the enhancement of the engineering properties of deficient soils to enable them perform and sustain their intended engineering use (Yoder and Witczak, 1975; Gillott, 1987; Osinubi, 1995; Nicholas and Lester, 1999; Sherwood, 1993). Its objectives are: improvement of the strength of the soil and bearing capacity, decreasing permeability and water absorption, and to increasing the durability under varying moisture content.

The simplest stabilization processes are compaction and drainage (if water drains out of wet soil it becomes stronger). The other process is by improving gradation of particle size and further improvement can be achieved by adding binders to the weak soils (Rogers and Glendinning, 1996). Soil stabilization is the process that involves the improvement of the engineering properties of soil to make it stable. It can be done by the use of controlled compaction, proportioning and the addition of suitable different types of admixtures and stabilizers (Bairwa *et al.*, 2013). Soil stabilization can be accomplished by several methods.

Through soil stabilization, unbound materials can be stabilized with cementitious materials (cement, lime, fly ash, bitumen or combination of these). The stabilized soil materials have a higher strength, lower permeability and lower compressibility than the native soil (Keller Inc., 2011). The method can be achieved in two ways, namely; (1) in situ stabilization and (2) ex-situ stabilization. Stabilization is not necessary a magic wand by which every soil properties can be improved for better (Ingles and Metcalf, 1972). The chief properties of soil which are of interest to engineers are volume stability, strength, compressibility, permeability and durability (Ingles and Metcalf, 1972; Sherwood, 1993; EuroSoilStab, 2002). For a successful stabilization, laboratory tests followed by field tests may be required in order to determine the engineering and environmental properties. Laboratory tests although may produce higher strength than corresponding material from the field, but will help to assess the effectiveness of stabilized materials in the field. Results from the laboratory tests, will enhance the knowledge on the choice of binders and amounts (EuroSoilStab, 2002).

2.1.1 Mechanical stabilization

Under this category, soil stabilization can be achieved through physical process by altering the physical nature of native soil particles by either induced vibration or compaction or by incorporating other physical properties such as barriers and nailing. Mechanical stabilization by compaction means is the densification of the soil by the application of mechanical energy. It involves the modification of the water content as well as the gradation of the soil. The objective of mechanical compaction is the improvement of the engineering properties of the soil mass, and the several advantages which are obtained through compaction are as follows (O' Flaherty, 1988):

I. Reduction in settlement due to reduced void ratio

ii. Increase in soil strength

iii. Reduction in shrinkage.

2.1.2 Chemical stabilization

Under this category, soil stabilization depends mainly on chemical reactions between stabilizer (cementitious material) and soil minerals to achieve the desired effect. Generally, the addition of organic (bitumen) or inorganic (cement or lime) chemical compounds, to expansive soils increase the strength, bearing capacity and durability of the soil. These organic or inorganic chemical compounds perform cementations and bonding agents or water proofers/repellants (Slate and Johnson, 1953; Osinubi, 1997a, b).

Organic compounds including resinous and bituminuous materials act as water proofers and sometimes behave similar to glue. These water-proofing agents reduce the capacity for water intake and help the soil to retain its dry strength, even under wet condition (Bowles, 1979; O'Flaherty, 1988)

Inorganic agents employed for soil stabilization, include Portland cement, lime, slag, sodium silicate, etc. Their functions are to reduce plasticity and facilitate densification (Balogun, 1991). The transformation of soil index properties by adding chemicals such as cement, cement kiln dust, fly ash, lime, or a combination of these, often alters the physical and chemical properties of the soil including the cementation of the soil particles. There are two primary mechanisms by which chemicals alter the soil into a stable subgrade (Production Division Office of Geotechnical Engineering, PDOGE 2008):

i. Increase in particle size by cementation, internal friction among the agglomerates, greater shear strength, reduction in the plasticity index, and reduced shrink/swell potential.

ii. Absorption and chemical binding of moisture that will facilitate compaction.

2.1.2.1 Lime stabilization: Chemical modification by adding lime and lime-pozzolana mixes has been practiced for the last two decades (Ramana *et al.*, 1986). The use of lime for stabilization dates back to early times. Its principal use is in highway construction and maintenance, airfields construction, building foundation, rail round beds and under hydraulic conditions where the soil is partly or wholly submerged (e.g. irrigation canals, reservoirs, levees and dams) (Sani, 2012)

Lime stabilization may refer to pozzolanic reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds (Sherwood, 1993, EuroSoilStab, 2002). The effect can be brought by either quicklime, CaO or hydrated lime, Ca $(OH)_2$. Slurry lime also can be used in dry soils conditions where water may be required to achieve effective compaction (Hicks, 2002).

There are two phases of stabilization in a lime-soil system. The first, one is an immediate reaction of cation exchange; the second is flocculation agglomeration. The second one occurs to some extent with all fine-grained soils; due to textural changes caused by these reactions the soils are improved. These improvements are reflected in improved workability, immediate strength improvement and reduce swell susceptibility (Ramadas *et al*., 2011).

When lime is mixed with clayey material in the presence of water, several chemical reactions take place. They include cation exchange, flocculation-agglomeration, pozzolanic reaction, and carbonation (Mallela *et al*., 2004). Cation exchange and flocculation-agglomeration are the primary reactions, which take place immediately after mixing. During these reactions, the monovalent cations that are generally associated with clay minerals are replaced by the divalent calcium ions. These reactions contribute to immediate changes in plasticity index, workability, and strength gain.

Pozzolanic reaction occurs between lime and, the silica and alumina of the clay mineral and produces cementing material including calcium-silicate-hydrates and calcium alumina hydrates. The basic pozzolanic reactions are as follow:

$$Ca(OH)_2 + SiO_2 \rightarrow CaO\text{-}SiO_2\text{-}H_2O \quad (2.1)$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow CaO\text{-} Al_2O_3\text{-}H_2O \quad (2.2)$$

Pozzolanic reactions are time and temperature dependent and may continue for a long period of time. Addition of lime to soil increases its pH; studies have shown that when the pH of the soil increases to 12.4, which is the pH of saturated limewater, the solubility of silica and alumina increase significantly. Therefore, as long as sufficient calcium from the lime remains in the mixture and the pH remains at least 12.4, pozzolanic reaction will continue. In some instances, lime reacts with carbon dioxide to produce calcium carbonate instead of calcium silicate hydrates and calcium alumina hydrates. Such carbonation is an undesirable reaction from the point of soil improvement (Mallela *et al*., 2004).

Lime has been considered to be the most appropriate for the stabilization of highly clayed soils having fine contents in excess of 25 % because it makes the soil more friable, less plastic and hence easier to work. The reactions of lime with soils result in strength gain mainly from chemical reactions between the lime, clay-grade minerals and amorphous constituents in the soil.

Improvement in the soil properties for soil stabilization has been attributed to the soil–lime reaction (Clare and Cruchley, 1957; Locat *et al*., 1990). The cation exchange, the pozzolanic reactions and carbonation are the mechanisms used in explaining the chemical changes occurring in the soil properties for soil–lime mixes (O'Flaherty, 2002). Cation exchange is believed to be mainly responsible for the change in plasticity of the soil, and magnitude of this change is affected by the soil clay mineralogy.

The transformation of the soil into a stabilized mass, which increases its strength and durability is due to the long-term reaction including pozzolanic reaction, where calcium from the lime reacts with the soluble alumina and silica from the clay and IOT in the presence of water to produce stable calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and calcium aluminosilicate hydrates (CASH) which generate long-term strength gain and improve the geotechnical properties of the soil. (Diamond et al., 1964; Sloane, 1965; Ormsby and Kinter, 1973a,b; Choquette et al., 1987; Osinubi and Medubi 1997a, b; Mohammed and Anita, 1998;Mohammed *et al*., 2001).

The optimum amount of lime for maximum strength gain in stabilizing soil with lime according to Eades and Grim (1960) is 4 - 6 % for Kaolinite, about 8 % for illite and montmorillonite. Ola (1978) found a linear relationship between the strength of lime – stabilized black Cotton soil and lime content (up to 10 % lime). Akawwi and Al-Kharabsheh (2002) recorded 3.5 – 5 % quicklime by dry weight of soil used to improve and stabilize expansive soils in Amman, Jordan.

2.1.2.2 Cement stabilization;

Stabilization of soils with cement usually involves the mixing of predetermined quantities of the additive with pulverized soil particles; and the mixture is termed 'soil-cement'. Soil-cement mixtures have been used for road sub base or base course. Stabilization of soil with ordinary Portland cement (OPC) produces hardened materials which are capable of bearing loads for engineering purposes. TRRL (1977) and CEBTP (1980) recommended a minimum of 15 % for soil fraction passing 0.425 mm sieve and plasticity index greater or equal to 10. Generally, gravels require about 10 % by dry weight of cement, sand requires about 7–10 %, silt about 12 to 15 % and clays, 12 to 20 % by dry weight of cement. (Gillott, 1987).

Hydration is the first phase of the cement stabilization reaction. Cement hydration produces a cementitious compound; a product of cement and water. It generates bonding between the reaction products (Calcium–silicate hydrates and aluminium hydrates) and the soil particles. It results in agglomeration and flocculation of the clay particles due to exchange of ions at the surface of the particles which manifest in an early strength development, immediate swell, shrinkage and plasticity reduction.

In highway construction, Portland cement is normally added to soils at optimum moisture content (OMC) and allowed to cure while the soil – cement mixture hardens by process of hydration. Yoder and Witczak (1975), Nelson and Miller (1992), Indraratna *et al*., (1995) reported decrease in liquid limit, plastic limit and swelling potentials of clays when treated with cement. However, researchers such as Maclean (1953), Ingles and Metcalf (1972) and Ibrahim (1983) reported that cement stabilization may not be effective for soils of high plastic limit (of about 20 %) or liquid limit in excess of about 45 to 50 % and high organic matter as well as montmorillonite–rich soil.

Kedzi (1979) identified two types of reaction for soil-cement mixtures. The first being the hydration of cement while the second is the reaction between the free lime product of hydration of cement and alumina of the clay fraction of the soil. The primary reaction results in the formation of calcium silicate hydrates (CSH), which are cementing substances and are responsible for the initial strength development, while the secondary reaction is pozzolanic in nature, and it is responsible for the time dependent gain in strength. The amount of reduction of maximum dry density (MDD) is dependent on the rate of hydration which is expected to decrease with increase in both time and cement content. O'Glesby and Hicks (1982) attributed the effects of OPC in the strength properties of soil as (1) the surface action of cement quickly produces flocculation and reduces the moisture affinity of clay soils; and (ii) the reaction which is time dependent, promotes the cementation of the soil cement mix. When OPC hydrates, it liberates calcium silicates and aluminum ions into the water and these subsequently combine to form hydrated calcium silicate, which constitute the matrix of the hardened cements (Neville and Brooks, 1994).

2.1.3 Admixture stabilization

As it has been proven that the conventional stabilization of expansive soils with lime or cement or both is effective; however the cost of these stabilizers is high thereby making the process uneconomical. In various attempts to achieve an economically effective stabilization of black cotton soil, many chemical/agricultural or industrial additives have been mixed with lime or cement or both.

2.1.3.1 Chemical admixture stabilization

Balogun (1991) indicated that a significant increase in the geotechnical properties of black cotton soil is achieved with addition of 2 % sodium chloride with lime–clay mixture. An increase in dry unit weight as well as the thioxotropic strength of black cotton soil was also reported by Sambhandharasksa and Moh (1971) on the admixture of high sodium chloride with lime. Maclean (1953) used water soluble calcium chloride simultaneously with cement to stabilize clay soils with appreciable amount of organic matter; noting that the absorption capacity of the organic matter for calcium ions permits the calcium from OPC to complete the reaction with the other compounds in the normal way.

2.1.3.2 Industrial / agricultural wastes admixture stabilization:

It is worthy to note that most industrial or agricultural wastes possess pozzolanic properties, that is having cementituous tendencies on exposure to moisture (O'Flaherty, 1988). Pozzolanas are, siliceous and aluminous materials which themselves possess little or no cementitious value but, will, in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature, to form compounds possessing cementitous properties (Robert, 1993).

In line with the above, recent researchers in the Department of Civil Engineering, Ahmadu Bello University, Zaria, have focused on the use of these agro – industrial wastes as possible stabilizers/admixtures. Studies have shown that solid minerals and agricultural wastes could be used for the stabilization of expansive soils (Fakiyesi and Osinubi, 1995; 1996; Osinubi, 1997). Their admixtures with lime or cement or both have also been considered in improving the engineering properties of expansive soils (Osinubi and Toro, 1996; 1997; Osinubi and Medubi, 1997a, b). Recent studies have also focused on the use of bagasse ash as possible stabilizers/admixture for the stabilization of expansive soils (Osinubi and Stephen, 2005; 2006a, b; 2007; Osinubi and Mustapha, 2005; 2008; Osinubi and Eberemu, 2006; Osinubi *et al*., 2007a, b; 2008a, b; 2009). Stephen (2006) studied the potential of bagasse ash as stabilizer on black cotton soil and Moses (2006) and Osinubi *et al*., (2008a, b) admixed lime and cement with baggase ash in stabilizing black cotton soil (Oyelakin, 2011; Sani, 2012)

Another agricultural waste, locust bean waste ash (LBWA) was studied by Akinmade (2008) who evaluated its effect on the geotechnical properties of black cotton soil. The results obtained showed some favourable improvements on the geotechnical properties, especially with the reduction of the swelling pressure from 42.6 to 32.2 kN/m^2, but it was, discovered that the ash could not be used as a stand – alone stabilizer because of its low calcium oxide content.

Similarly locust bean waste ash was used as an admixture with cement kiln dust (CKD), cement and lime by Sani (2012), Oyelakin (2011) and Ovuarume (2011), respectively. The respective results obtained showed some favourable improvements on the geotechnical properties, especially with the reduction of the swelling pressure and potential, plasticity index, shrinkage limit, permeability and general increase in strength. This study looked at the possibility of using iron ore tailing (an industrial waste) as an additive/admixture with lime for the achievement of the above listed developments.

There are number of studies on the use of industrial waste materials to improve the performance of weak soils. Ali and Koranne (2011) presented the effect of stone dust and fly ash on properties of expansive soil. They concluded that there was a marked improvement in the properties of expansive soil if stone dust and fly ash is mixed in equal proportions. There was a significant control in the swelling behaviour of the expansive clay.

Cokca (2001) studied the effect of Fly ash on the expansive soil. He found that the plasticity, activity and swelling potential of the samples decreased with increasing percent stabilizer and curing time and the optimum content of fly ash in decreasing the swell potential was found to be 20%. It was concluded that both high calcium and low calcium class C fly ashes can be recommended as effective stabilizing agents for improvement of expansive soils.

Kumar and Prasanna (2012) studied the effect of silica and calcium extracted from rice husk ash on geotechnical properties of expansive soils. They concluded that the characteristics of such soils are improved remarkably.

Similarly researchers such as Kumar (2012), Phanikumar *et al*. (2004), Qian *et al*., (2011), Osman *et al*. (2013), Rezende and Carvalho. (2003), Kamon and Katsumi (1994), Yorimichi and Kazuhiko. (1999), Mishra, *et al*. (2014) investigated the use of industrial wastes like fly ash, granite mill tailings, marble dusts, granite dust, other stone wastes to improve the properties of weak/ expansive soils. They concluded that these industrial wastes can increase the strength and decrease the swelling behaviour of expansive soils if used individually or as an admixture to such soils.

2.1.3.2.1 Iron ore tailing

Mine tailings is an industrial by-product obtained from mining industry. The effective disposal of mine tailings (MT) is a great challenge to both civil engineers and mining engineers. In recent years there is an increase in trend to utilize the mine tailings for geotechnical applications, provided they are treated with some admixtures (Ramesh *et al*., 2012)

The Itakpe iron ore deposit in Nigeria which has a total estimated reserve of about 182.5 million metric tonnes consists mainly of quartzite with magnetite and hematite. The deposit has been developed to supply iron ore concentrates to Ajaokuta steel plant and the Delta steel plant, Aladja, in Nigeria. (Soframine, 1987). Ajaka, (2009) report that National

Iron Ore Mining Company (NIOMCO) Itapke plant has an average of 22 per cent iron mineral tailing (see Table 2.1) and high percentages of silicon oxides from analysis of the chemical composition of iron ore as obtained from the plant and processed iron ore tailing (see Tables 2.2 and 2.3)

Table 2.1: Grades of copper ores treated by some companies

Plant location	Plant operator (company)	Average % iron mineral in tailings
USA	Mount wright mine	9
Canada	Iron ore company, Labrador	11
	Quebec cartier mine	9
Australia	Olympic dam	7
	North mining company	11
	Ernest henry mine	8
Chile	Candelaria mine	9
Mauritania	Iron ore mine	10
United Kingdom	Koivusaarenneva iron ore, kälviä, Finland	8
Nigeria	NIOMCO plant, itakpe, kogi state	22
India	Kudremulah iron ore company Ltd, India	11
	Kiriburu iron ore mine	60*
Sweden	LKAB iron ore mine	8

Source: Ajaka (2009)

* This iron ore contains large amount of fine-grain iron minerals which are not suitable as feed for a blast furnace

Table 2.2: Chemical composition of the Itakpe iron ore as obtained from the plant

Chemical component	Fe_2O_3 /Fe_3O_4	SiO_2	AI_2O_3	CaO	MgO	P	S	Na_2O	K_2O	TiO
% Composition	35.57	42.05	3.20	1.25	0.35	0.95	0.03	0.52	0.64	0.17

Source: Ajaka (2009)

Table 2.3: Chemical composition of the Itakpe iron ore process tailing obtained from the plant

Chemical component	Fe_2O_3/Fe_3O_4	SiO_2	Others
% Average composition	22	78	2

Ajaka (2009)

Mine tailings can be effectively utilized for civil engineering constructions which will minimize the disposal problems and reduce the environmental hazards (Pebble Project, 2005). Surendra *et al*., (2007) investigated that the addition of gold mine tailings at different proportion in to ordinary Portland cement, Black cotton soil and Red soil for manufacturing of cement-tailings bricks and soil-tailings bricks resulted in increase in the compressive strength and reveals that soil-tailings are more economical than cement-tailings bricks.

Ramesh *et al*., (2013) reported that the liquid limit, plastic limit and plasticity index of black cotton soil and mine tailings mixtures decrease; reduction in plasticity index is the indication of improvement of properties of soil with the addition of lime and mine tailings. The unconfined compressive strength of red earth increased with increase in mine tailings content. However, the strength increase peaked at 10 % mine tailings content with and without curing, which is considered as optimum percentage. The unconfined compressive strength of red earth treated with optimum percentage of mine tailings increases further with the addition of various percentage of lime with and without curing due to pozzolanic reaction. The increase in strength with the addition of 3 % lime was taken as the optimum percentage. From the study, it was concluded that mine tailings can be effectively used for lime stabilization of soils. The use of mine tailings for geotechnical application will minimize the disposal problem and reduce the environmental hazards.

Roy *et al*., (2007) investigated the effects of gold mine tailings at different proportion and ordinary Portland cement on black cotton soil and red soil for manufacturing bricks. It was reported that although the strength of the bricks increased, however, the soil – tailing bricks are more economical than cement-tailings bricks. Ergin *et al*., (1986) reported that addition of lime in Etibank-Uludag tungsten mine tailings in Turkey resulted in significant improvement of the soil.

2.1.3.2.2 Pozzolanas

Pozzolanas are siliceous and aluminous materials, which in itself possess little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties. Clay minerals such as kaolinite, montmorillonite, mica and illite are pozzolanic in nature. Artificial pozzolanas such as ashes are products obtained by heat treatment of natural materials containing pozzolanas such as clays, shales and certain silicious rocks. Silica in form of nutrient are taken up by Plants from soils and when the plants are burnt, silica taken from soils as nutrients remains behind in the ashes contributing to pozzolanic element. Rice husk ash and rice straw and bagasse are rich in silica and make an excellent pozzolana (Sherwood, 1993). Iron ore tailing is a pozzolana and is classified as Class F in the classification of pozzolanas as given by ASTM C618-12a (ASTM, 2013) is summarized in Table 2.4

Table 2.4: Properties of pozzolanas

Property	Class N	Class F	Class C
Chemical Properties			
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	70	70	50
SO_3 (Max %)	4	5	5
MgO (Max %)	5	5	5
Loss on ignition	10	2	6
Physical properties			
Moisture content (%)	3	3	3
Fineness (%) on sieve No. 200 (mm)	85	85	85
Pozzolanic activity			
Index with OPC at 28 days (%)	75	75	75
Pozzolanic Activity Index with lime at 7 days	5.5	5.5	5.5

OPC – Ordinary Portland Cement
Source: (ASTM, 2013)

2.2 Black Cotton Soil

Black cotton soils are a type of expansive soils which can be found anywhere in the world but they are basically confined to semi–arid and arid regions of the tropical zones. These areas are naturally characterized by marked dry and wet seasons with low rainfall, poor drainage and high afternoon temperatures. The climate condition is such that the annual evaporation exceeds the precipitations (Chen, 1988). They are found in the north-eastern part of Nigeria (see Fig. 2.1), Cameroon, Lake Chad, Sudan, Ethiopia, Kenya, South Zimbabwe, South Africa and other Eastern African countries. They are also found in India, Australia, South- Western USA and Israel (Ola, 1978; Tomlinson, 1999).

Two groups of parent materials have been associated with the formation of expansive soils. The first group comprises sedimentary rocks of volcanic origin which can be found in North America, South Africa and Israel (Ola, 1978), while the second group of parent materials are basic igneous rocks found in India, Nigeria and South–Western USA (Plait, 1953). The most well known example of expansive soils is the black cotton soil which is dark grey to black in colour and the name originated from India where locations of these soils are favourable for growing cotton.

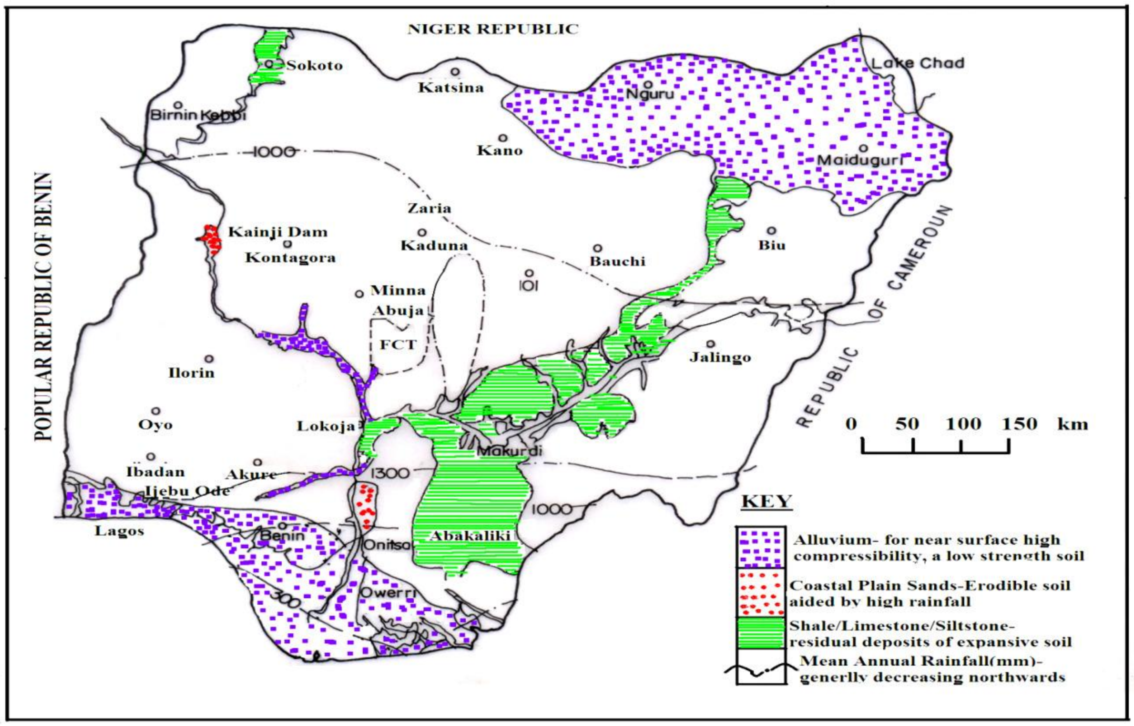


Figure 2.1: The area geologic formations considered to have expansive residual soils {modified after Adesunloye (1987)}.

2.2.1 Origin of black cotton soil

Tropical black clay otherwise known as Canada's swelling clays, India's black cotton soil and Kenya black cotton soils can be found all over the world (Chen, 1988).

Warren and Kirby (2004) refer to black cotton soils as "swelling soils", "heaving soils" and "volume change" soils. Sahel (1993) describes expansive clay formations as being favoured by the geology, climatic condition and the environment of extreme disintegration, strong hydration and restrained leaching. Expansive soils swell and shrink considerably with changes in moisture content Due to the problems associated with these soils, road and building construction on this type of soil demand special knowledge which is in the hands of relatively small group of experts (Ibrahim, 1983). An engineering definition of these soils is "a dark grey or black soil with a high content of clay usually over 50 % in which montmorillonite is the predominant clay mineral and which are commonly expansive" (Morin, 1971).

Black cotton soils (BCS) are black clays that are produced from the breakdown of basic igneous rocks, where seasonal variation of weather is extreme. Specifically, Nigerian black cotton soils are formed from the weathering of shaly and clayey sediments and basaltic rocks. According to Ola (1983), the Nigerian black cotton soils contain more of the montmorillonite with subsequent manifestation of swelling properties and expansive tendencies.

The parent igneous rocks are made up of calcium-rich feldspar and dark minerals which are high in the weathering order and all the constituents are weathered to form amorphous hydrous oxide and under suitable conditions clay minerals develop. The absence of quartz leads to the formation of fine grained plastic soil highly impermeable and easily becomes waterlogged. Other conditions favouring the formation of BCS are evaporation exceeding precipitation, poor leaching, alkaline conditions and retention of magnesium and calcium in the soil (Ola, 1983).

2.2.2 General characteristics of black cotton soil

Black cotton soil (BCS) being an expansive soil swells excessively exerting many kilo Newton per square area of swelling pressure when wet and shrinks extremely, developing cracks, often measuring 70 mm wide and 1.0 m deep and may extend up to 3.0 m in a high deposit (Adeniji,1991). When wet, the soil has high index properties, its bearing value and strength is low. These undesirable properties of BCS are consequent of the presence of the expansive clay mineral, montmorillonite, which is abundant in the soil. Ola (1983) reported 70 % montmorillonite in the Nigerian black cotton soils. Generally, black cotton soils have comparatively high percentage of clay, more than 90 % with substantial proportions of silt and sand. Their organic content is low and they are alkaline in composition with a pH greater than 7.0. The soil is black to grey in colour and it contains a very high percentage of humus (i.e., 3 to 15 %).

Although it was reported by Nelson and Miller (1992) that there is no standard classification for expansive soils, different methods are practically employed in different parts of the world. NBRRI (1983) classified the variability of black cotton soil in terms of particle size distribution, clay and silt content, liquid and plastic limits as well as swelling potentials as summarized in Table 2.5.

Table 2.5: Categorization of Black Cotton Soil of North–Eastern Nigeria

S/No	Plasticity Index (%)	Free Swell (%)	% Lesser than 1µm	Swelling Potential
1	< 20	<50	<20	Low
2	15 – 30	50 – 80	15 – 30	Medium
3	> 30	> 80	> 30	High

Source: NBRRI (1983)

2.2.3 Mineralogy and chemical composition of black cotton soil

Montmorillonite and kaolinite are the two predominant clay minerals found in BCS Ola (1983). The Nigerian BCS contains about 70 % montmorillonite and 30 % kaolinite Ola (1983). The swell and shrink characteristics of the soil are largely due to montmorillonite mineral while kaolinite is likely responsible for high strength value because of its inability to swell with absorbed water.

The montmorillonite clay structure consists of layer sheet formed and stacked one above the other and the bonding between successive layers is by van der Waals forces and by cation that may be present to balance charge deficiencies in the structure. These bonds are, however, weak and easily separated by cleavage or adsorption of water and other liquids. There is an extensive isomorphous substitution for aluminium and silicon with its lattice which gives the clay a net negative charge resulting in the water absorbing tendencies and an attraction for hydroxyl ions and water molecules to the clay surface (Nelson and Miller, 1992).

There is an extensive isomorphous substitution for aluminium and silicon with the lattice of the montmorillonite crystal. Aluminium in the octahedral sheet may be replaced by Magnesium, Zinc, Iron, Nickel, Lithium or other cations. Aluminium may replace up to 15 % of the silicon ions in the tetrahedral sheet. Possibly, some of the silicon positions can be occupied by phosphorous (Grim, 1968). Isomorphous substitution in the clay mineral gives the clay a net negative charge resulting in the water absorbing tendencies as there is an attraction for hydroxyl ions and water molecule to the clay surface.

2.2.4 The effect of black cotton soil on highway pavements

The most vulnerable engineering structure susceptible to damage due to shrink-swell potential (volume change) of black cotton soil are the highway pavements because of their light weights and very shallow foundations. The multi– layered flexible road pavement is a complex structure made up of materials which engineering properties is very much affected by the loading to which they are subjected and also by the environmental conditions (Aitken, 1971)

A road pavement is expected to fulfill two basic functions: to remain structural sound to satisfy the engineer’s design; and to provide a satisfactory ride to the road user during its design life. Unfortunately and very frequent in practice, road pavements do not fulfill their basic functions especially when they are constructed on expansive soils. There is, therefore, a need to incorporate an economical soil stabilization process before these roads are constructed to forestall these unfortunate results, because experience has clearly shown that the cost of repairs (of bad roads) is very much higher than the cost of a proper initial design, and the results are much less satisfactory (Krazynski, 1980).

2.3 Microanalysis of Soil

In recent years, there has been growing interest in the research of soil microstructure. From the image of soil microstructure, some micro-parameters such as porosity and soil particle orientation degree could be extracted (Wei, 2010). The properties of the clay sub-fractions obtained in the course of this experiment were studied by two analytical methods, scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS) analyses.

The new generation scanning electron microscope (SEM), utilizing energy dispersive X-ray spectrometers (EDS), incorporate computer automation and detector technology that allows for rapid elemental analyses of small particles or inclusions. Automated SEM-EDS analyses remove biases inherently present in manual optical analyses and provide elemental and morphological information. This technique allows for a more complete characterization of particulate within a sample in a time-efficient manner. Whether the analysis involves searching a sample for specific materials of interest, or classification of all particulate within a sample, automated SEM-EDS can provide rapid and accurate results (Brian, 2013).

2.3.1 Determination of clay fabric by scanning electron microscope (SEM*)*

Clay fabric (or clay microstructure) is defined as the orientation and arrangement or spatial distribution of the solid particles and the particle-to-particle relationships (Bennett et al. 1991). Fabric changes in clay are mainly related to consolidation, mineralogy, and grain size, as well as diagenesis (O'Brien, 1970; Bennett *et al*., 1981; Bryant *et al*., 1991; Tribble *et al*., 1991). The microstructure of clay fabric strongly influences and largely controls the physical and mechanical properties of sediments, including its consolidation behavior (Bennett *et al.*, 1991). Clay fabric with preferred orientation provides better sediment integrity and higher shear strength because of greater surface area contacts, and higher bonding force, compared to clay sediment with random microstructure that has lower shear strength. Thus, fabric alteration appears to be an important factor influencing both shear wave velocity and shear strength increase of the core sample (Kim *et.al*., 2007).

The micro fabric of this sediment section is most likely in the initial stages of consolidation, where the microstructure has sufficient strength to resist the stresses of the small overburden load impressed upon it (Bolt, 1956; Lambe, 1958; Ingles, 1968; Bryant *et al*.. 1991). The micro pores in soil provide important information on the shear strength, compressibility, and hydraulic conductivity and soil water characteristics of a soil (Li and Zhang, 2009). Soil micro pores structure is difficult to measure and is highly variable for a single soil type. Micro pores structure changes with stress state, transfer of water and air, temperature, flocculation, long term gravimetric actions and weathering (Li and Zhang, 2009).

Al-Rawas and McGown (1999) and Katti and Shanmugasundaram (2001) used SEM micrographs to put forward methodologies to describe microfabrics changes of expansive clays subjected to wetting. Also using SEM, Cui *et al*., (2002) successfully detected microstructural changes – progressive expansion of aggregates clogging the macropores – undergone by 70-30 % Kunigel clay/Hostun sand mixture on wetting under confined conditions.

2.3.2 Relationship between microstructure and engineering properties

Many macroscopic soil properties are often explained in terms of; micro-structural behaviour, distribution and connectivity of pores, particle size, shape and distribution, along with the arrangement of grains and grain contacts in addition to volumetric and gravimetric state variables-void ratio, water content, degree of saturation and the stress history (both mechanical and hydraulic) undergone by the material (Romero and Simms, 2008). A classic example is the variation in permeability of a soil at different compaction water contents; a soil compacted wet of optimum will exhibit lower permeability than the same soil compacted to the same porosity at dry of optimum. The difference was initially attributed to a change from a flocculated to a dispersed arrangement of clay particles (Lambe, 1958), though more recent studies (Garcia-Bengochea *et al*., 1979; Delage *et al*., 1996) have explained the change in permeability in terms of the quantity of clay aggregates brought about by compaction at different levels of water content.

Imaging of clay microstructure has also been used to explain the inapplicability of unique correlations between macroscopic parameters and hydraulic conductivity, compressibility, and shrinkage/swelling behaviour (Djeran-Maigre *et al*., 1998; Hetzel *et al*., 1994; Ben Rhaim *et al*,. 1998; Pusch and Schomburg 1999). These studies illustrated the importance of the size, shape and arrangement of clay aggregations, as well as the distribution and connectivity of pores, on soil behaviour, and how such aggregations and pores can change during wetting/ drying cycles, separating or combining depending on a number of factors, including type of clay mineral and the rate of drying or wetting. In general, the type and quantity of clay minerals in soils, as well as the interactions with the pore water in a soil have long been shown to strongly affect strength, permeability and compressibility (Marshall, 1958).

Mitchell (1956) reported on the fabric of natural clays and its relation to engineering properties. The microscopic study of thin sections, prepared by a special technique, from several clays at natural water content in both the undisturbed and remolded state has yielded direct information on the fabric. Photomicrographs are presented indicating various fabric features such as parallel clay orientation. The fabrics formed in in the undisturbed and remolded clays are explained in terms of inter-particle forces and history of the material subsequent to deposition or remolding. Studies on the micro analysis of soil particle with regard to micrograph, chemical analysis using energy dispersive X-ray spectroscopy, the fabric orientation and pores in the compacted clay can be used to determine the engineering properties of the soil. Effect of using additives for soil improvement can also be determined effectively using microanalysis.

2.3.3 Accuracy and sensitivity

X-ray intensities are measured by counting photons and the precision obtainable is limited by statistical error. For major elements it is usually not difficult to obtain a precision (defined as 2σ) of better than ± 1 % (relative), but the overall analytical accuracy is commonly nearer ± 2 %, owing to other factors such as uncertainties in the compositions of the standards and errors in the various corrections which need to be applied to the raw data. As well as producing characteristic X-ray lines, the bombarding electrons also give rise to a continuous X-ray spectrum, which limits the detachability of small peaks, owing to the presence of 'background'. Using routine procedures, detection limits are typically about 1000 ppm (by weight) but can be reduced by using long counting times. (Goldstein, *et al.*, 2003)

2.3.4 Spatial resolution

Spatial resolution is governed by the penetration and spreading of the electron beam in the specimen. Since the electrons penetrate an approximately constant mass, spatial resolution is a function of density. In the case of silicates (density about 3 gcm-3), the nominal resolution is about 2 μm under typical conditions, but for quantitative analysis a minimum grain size of several micrometers is desirable. Better spatial resolution is obtainable with ultra-thin (~100 nm) specimens, in which the beam does not have the opportunity to spread out so much. Such specimens can be analyzed in a transmission electron microscope (TEM) with an X-ray spectrometer attached, also known as an analytical electron microscope (AEM) (Goldstein, *et al*., 2003).

2.3.5 Sample preparation

Since the electron probe analyses only to a shallow depth, specimens should be well polished so that surface roughness does not affect the results. Sample preparation is essentially as for reflected light microscopy, with the provision that only vacuum compatible materials must be used. Opaque samples may be embedded in epoxy resin blocks. For transmitted light viewing, polished thin sections on glass slides are prepared. In principle, specimens of any size and shape (within reasonable limits) can be analyzed (Goldstein 2003). Holders are commonly provided for 25 mm (1") diameter round specimens and for rectangular glass slides. Standards are either mounted individually in small mounts or in batches in normal-sized mounts.

Many samples are electrically non-conducting and a conducting surface coat must be applied to provide a path for the incident electrons to flow to ground. The usual coating material is vacuum-evaporated carbon(~10nm thick), which has a minimal influence on X-ray intensities on account of its low atomic number, and (unlike gold, which is commonly used for SEM specimens) does not add unwanted peaks to the X-ray spectrum. However, steps should be taken to maintain as constant a thickness as possible (Goldstein, *et al*. 2003).

2.3.6 Image analysis

Image analyzers can be used with both optical and electron microscopes for quantification of fabric features. Digital imaging cameras can resolve reflected or transmitted light from the sample into pixels. The amount of light per pixel is then converted into an analog signal. After the entire image is acquired, the analog signal for each pixel is converted to digital form for analysis, manipulation, and storage. Image analysis offers greatly increased potential for quantitative description of different fabric elements. Examples of image analysis of soil specimens are given by Frost and Wright (1993), Tovey and Hounslow (1995) as well as Frost and McNeil (1998).

2.3.7 Pore size distribution analysis

The shape and distribution of voids are one of the three most important measures of fabric (microstructure), along with contact distributions and particle orientations. Pore information can be obtained by volumetric pore size distribution determinations and from image analysis of thin sections and SEM pictures (Mitchel and Soga, 2005).

2.3.7.1 Pore Image Analysis

The spatial distribution of local voids inside a soil specimen can be obtained by analyzing the images obtained from thin sections. Generally, two image analysis methods are available: (1) method of polygons and (2) mean free path.

In the first method the centroids of particles are located and linked to produce polygons, representing individual void elements as shown in Fig. 2.2*a*. Using this method, Bhatia and Soliman (1990) reported that looser specimens of sand exhibited a greater variability in local void ratio than denser specimens. Frost and Jang (2000) used this method to quantify the variation of local void distribution produced by different preparation methods. Moist tamped specimens had a higher standard deviation of local void ratio for the same mean void ratio than air-pluviated specimens.

The mean free path method measures the mean free path between particles by use of a scanning line that passes through both particles and voids as shown in Fig. 2.2*b*. The spacing and orientation of the line are varied, and a representative void is then produced by summing over the void lines found on a number of scanned lines in each direction (Kuo *et al*., 1998). Using this method, Masad and Muhunthan (2000) found that larger local voids exist in the horizontal direction than the vertical for a pluviated specimen.

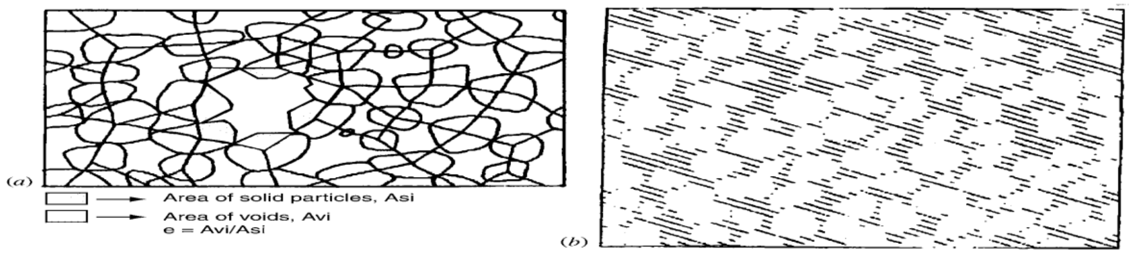


Figure 2.2 Image analysis methods to determine void fabric: (*a*) polygon method (after Bhatia and Soliman, 1990) and (*b*) mean free path method (Kuo *et al.*, 1998).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Black cotton soil

The soil sample used in this study was collected along Gombe –Biu road in Yamaltu Deba Local Government Area of Gombe State (latitude 10° 19’N and longitude 11° 30’E) using the method of disturbed sampling. In terms of extent of deposit, black cotton clays are not restricted to the area of study but are wide spread throughout the north-eastern Nigeria. The top soil was removed to a depth of 0.5 m before the soil samples were taken, sealed in plastic bags and put in sacks to avoid loss of moisture during transportation. The soil samples were then air- dried before pulverizing to obtain particles passing BS No. 4 sieve (4.76 mm aperture).

3.1.2 Iron ore tailing

The iron ore tailing used for the soil stabilization was collected from the National Iron Ore Mining Company, Itakpe in Ajaokuta Local Government Area of Kogi State, geographically located in north central Nigeria. It supplies the steel works of Ajaokuta and Aladja. The iron ore tailing was then passed through British Standard No 200 sieve and kept to be mixed with the ‘soil-lime’ in the appropriate percentages. The oxide composition of iron ore tailing (IOT) was determined at the Defense Industry Cooperation of Nigeria (DICON) using the method of X-Ray Fluorescence (Nuclear Energy Test). See Table 3.1 for typical result.

3.1.3 Lime

The lime used for the study was purchased in the open market at Kano road, central market Kaduna. Typical oxide composition of lime is shown in table 3.1

Table 3.1 Chemical compositions of lime and iron ore tailing

	Composition by weight (%)	
Oxide	***Lime**	****Iron ore tailing**
Lime (CaO)	54.92	0.607
Silica (SiO_2)	0.35	45.64
Alumina (Al_2O_3)	0.60	3.36
Alkalies (Na_2O)	0.02	0.405
Alkalies (K_2O)	0.04	0.607
Sulphur oxide ($S0_3$)	0.06	-
Tin oxide (TiO_2)	-	0.24
Manganese oxide (MnO)	0.09	0.067
Iron Oxide (Fe_2O_3)	0.14	47.7
Magnesium oxide (MgO)	-	0.393
Vanadium oxide (V_2O_5)	0.05	-
Loss on Ignition	43.67	3

* Ovuarume (2011).
**Ishola (2014)

3.2 Methods

3.2.1 Natural moisture content

The natural moisture content of the soil as obtained from the site was determined in accordance with BS 1377 (1990) Part 2. Three containers was cleaned and weighed to the nearest 0.01g (M_1). The sample as freshly collected was crumbled and placed loosely in the containers and the containers with the samples were weighed together to the nearest 0.01g as M_2. The containers were then placed in the oven and dried at 105 -110°C for 24 hours. The containers and the samples were then removed and weighed dry to the nearest 0.01g as M_3. The natural moisture content (as collected from the site) is calculated as the average of the three oven dried samples given by eqn. (3.1):

$$W = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \tag{3.1}$$

where;

W= Moisture content (%)

M_1= weight of empty container (g)

M_2= weight of container+ wet soil (g)

M_3= weight of container dry soil (g)

Detail result are shown in Appendix Table A4.1a

3.2.2 Specific gravity

The determination of specific gravity was carried out according to BS 1377 (1990) for fine–grained soils. The density bottle and the stopper were weighed to the nearest 0.001 g (M_1). The air dried soil was transferred into the density bottle, and the bottle, content and the cover were weighed as M_2. Water was then added just enough to cover the soil, the solution was gently stirred to remove any air bubble. The bottle was then completely filled up and covered. The covered bottle was then wiped dry and the whole weighed to the nearest 0.001 g (as M_3). The bottle was subsequently emptied and filled completely with water, wiped dry and weighed to the nearest 0.001 g (M_4). The specific gravity is calculated using eqn. (3.2):

$$G_S = \frac{M_2 - M_1}{(M_4 - M_1)(M_3 - M_1)} \qquad (3.2)$$

where;

G.s = Specific gravity

M_1 = mass of empty density bottle (g)

M_2 = mass of density bottle +dry soil (g)

M_3 = mass of density bottle +soil+ water (g)

M_4 = mass of density bottle filled with water (g)

To obtain a more accurate result three density bottles were used and their average taken. The same procedure was repeated for all the percentages of the admixtures.

.

3.2.3 Free swell

The test was conducted in accordance with the United States Bureau of Reclamation (USBR) method (Holtz and Gibbs, 1956). About 10 g of soil passing BS No 4 sieve (425 µm aperture) was oven dried and allowed to cool down in a desiccator. The sample was slowly poured into a 100 cm^3 measuring cylinder to which water was added in order to fill the cylinder. The cylinder was then agitated in order to obtain a homogenous mixture of soil and water after which it was allowed to settle for 2 hours or more before the swell volume was recorded. Free swell was calculated using:

$$\text{Free Swell} = \frac{\text{Final Volume} - \text{Initial Volume}}{\text{Initial Volume}} \times 100\% \qquad (3.3)$$

The same procedure was repeated for all the percentages of the admixtures.

3.2.4 Cation exchange capacity

The test was carried out in accordance with the procedures given by ISRIC (1998) 10 g of 2 mm sieved soil was put into a 100 m^3 plastic beaker, about 40 ml of Ammonium acetate (1N pH7.0) was added, stirred with a glass rod and left over night. The soil was filtered with a light suction using a 55 mm Bucher funnel, the soil was leached so that it could fit in a funnel with Ammonium acetate of a volume of 250 cm^3. The leachate was tested from the soil to know if it was calcium free, the presence of calcium was indicated by a white precipitate or turbidity. The electrolyte was washed out with 150-200 ml of isopropyl alcohol. Chloride was tested for in the leachate with (0.1N $AgN0^3$) till the leachate became negligible, the soil was tested to drain thoroughly, and then the leached soil was acidified to a volume of 250 ml. 50 ml of boric acid was measured into 250 ml conical flask and a few drops of mixed indicator was added. The acidified soil was poured into a 500 ml flask and the flask was connected to the steel, some anti bump and 10 ml of 1N NaOH was added into the flask and distilled over the boric acid in the conical flask, 150 ml distilled was collected. The NH_4-borate was titrated with a standard acid 0.1N HCl. The cation exchange capacity (CEC) was calculated using equation (3.4):

$$\mathrm{CEC} = \frac{(\mathrm{Titre} - \mathrm{B}) \times \mathrm{NA} \times 100}{\mathrm{Weight\ of\ Soil}} \tag{3.4}$$

where;

B = Blank

NA = Normality of acid

This same procedure was then repeated for each of the sample with lime and IOT admixture.

.3.2.5 Batch equilibrium

The procedures adopted for Batch Equilibrium Adsorption Test was in accordance with that described by Shackelford and Daniel (1991). Batch equilibrium tests were performed with soil-IOT/lime mixtures to determine the leaching potential of iron from the soil-IOT/cement mixtures into the environment. This involves a single batch extraction test carried out by preparing a series of 120 ml distilled water containing soil-lime-IOT mixtures (30 g dry weight) in 1:4 mixing ratio. The soil-lime-IOT mixtures were agitated in a mechanical shaker for a period of 48 hours. At the end of the 48 hours, the slurry was decanted and filtered using filter paper for laboratory analysis. The equilibrium concentrations of the contaminant constituents were carried out using Atomic Adsorption Spectrometer (AAS). The pH of the samples was also measured. The mass of solute adsorbed/desorbed per mass of soil solid was determined using the following:

$$C_s = \frac{(C_i - C_f) \times V}{M_s} \tag{3.5}$$

where;

C_s = Mass of solute adsorbed/desorbed per mass of soil solid (mg/l)

C_i = Initial concentration of leachate (mg/l)

C_f = Equilibrium concentration of solute (mg/l)

V = Volume of leachate used (cm3)

M_s = Mass of dry soil (g)

3.2.6 Particle size distribution

3.2.6.1 Wet sieving

The particle size analysis was carried out in accordance with BS 1377(1990) Part 2. 200g of the soil sample was weighed, wet sieve to remove clay and silt particles using BS No 200 sieve (0.075 mm aperture) under tap water. Washing was done carefully to avoid damage to the sieves. After washing, drying of the sample was dried in an oven set to a constant weight at 105˚C for 24 hours. After drying the standard BS sieves were arranged in descending order of sieve size. The oven dried samples were transferred individually into the sieves then shake for at least 10 minutes manually. After sieving the mass retained on each sieve was weighed. The percentages passing each sieve size was calculated and plotted on a semi-log graph; percentage passing against sieve sizes. The same process was repeated for the remaining percentages of the admixture.

3.2.6.2 Dry sieving

The particle size analysis test was carried out in accordance with BS 1377; 1990 Part 2. dry sieving was conducted by measuring 200 g of the dry soil sample passing sieve No 4 (4.76 mm aperture).The dry sample was then mix properly with the optimum moisture content of the mix obtained from compaction test and air drying it in the laboratory for 48 hours. Dry sieving was carried out on the dried sample to obtain the particle size distribution.

3.2.7 Atterberg limits

The test includes the determination of the liquid limits, plastic limits and the plasticity index for the natural soil and the stabilized soils. They were also conducted in accordance with Test 1(A) BS 1377 (1990) Part 2 for the natural soil and BS 1924 (1990) for the stabilized soils.

3.2.7.1 Liquid limit

The soil sample for liquid limit was air dried and 200 g of the material passing through BS No 40 sieve (425 μm aperture) was obtained and thoroughly mixed with water to form a homogeneous paste on a flat glass plate A portion of the soil water mixture is then placed in the cup of the Casagrande apparatus, leveled off parallel to the base and divided by drawing the grooving tool along the diameter through the centre of the hinge. The cup was then lifted up and dropped by turning the crank until the two parts of the soil come into contact at the bottom of the groove. The number of blows at which that occurred was recorded and a little quantity of the soil was taken and its moisture content was determined as in section 3.2.1. The test was performed for well–spaced out moisture content from the drier to the wetter states. The values of the moisture content (determined) and the corresponding number of blows was then plotted on a semi–logarithmic graph and the liquid limit was determined as the moisture content corresponding to 25 blows. This same procedure was then repeated for each of the sample with lime and IOT admixture for the percentages listed earlier.

3.2.7.2 Plastic limit

A portion of the soil/soil–lime–IOT mixes used for the liquid limit test was retained for the determination of plastic limit. The ball of the soil/soil admixtures was moulded between the fingers and rolled between the palms of the hand until it dried sufficiently (even though the soil was already relatively drier than the ones used for liquid limit). The sample was then divided into approximately four equal parts. Each of the parts was rolled into a thread between the first finger and the thumb. The thread was then rolled between the tip of the fingers of one hand and the glass. This continued until the diameter of the thread was reduced to about 3 mm in five to ten forward and backward movements of the hand. The movement continued until the thread sheared both longitudinally and transversely. The crumbled soil was then put in the moisture container and the moisture content determined.

3.2.7.3 Plasticity index:

The plasticity index (PI) of the soil/soil–lime–IOT mixed is the difference between the liquid limit (LL) of the natural/various mixes of the soil and their corresponding plastic limit (PL). The plasticity index of the samples was calculated as:

$$PI = LL - PL \tag{3.6}$$

where

PI=Plasticity Index (%)

LL=Liquid Limit (%)

PL= Plastic Limit (%)

3.2.7.4 Linear shrinkage

The test was conducted in accordance with Test 5, BS 1377 (1990). It involved the mixing of about 125 g of soil passing the BS No. 40 sieve (425 μm aperture) with water in order to obtain a homogenous paste (the water added to the natural soil corresponded to the moisture content at liquid limit). The paste was then placed in the shrinkage mould and vibrated gently in order to expel air pockets from the mixture. The soil was then leveled by spatula and air-dried at 60 ^{0}C until the soil shrank clear of the mould. Subsequent drying was made at 105–110 ^{0}C in an oven in order to complete the shrinkage. On cooling, the length of the sample was measured with a ruler and the linear shrinkage was calculated using eqn. (3.7):

$$\text{Linear Shrinkage} = \frac{\text{Initial Length} - \text{Dried Length}}{\text{Initial Length}} \times 100\% \qquad (3.7)$$

The same procedure was repeated for all the percentages of the admixture.

3.2.8 Compaction characteristics

3.2.8.1 Maximum dry density

The compaction tests were carried out for the natural soil and the stabilized soils (in different percentages); all according to BS 1377 (1990) Part 4, using the British Standard light, West African Standard and the British Standard heavy, in accordance with the Nigerian General Specification (1997) 3 kg of the soil/soil-admixture sample was mixed thoroughly with 8 % of water (and the water was added at 8 % for each of the compaction). The sample was then compacted into the 1000 cm^3 (of mass m_1); in three layers of approximately equal mass with each layer receiving 27 blows of 2.5 kg rammer falling through a height of 300 mm, for the British Standard light compaction; 10 blows of 4.5 kg rammer in five layers for West African Standard compaction and 27 blows of 4.5 kg rammer in five layers for the British Standard Heavy. The blows were uniformly distributed over the surface of each layer. The collar was then removed and the compacted sample leveled off at the top of the mould with a straight edge. The mould containing the leveled sample was then weighed to the nearest 1 g, m_2. Two small samples were then taken from the compacted soil for the determination of moisture content. The sample was then removed from the mould, crushed and addition water added (8 %) and the same procedure was repeated until minimum of five set of samples were taken for moisture content determination. The bulk density in Mg/m^3 was later calculated for each compacted layer using:

$$\rho = \frac{M_2 - M_1}{1000} \tag{3.8}$$

The dry density was also calculated using the equation:

$$\rho_d = \frac{100\rho}{1000 + w} \tag{3.9}$$

where w is the moisture content of each compacted layer.

The values of the dry densities as obtained from eqn. (3.9) were plotted against their respective moisture contents and the maximum dry density (MDD) was deduced as the maximum point on the resultant curves.

3.2.8.2 Optimum moisture content

The corresponding values of moisture contents at maximum dry densities (MDD), deduced from the graph of dry density against moisture contents, gives the optimum moisture content (OMC).

3.2.9 Strength characteristics

3.2.9.1 Unconfined compressive strength

The unconfined compressive strength (UCS) tests were performed on the soil samples according to BS 1377; 1990 Part 7 using the British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) energy levels. The natural soil sample/the stabilized soil samples were compacted in 1000 cm^3 moulds at their respective OMC. The samples were extruded from the moulds and trimmed into a cylindrical specimen of 38.1 mm diameter and 76.2 mm length. The three cylindrical specimens from the mould were wax cured for 7 days, second for 14 days and the third for 28 days. At the elapsed day of wax curing, the specimens were de-waxed and then placed centrally on the lower platen of a compression testing machine and a compressive force was applied to the specimen with a strain control at 0.10 % mm. Record was taken simultaneously of the axial deformation and the axial force at regular interval until failure of the sample occurred. The UCS of the sample was determined at the point on the stress–strain curve at which failure occurred. The UCS was calculated from the following equation.

$$\delta = \frac{\lfloor R \times C_r \times (100 - E\%) \times 1000 KN/m^2 \rfloor}{(100 \times A_o)} \qquad (3.10)$$

Where $E\% = \frac{V}{L_o}$

E% = Strain percent

v = Amount of compression at any stage

R = Load ring reading at strain E

C_r = Mean calibration of load ring

L_o = Initial length of specimen

A_o = Initial cross sectional area

δ = Compressive stress at strain E

3.2.9.2 California bearing ratio

The California bearing ratio (CBR) test was conducted in accordance with BS 1377(1990) and BS 1924 (1990) for the natural and treated soils. The CBR is expressed by the force exerted by the plunger and the depth of its penetration into the specimen; it is aimed at determining the relationship between force and penetration.

5.0 kg of the soil sample/soil-admixture sample were mixed at their respective optimum moisture contents in 2360 cm^3 mould, at the three compaction energies. For BSL, the compaction was in three layers each receiving 62 blows from the 2.5 kg rammer; for the WAS, the samples were compacted in five layers with 25 blows from the 4.5 kg rammer and the BSH, the sample received 62 blows in 5 layers from the 4.5 kg rammer.

The base plates were removed (after compaction) and the compacted specimens placed in sealed plastic bags for curing (for 6 days) and after the sixth day, the specimens were immersed in water for 24 hours before testing according to Nigerian General Specifications (1997). The base plates were later replaced and the specimens transferred to the CBR testing machine and positioned on the lower plate of the machine. The plunger was then made to penetrate the specimen at a rate 1.3 mm/min until the specimen failed. The mould was then inverted, base plate removed and the procedure repeated for the base of the specimens.

From the values of the penetration and force recorded, a curve of force against penetration was obtained. The CBR value was calculated at penetration 2.5 mm or 5.0 mm;

the greater of the two values and as their means where the value are within 10 % of each other. The CBR was calculated using eqn. (3.11):

$$\mathrm{CBR} = \frac{\text{Measured Load}}{\text{Standard Load}} \times 100 \qquad (3.11)$$

Where; standard load = 13.24 kN of 2.5mm penetration

= 19.96 kN of 5.0mm penetration

3.2.10 Durability

The durability assessment (under adverse field conditions) of the soil sample was determined by resistance to loss in strength when immersed in water. It was expressed as the ratio of UCS of the specimen cured for 7 days and soaked for another 7 days to the UCS of the specimen cured for 14 days (see eqn. 3.12)

$$\text{Resistance to loss in strength} = \frac{\text{UCS}(\text{7day cured+7day soaked})}{\text{UCS}(\text{14day cured})} \times 100\% \qquad (3.12)$$

3.2.11 Statistical analysis

Often the problem of analyzing the quality of the estimated regression line is handled by an analysis-of-variance (ANOVA) approach: a procedure whereby the total variation in the dependent variable is subdivided into meaningful components that are then observed and treated in a systematic fashion.

Suppose that we have *n* experimental data points in the usual form *(xi.-yi)* and that the regression line is estimated then,

$$S_{yy} = bS_{xy} + SSE \qquad (3.13)$$

An alternative and perhaps more informative formulation is

$$\sum_{i=1}^{n}(y_i - \bar{y})^2 = \sum_{i=1}^{n}(\hat{y} - \bar{y})^2 + \sum_{i-1}^{n}(y_i - fc)^a \qquad (3.14)$$

So we have achieved a partitioning of the total corrected sum of squares of *y* into two components that should reflect particular meaning to the experimenter. We shall indicate this partitioning symbolically as.

$$SST = SSR + SSE \tag{3.15}$$

The first component of the right, *SSR*, is called the regression sum of squares and it reflects the amount of variation in the parallel-values explained by the model, in this case the postulated straight, line. The second component is the familiar error sum of squares, which reflects variation about the regression line. Suppose that; we are interested in testing the hypothesis

HQ: β = 0,

HI: β ≠ 0,

Where the null hypothesis says essentially that the model is *μy\x* = *a*. That is, the variation in *Y* results from chance or random fluctuations which are independent of the values of *x*. Under the conditions of this null hypothesis it can be shown that *SSR/o2* and *SSE/σ2* are values of independent chi-squared variables with 1 and n —2 degrees of freedom, respectively, it follows that *SST/a2* is also a value of a chi squared variable with *n* — 1 degrees of freedom. To test the hypothesis above, we compute

$$\mathrm{f} = \frac{\mathrm{SSR}/1}{\mathrm{SSE}/(\mathrm{n}-1)} - \frac{\mathrm{SSR}}{\mathrm{S}^2} \tag{3.16}$$

and reject HQ at the n-level of significance when f > fa(l, n — 2). When the null hypothesis is rejected, that is, when the computed F-statistic exceeds the critical value fQ (l,n — 2), we conclude that there is a significant amount of variation in the response accounted for by the postulated model, the straight-line function. If the F-statistic is falling in the reject region, we conclude that the data did not reflect sufficient evidence to support the model postulated. The computations are usually summarized by means of an analysis-of-variance table; it is customary to refer to the various sums of squares divided by their respective degrees of freedom as the mean squares.

3.2.12 Microanalysis

A scanning electron microscope (SEM) is one that relies on energy to produce the viewed image. The natural untreated soil and optimally treated soil-lime-IOT samples were analyzed by Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectrometer (EDS). The changes of microstructural development of soils due to lime/IOT-addition play significant role in the geotechnical properties and the mechanical behavior of stabilized soils. The changes of the microstructural of the two tested soils cured for 7 and 28 days; natural untreated BCS and stabilized treated BCS optimally blended with 8 % lime + 8 % IOT were investigated in the Department of Chemical Engineering, Ahmadu Bello University, Zaria, using PHENOM WORLD scanning electron microscope operated at 5kv and 15kv image and BSD full for 7 and 28 days curing periods, respectively. Individual analyses from different zones of the sample were performed by EDS. Since the electron probe analyses only to a shallow depth, specimens are well polished so that surface roughness does not affect the results. Sample preparation is essentially as for reflected light microscopy, with the provision that only vacuum compatible materials must be used. Opaque samples may be embedded in epoxy resin blocks. For transmitted light viewing, polished thin sections on glass slides are prepared. In principle, specimens of any size and shape (within reasonable limits) can be analyzed. Holders are commonly provided for 25 mm (1") diameter round specimens and for rectangular glass slides. Standards are either mounted individually in small mounts or in batches in normal-sized mounts.

Many samples are electrically non-conducting and a conducting surface coat must be applied to provide a path for the incident electrons to flow to ground. The usual coating material is vacuum-evaporated carbon(~10nm thick), which has a minimal influence on X-ray intensities on account of its low atomic number, and (unlike gold, which is commonly used for SEM specimens) does not add unwanted peaks to the X-ray spectrum. However, steps should be taken to maintain as constant a thickness as possible (Goldstein, 2003).

A scanning electron microscope was used in this study to examine the structural arrangement in specimens of natural black cotton soil and lime treated BCS optimal blend (8 % lime + 8 % IOT). The specimens were prepared using BSL compactive effort and cured for 7 and 28 days then a section of it was scanned in the microscope at spatial resolution of of 10 µm and100 µm respectively. The elemental analysis at different zones of the scanned sample was done by the EDS in form of a plot with the energy in kiloelectronvolt (keV) on the abscissa and the Intensity in counting phantons per electronvolt (cps/eV) on the ordinate. The EDS result gives the bulk surface characterization of each of the particles. The nature of these compositional differences can be investigated further through the individual element maps and the targeted point analysis of different surface chemical phases (Clare, 2012).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Properties of Materials Used in the Study

4.1.1 Black cotton soil

Results of preliminary investigations conducted on the natural black cotton soil show that the soil is fine-grained, with a natural moisture content of 19.5 %. The index properties are summarized in Table 4.1. The particle size distribution is shown in Fig. 4.1. The soil belongs to the CH group in the Unified Soil Classification System (UCSC), (ASTM, 1992) or A-7-6(26) soil group of the American Association of State and Transportation Officials (AASHTO) soil classification system (AASHTO, 1986). The soil is grayish black in colour (from wet to dry states) with a liquid limit of 58.8 %, plastic limit of 27.17 % and plasticity index of 28.6 %.

The soil has a free swell of about 52.5 %, soaked CBR values of 3, 4 and 8 % and unconfined compressive strength (UCS) values of 107.24, 326.25 and 408.35 kN/m^2 when compacted with British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) energies, respectively. The natural soil was found to be highly plastic and falls below the standard recommendation for most geotechnical construction works especially highway construction (Butcher and Sailie, 1984; Osinubi and Medubi 1997a). Detailed test results are given in Tables A4.1a - A4.17c in the Appendix.

Table 4.1: Properties of the natural black cotton soil used in the study

Property	**Quantity**
Natural Moisture Content, %	19.5
Percentage Passing BS No. 200 Sieve (75 µm aperture)	80.7
Liquid Limit, %	56.8
Plastic Limit, %	29.2
Plasticity Index, %	27.6
Linear Shrinkage, %	18.1
Free Swell, %	52.5
Specific Gravity	2.48
AASHTO Classification	A-7-6 (25)
USCS	CH
NBRRI Classification	Medium swell potential
Maximum Dry Density, Mg/m3	
British Standard light	1.56
West African Standard	1.64
British Standard heavy	1.68
Optimum Moisture Content, %	
British Standard light	23.5
West African Standard	20.0
British Standard heavy	19.3
Califonia Bearing Ratio (24 hours soaking), %	
British Standard light	3
West African Standard	4
British Standard heavy	8
Unconfined Compressive Strength, kN/m^2	
British Standard light	107.24
West African Standard	326.25
British Standard heavy	408.35
pH	6.42
Cation Exchange Capacity, Cmol/kg	52.8
Colour	Greyish black
Dominant clay mineral	Montmorillonite

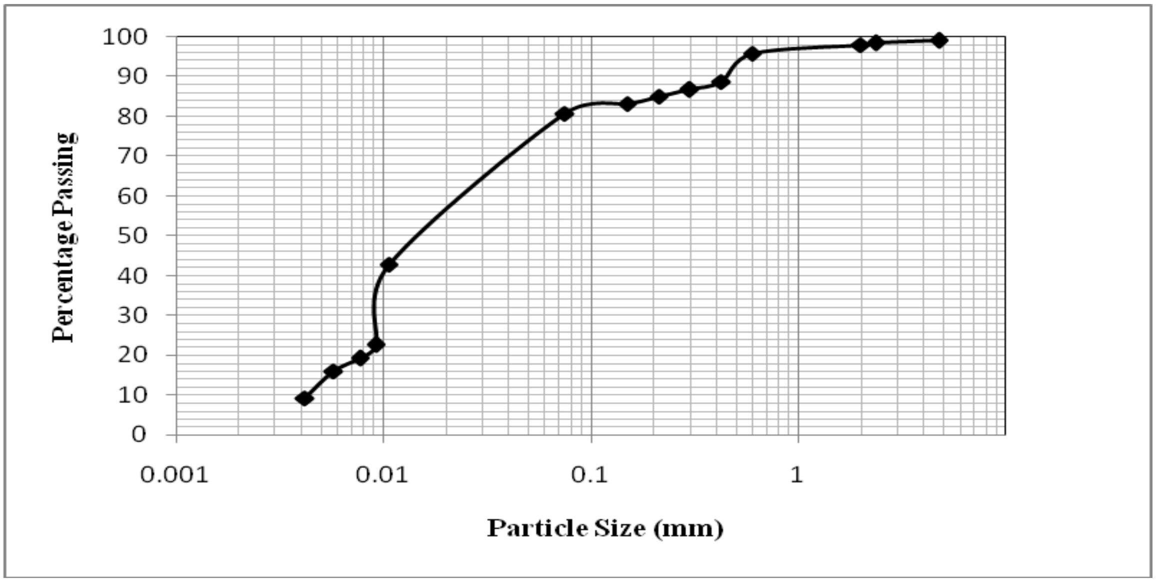


Fig. 4.1: Particle size distribution curve for the natural black cotton soil

4.1.2 Additives

The cementing characteristics of IOT are dependent on its oxide composition. The amount of CaO in IOT was found to be very low compared to that in the lime. The silicon dioxide in IOT on the other hand is higher than that in lime. However, the total amount of calcium oxide in lime and IOT was used in the stabilization process of the deficient natural black cotton soil. The comparatively high silicon and aluminium oxides in IOT also aided those in lime to provide the required improvement of the properties of the natural soil.

4.1.3 Specific gravity

The variation of the specific gravity of black cotton soil - lime mixture with iron ore tailing content is shown in Fig. 4.2. The specific gravity value of black cotton soil gradually increased from 2.48 for the natural soil to a peak value of 2.59 at 0% lime 10 % IOT treatment. The observed trend could be attributed to higher combined specific gravity of lime (2.10) and IOT (3.29) replacing the soil material with lower specific gravity (2.48). Specific gravity of IOT obtained were within the range reported by other researchers (Haile *et al*., 2000; Qiu and Sego, 2001; Demers and Haile, 2003).

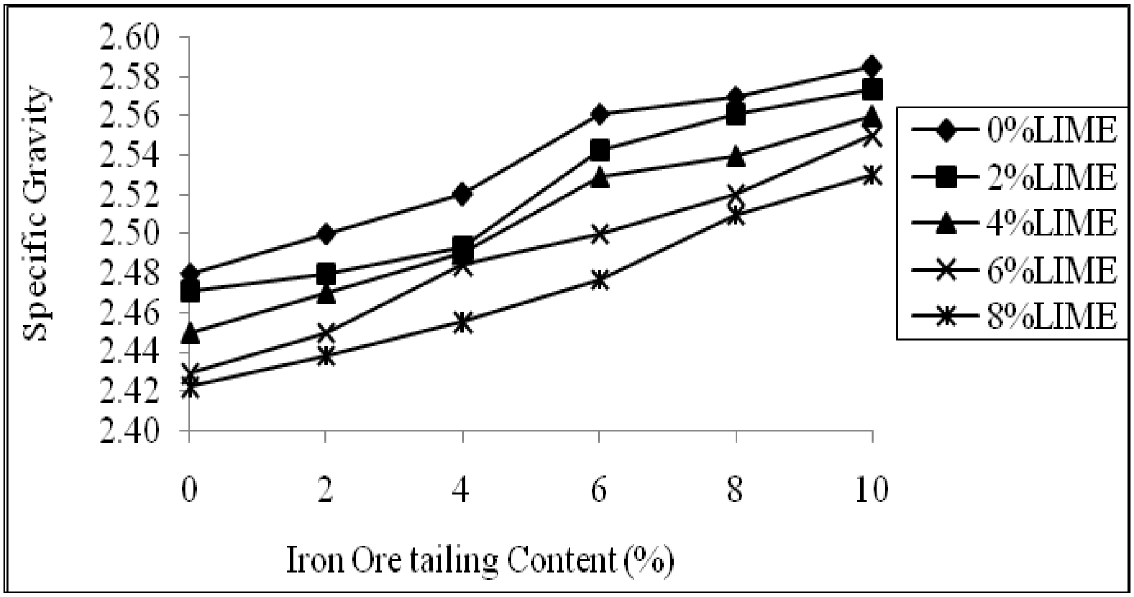


Fig. 4.2: Variation of specific gravity of black cotton soil - lime mixtures with iron ore tailing content

A two-way analysis of variance (ANOVA) test on specific gravity results (see Table 4.2) shows that the relative effects of lime and IOT on black cotton soil were statistically significant with IOT having a more pronounced effect. Detailed test results are given in Tables A4.19 in the Appendix.

Table 4.2: Two - way analysis of variance for specific gravity of black cotton soil-lime-iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
Specific gravity	Lime	4	111.97	2.15E-13	2.87	F_{CAL}>F_{CRIT}, Significant
	IOT	5	279.43	8.72E-18	2.71	F_{CAL}>F_{CRIT}, Significant

4.1.4 Free swell

The free swell criterion provides a reference point for the behaviour of the stabilized soil after immersion in water. Fig 4.3 shows the variation of free swell of black cotton soil - lime mixtures with iron ore tailing content. It was observed that the free swell decreased significantly for each of the test series when compared with the free swell value of 52.5 % obtained for the untreated soil. The lowest free swell value of 30 % was recorded for 8 % lime / 6 % IOT treatment of black cotton soil. However higher dosages of IOT produced no further reduction in the swelling potential of the soil. The reduction in swelling characteristics of the soil could be attributed to the physico–chemical reaction between the soil and the lime/IOT blend, which aided the formation of calcium silicate in the soil. This was responsible for the substitution of Ca^{2+} for absorbed H^{+} ions and the neutralization of the net montimorillonite clay layer negative charge. Orazulike (1992) reported that this is the phenomenon upon which chemical stabilization of soils works.

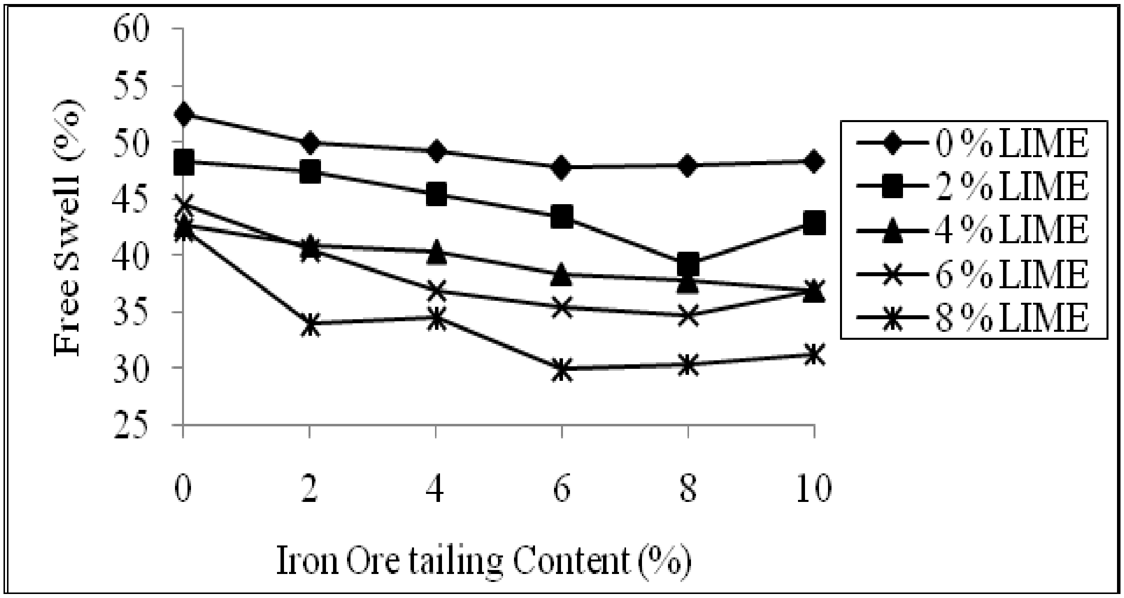


Fig 4.3 Variation of free swell of black cotton soil - lime mixtures with iron ore tailing content

The two – way analysis of variance (ANOVA) test on the free swell results (see Table 4.3) shows that the relative effects of lime and IOT on black cotton soil were statistically significant with lime having a more pronounced effect on black cotton soil than IOT. Detailed test results are given in Tables A4.20 in the Appendix.

Table 4.3: Two-way analysis of variance for free swell of black cotton soil- lime-iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
Free swell	Lime	4	90.78	1.58E-12	2.87	$F_{CRIT} > F_{CRIT}$, Significant
	IOT	5	18.33	7.39E-07	2.71	$F_{CRIT} > F_{CRIT}$, Significant

4.1.5 Cation exchange capacity

Some clay undergo isomorphous substitution, that is, substitution of cation of one kind by another while retaining the same crystal structure. This substitution, along with the dissociation of hydroxyl ions, results in a residual negative charge on the surface of the clay’s mineral particles. Positively charged ions (i.e, cations), are therefore adsorbed on its surface. These ions are not strongly held and can be replaced by other ions present in water. This phenomenon is described as cation exchange. CEC is a calculated value that is an estimate of the soils ability to attract, retain, and exchange cation elements or simply put, CEC refers to the quantity of negative charges in soil existing on the surfaces of clay that is available to bind positively charged ions (cations). Searle (1984).

The variation of the cation exchange capacity (CEC) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.4. Generally CEC value black cotton soil – lime mixtures decreased from 52.2 Cmol/kg for the natural soil to a value of 26.4 Cmol/kg at 6 % lime / 10 % IOT treatment; this corresponds to 49.4 % decrease.. The reduction in CEC could be due to the low CEC values of 21.6 and 24.6 Cmol/kg recorded for lime and IOT respectively.

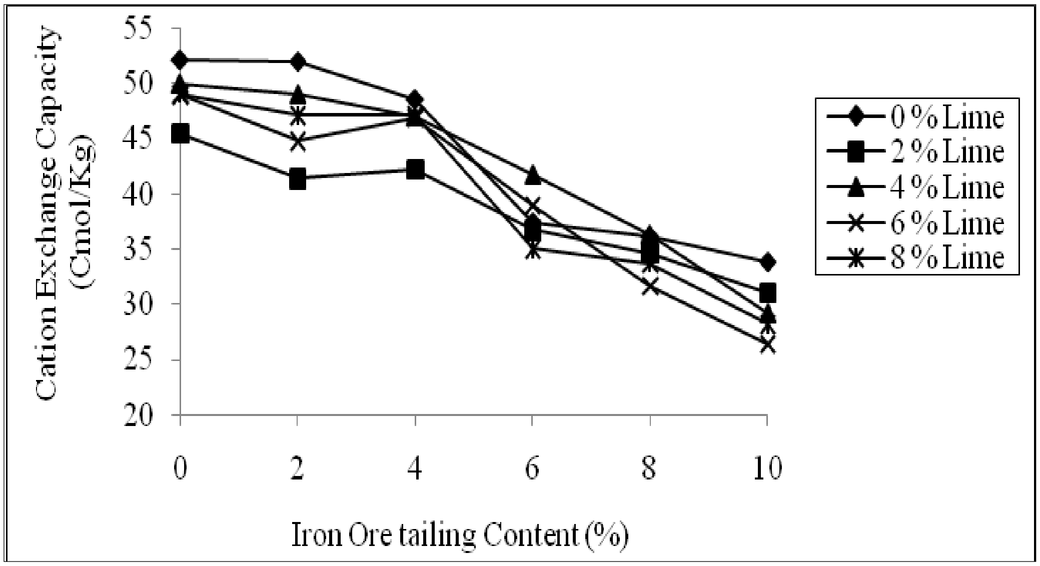


Fig. 4.4 Variation of cation exchange capacity of black cotton soil – lime mixtures with iron ore tailing content

Another reason for the reduction in CEC could be the decrease in the clay size fraction of the soil (Warrick, 2002; Salahedin, 2013). The decrease in CEC of black cotton soil (BCS) could also probably be attributed to the reduction of pH of black cotton soil by lime that had a higher calcium hydroxide content which supplied free Ca^{2+} required for the cation exchange between the clay mineral particles (Akinmade, 2008 and Salahedin, 2013).

The two-way analyses of variance (ANOVA) on CEC results (see Table 4.4) were statistically significant with IOT having a more pronounced effect. Detailed test results are given in Table A4.21 in the Appendix.

Table 4.4: Two-way analysis of variance for cation exchange capacity of black cotton soil - lime - iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
CEC	Lime	4	5.03	5.73E-03	2.87	$F_{CRIT} > F_{CRIT}$, Significant
	IOT	5	66.05	9.65E-12	2.71	$F_{CRIT} > F_{CRIT}$, Significant

4.2 Particle Size Distribution

4.2.1 Wet sieving

The particles size distribution from hydrometer test of black cotton soil-lime mixtures with IOT is shown in Fig 4.5(a) – (e). It was observed that the percentage fines reduced with increase in IOT content from a value of 80.7 % for the natural soil to 78.3 % for 0 % lime /10 % IOT treatment (see Fig 4.5(a)). Similar trends of results were observed for the different percentages of lime considered (see Fig 4.5(b) - (e)). The reduction in fines fraction with increase in IOT content could be attributed to flocculation and agglomeration of the black cotton soil-lime mixtures and thus enabled the clay fraction to form larger soil sizes (Hopkins *et al.*, 2002; Akinmade, 2008; Oyelakin, Jung and Bobet, 2008; 2011; Jung and Al karagooly, 2012; Portelinha et al., 2012).

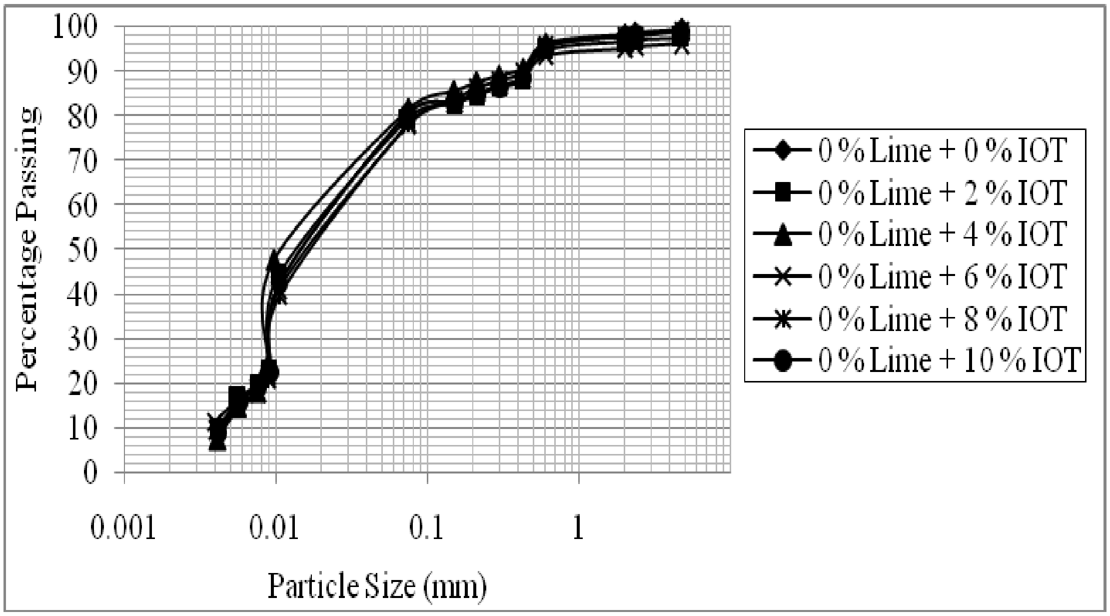


Fig. 4.5a: Particle size distribution curves for black cotton soil – 0 % lime – iron ore tailing mixtures

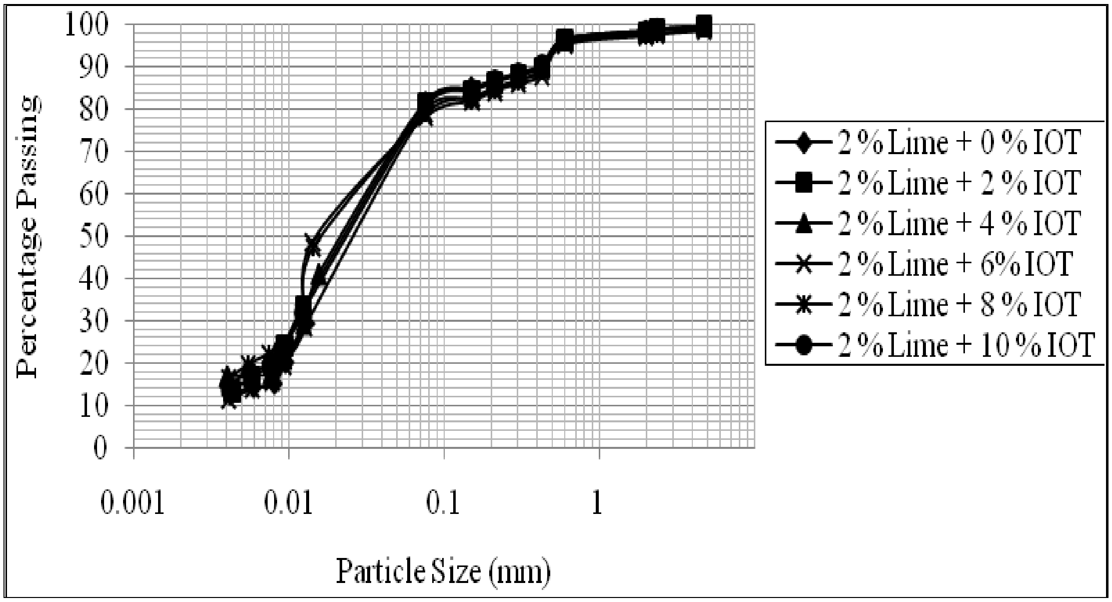


Fig. 4.5b: Particle size distribution curves for black cotton soil – 2 % lime – iron ore tailing mixtures

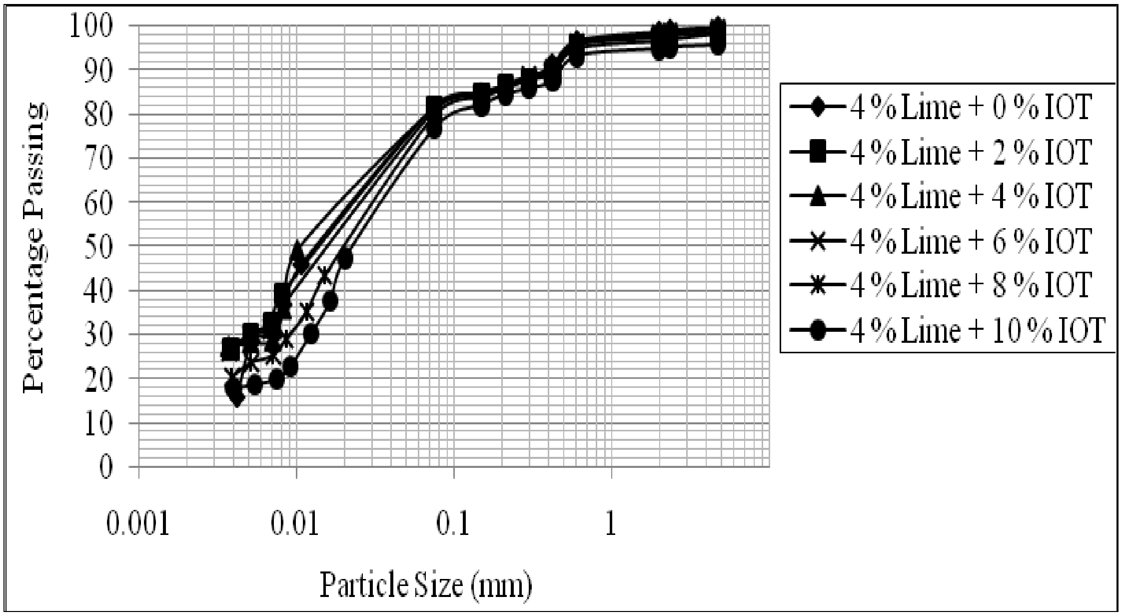


Fig. 4.5c: Particle size distribution curves for black cotton soil – 4 % lime – iron ore tailing mixtures

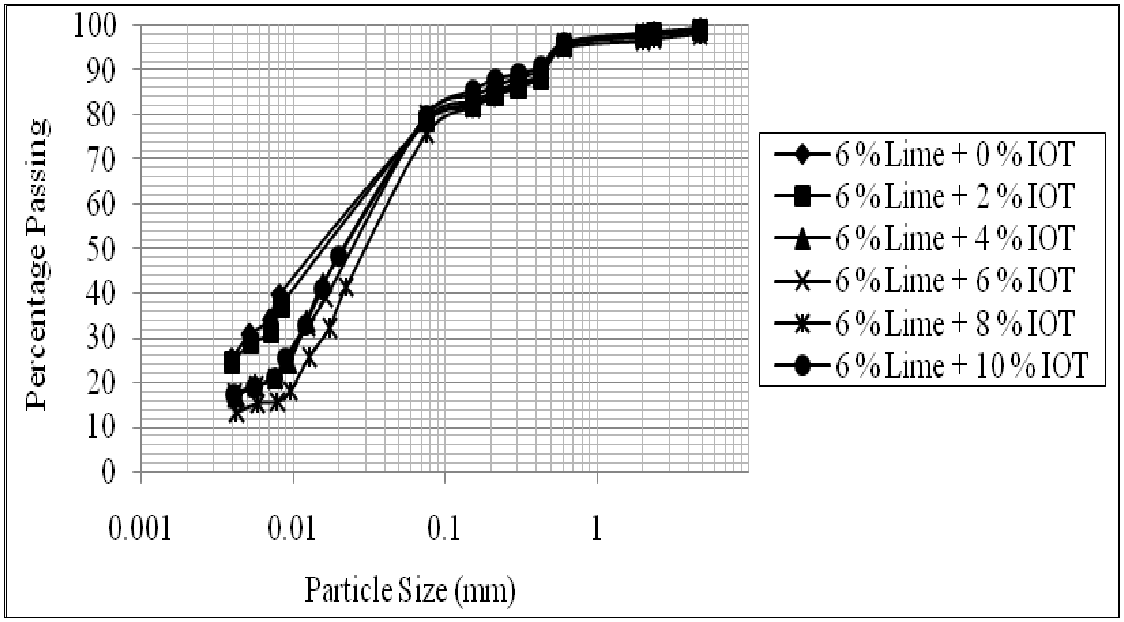


Fig. 4.5d: Particle size distribution curves for black cotton soil – 6 % lime – iron ore tailing mixtures

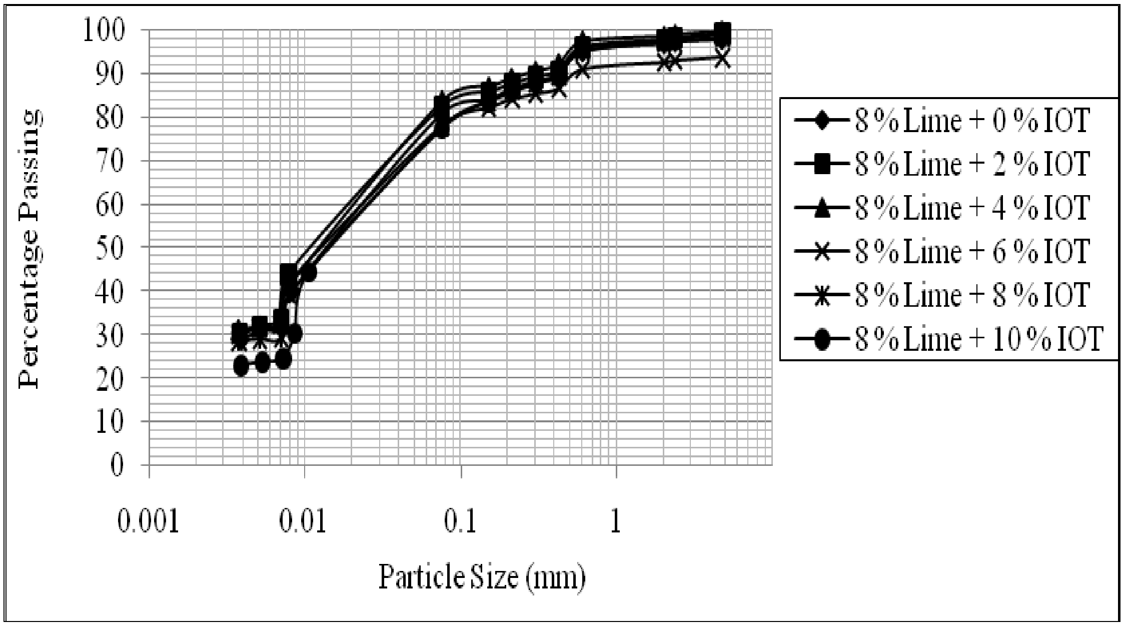


Fig. 4.5e: Particle size distribution curves for black cotton soil – 8 % lime – iron ore tailing mixtures

4.2.2. Dry sieving

4.2.2.1 Using optimum moisture content from British Standard light compaction

The particle size distribution curves of the stabilized black cotton soil using optimum moisture content (OMC) from BSL compaction are shown in Fig. 4.6 (a) – (e). A trend of reduction in the percentage of fines with increasing lime and IOT contents was noticed..

The reduction in clay content was due to the hydration of lime and IOT which acted as a nucleus to which soil particles adhered. With increase in lime and IOT contents the quantity of free silt and clay progressively reduced and coarser materials were formed in agreement with Kedzi (1979) and Osinubi (1995). Similarly the increase in the coarser particle could be due to high moisture content available for hydration of free lime and silica as well as agglomeration/bonding to take place in the soil-additives blend (Osula, 1991; Obeahon, 1993).

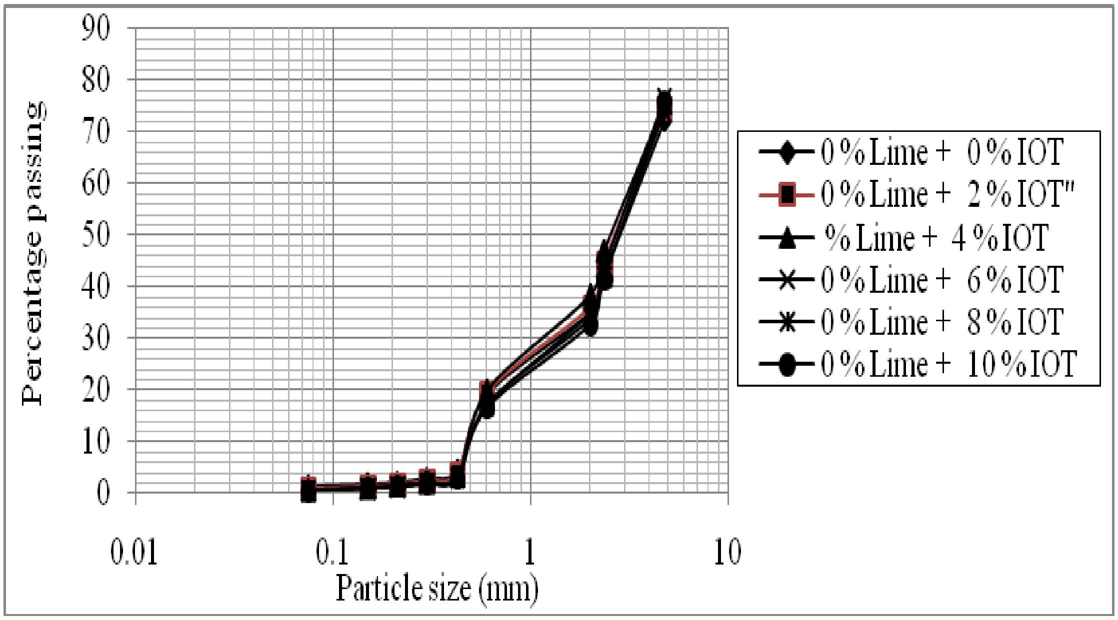


Fig. 4.6a: Particle size distribution curves for black cotton soil – 0 % lime – iron ore tailing mixtures (BSL compaction)

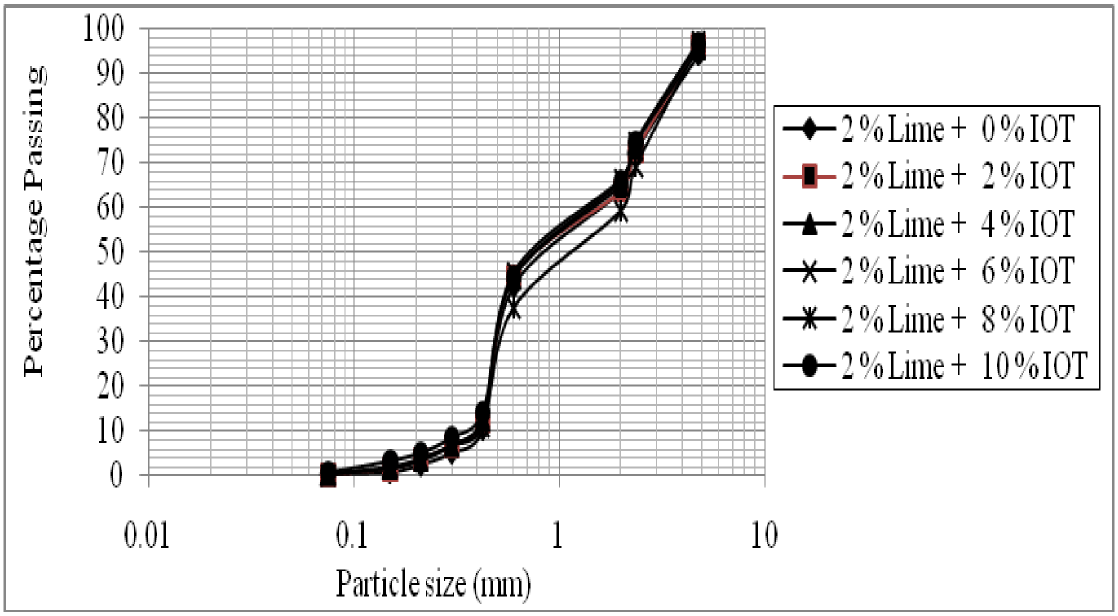


Fig. 4.6b: Particle size distribution curves for black cotton soil – 2 % lime – iron ore tailing mixtures (BSL compaction)

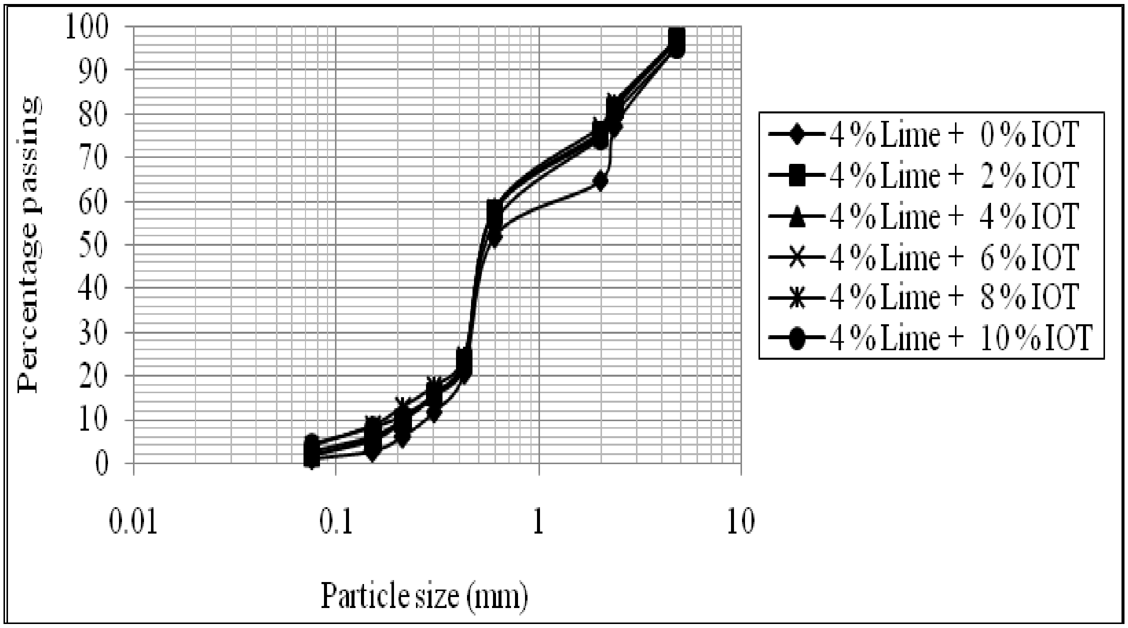


Fig. 4.6c: Particle size distribution curves for black cotton soil – 4 % lime – iron ore tailing mixtures (BSL compaction)

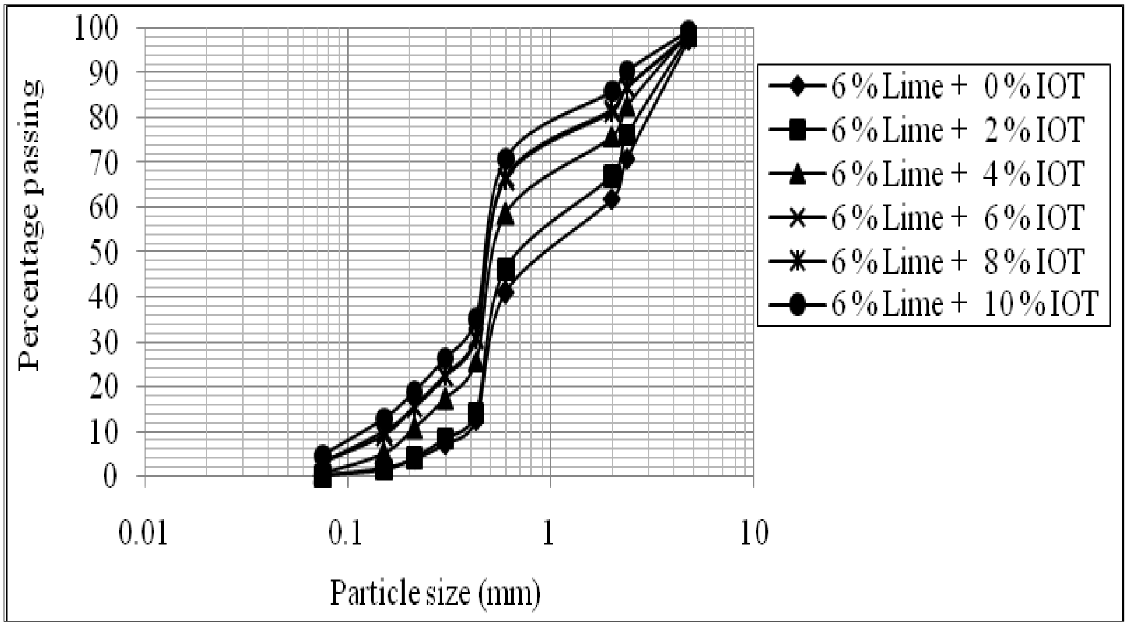


Fig. 4.6d: Particle size distribution curves for black cotton soil – 6 % lime – iron ore tailing mixtures (BSL compaction)

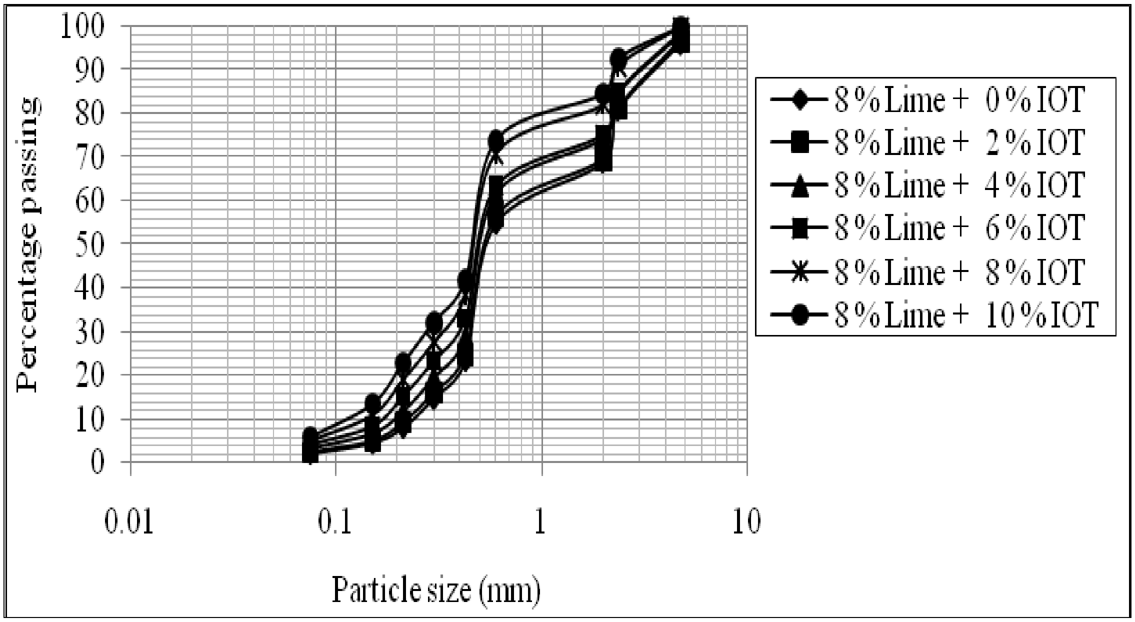


Fig. 4.6e: Particle size distribution curves for black cotton soil – 8 % lime – iron ore tailing mixtures (BSL compaction)

4.2.2.2 Using optimum moisture content from West African Standard compaction

The particle size distribution curves of the stabilized black cotton soil using optimum moisture content (OMC) for WAS compaction are shown in Fig. 4.7 (a) – (e). The effect of IOT content on particle size distribution caused the black cotton soil - lime - IOT mixtures to flocculate and agglomerate more and hence the soil - lime - IOT mixture became coarser enabling the clay particle to form pseudo silt sizes. The results are consistent with the findings reported by Osula (1991) and Obeahon (1993).

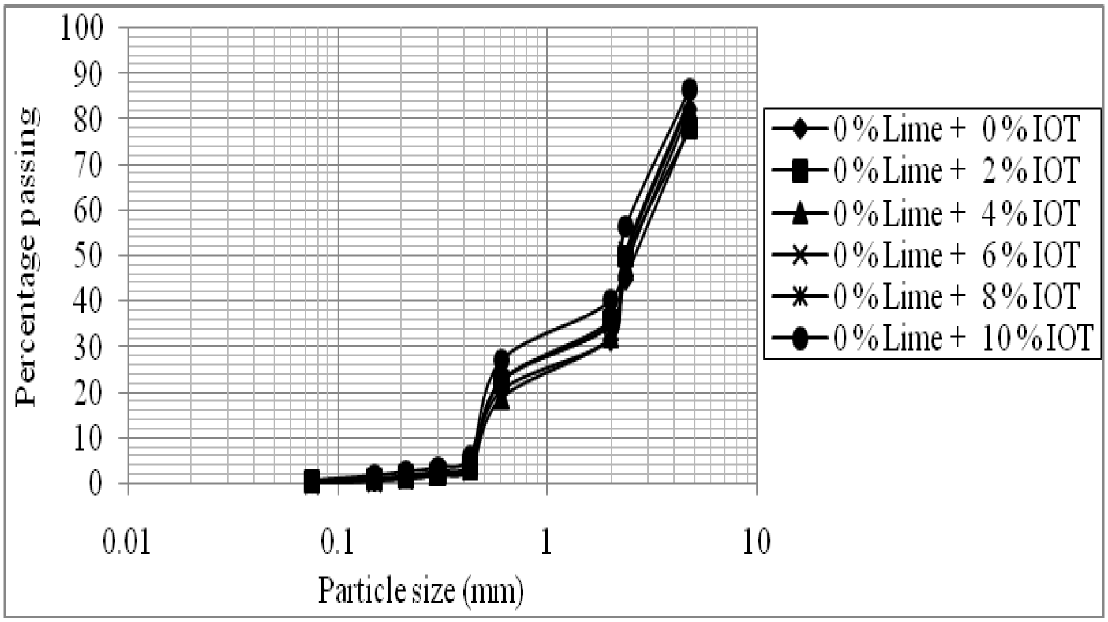


Fig. 4.7a: Particle size distribution curves for black cotton soil – 0 % lime – iron ore tailing mixtures (WAS compaction)

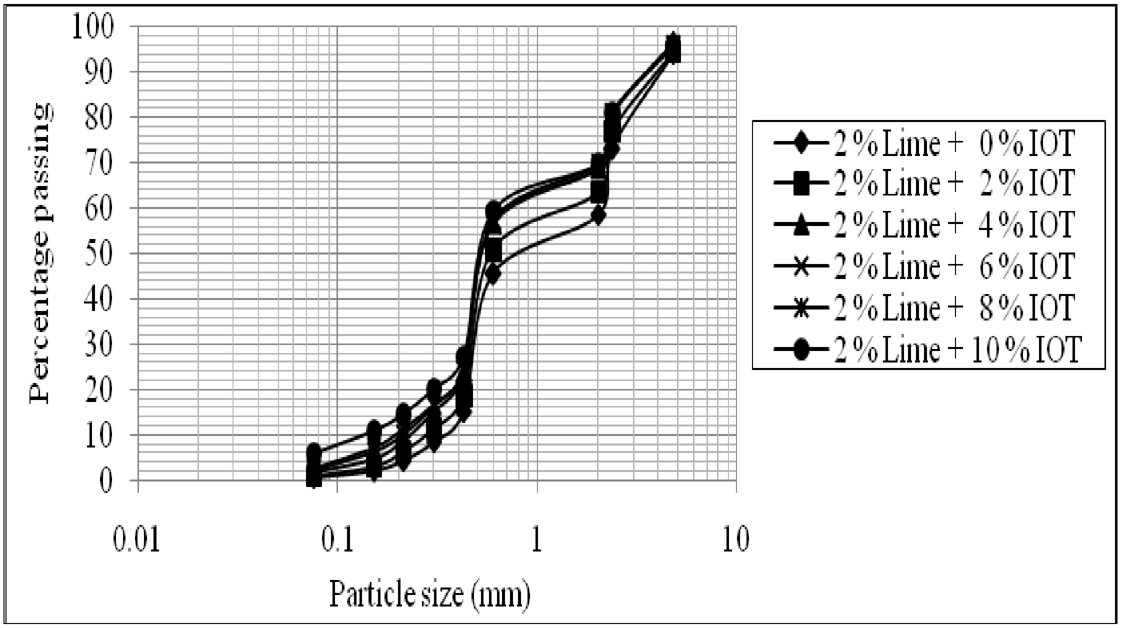


Fig. 4.7b: Particle size distribution curves for black cotton soil – 2 % lime – iron ore tailing mixtures (WAS compaction)

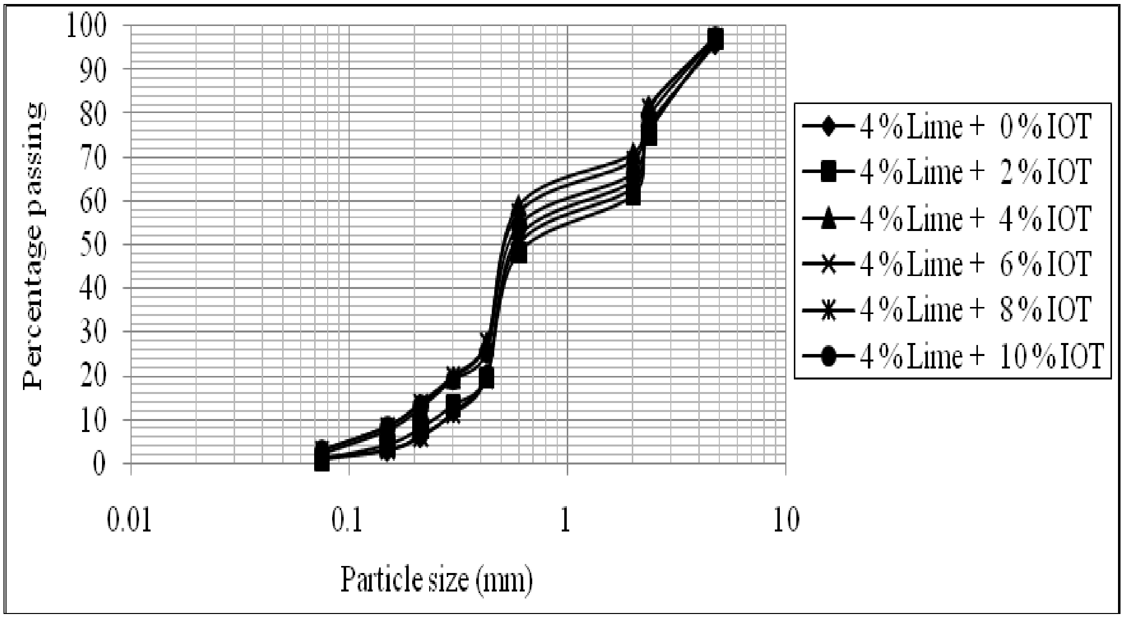


Fig. 4.7c: Particle size distribution curves for black cotton soil – 4 % lime – iron ore tailing mixtures (WAS compaction)

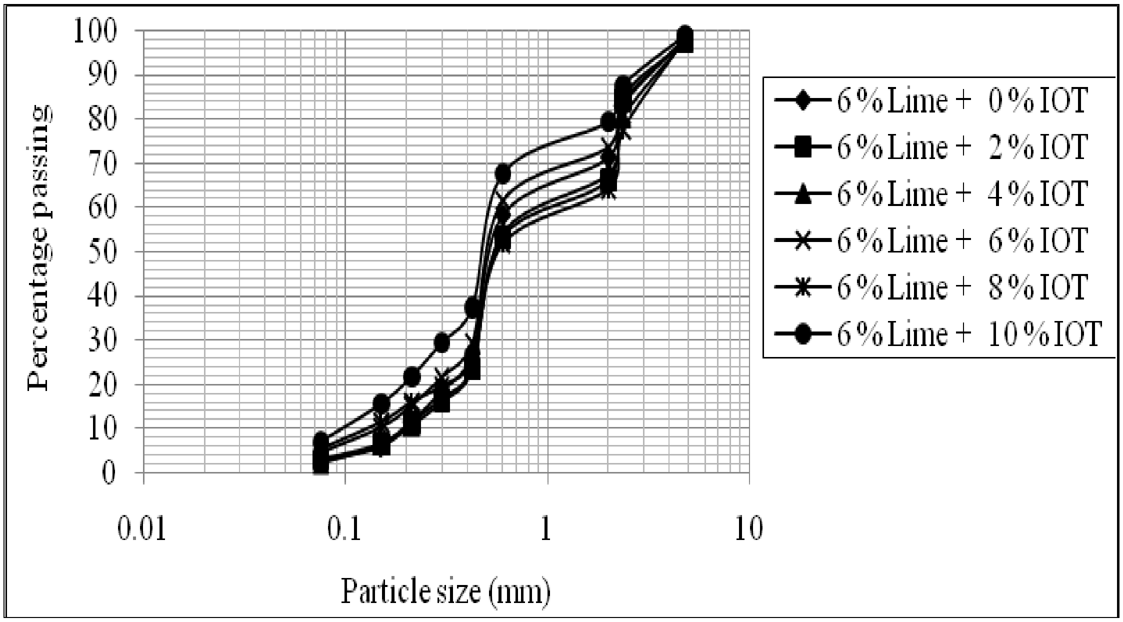


Fig. 4.7d: Particle size distribution curves for black cotton soil – 6 % lime – iron ore tailing mixtures (WAS compaction)

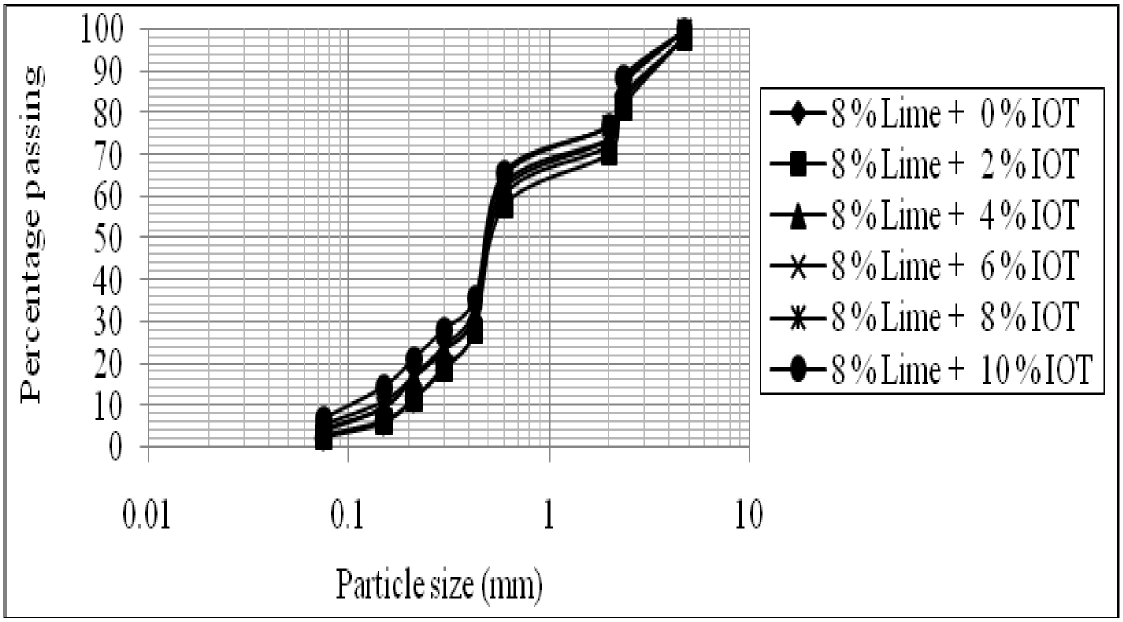


Fig. 4.7e: Particle size distribution curves for black cotton soil – 8 % lime – iron ore tailing mixtures (WAS compaction)

4.2.2.3 Using optimum moisture content from British Standard heavy compaction

The particle size distribution curves of the stabilized black cotton soil using optimum moisture content (OMC) for BSH compaction are shown in Fig. 4.8 (a) – (e). The effect of IOT content on particle size distribution caused the soil - lime – IOT mixture to flocculate and agglomerate more and hence the soil – lime – IOT mixture got coarser enabling the clay particle to form pseudo silt sizes. The results are consistent with the findings reported by Osula (1991) and Obeahon (1993). It could be observed that the available water as a result of the molding moisture content facilitates the agglomeration of the soil particles to form a macro structural particle. As the compactive effort increased the moulding moisture content decreased such that the agglomeration of the soil particle may not have been perfectly complete with increase in the percentage of the additives.

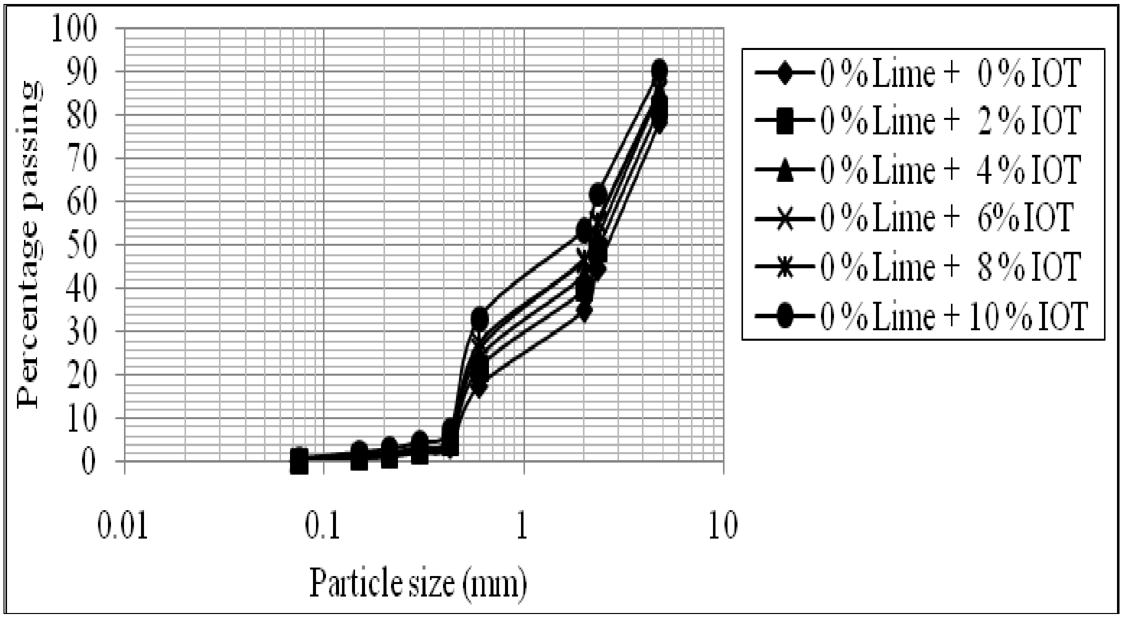


Fig. 4.8a: Particle size distribution curves for black cotton soil – 0 % lime – iron ore tailing mixtures (BSH compaction)

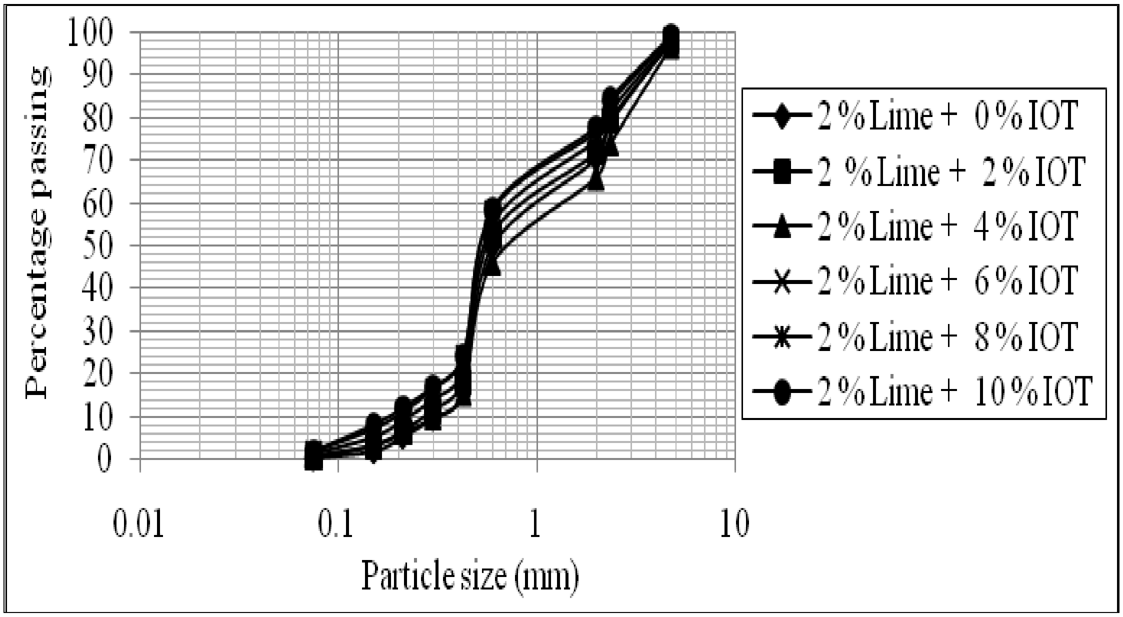


Fig. 4.8b: Particle size distribution curves for black cotton soil – 2 % lime – iron ore tailing mixtures (BSH compaction)

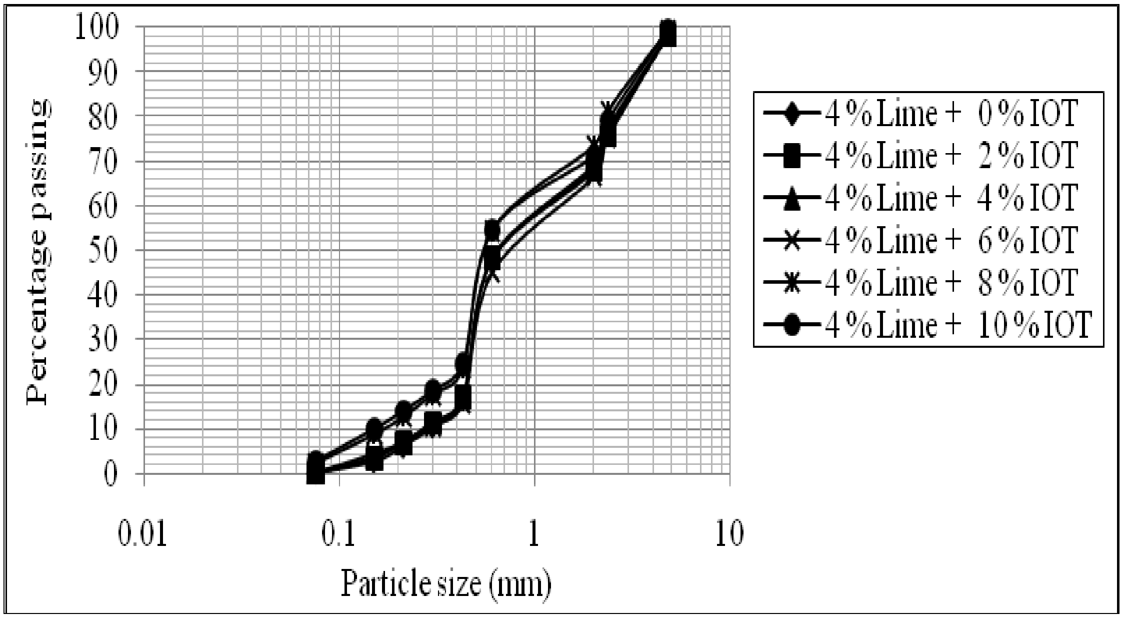


Fig. 4.8c: Particle size distribution curves for black cotton soil – 4 % lime – iron ore tailing mixtures (BSH compaction)

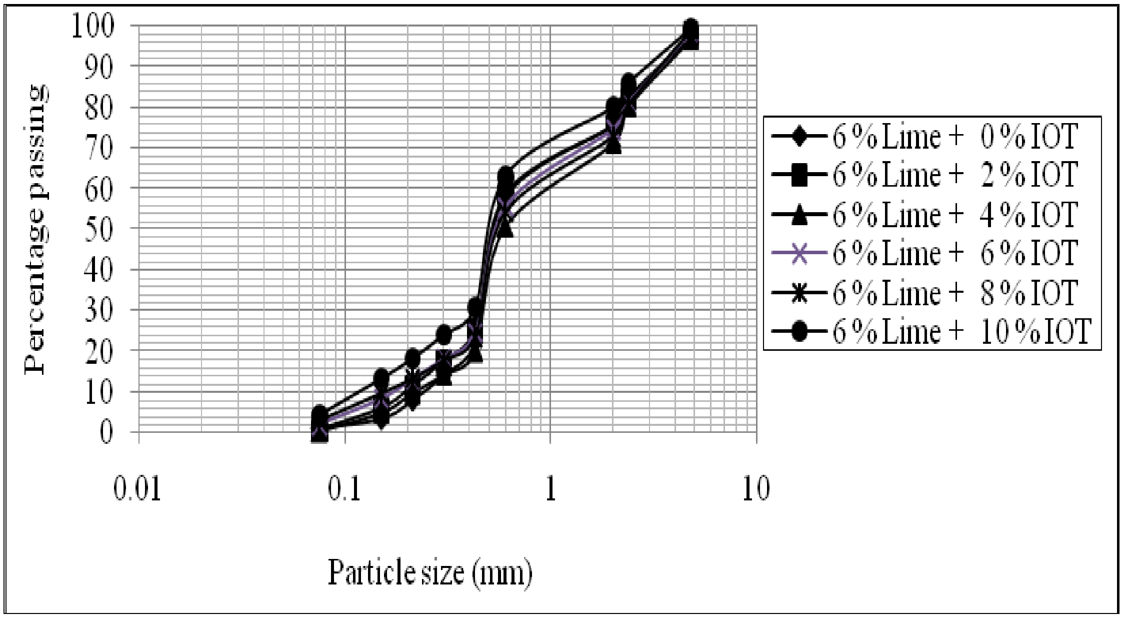


Fig. 4.8d: Particle size distribution curves for black cotton soil – 6 % lime – iron ore tailing mixtures (BSH compaction)

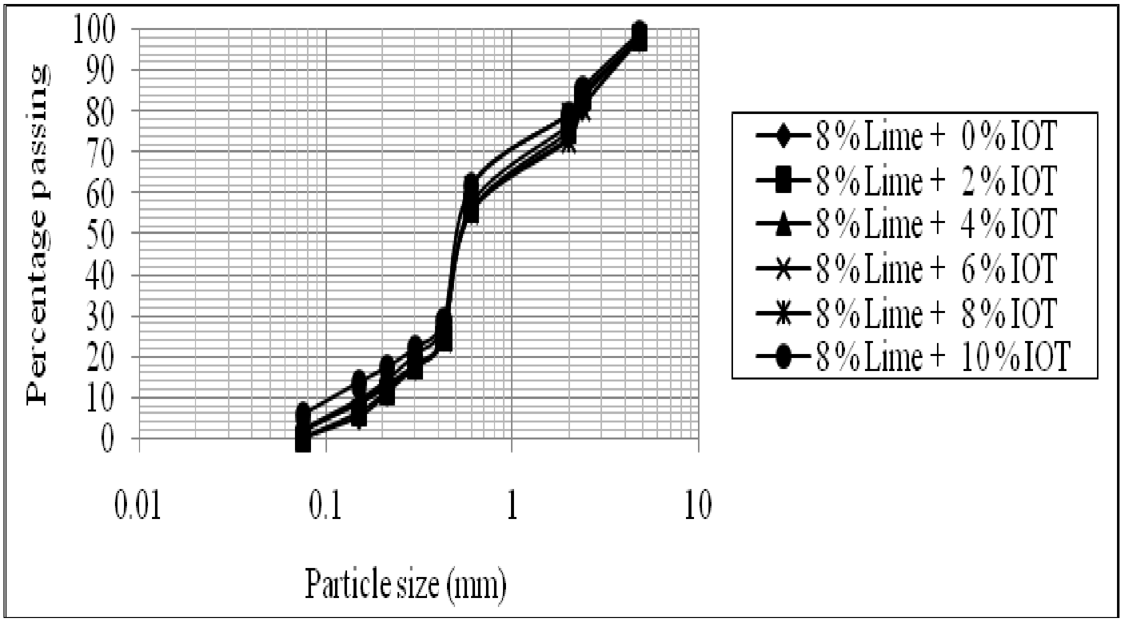


Fig. 4.8e: Particle size distribution curves for black cotton soil – 8 % lime – iron ore tailing mixtures (BSH compaction)

Detailed test results for sieve analysis are given in Table A4.5 a – d in the Appendix.

4.3 Atterberg Limits

4.3.1 Liquid limit

The variation of liquid limit (LL) of black cotton soil - lime mixture withiron ore tailing content is shown in Fig. 4.9a. Generally, liquid limit decreased with higher lime and IOT content. The overall reduction in the liquid limit of soil could be attributed to the effect of the lime/IOT blend on the high affinity for H^+ of the clay and silt fraction of the soil as well as the flocculation and agglomeration of the clay particles. The dissolved Ca^{2+}, Si^{2+} and Al^{3+} in the stabilizer-admixture blend responsible for the displacement of the Mg^{2+}, Fe^{2+} and other cations in the soil may in part be responsible for the reduction in the number of interlayer molecules of montimorillonite clay mineral (Umar and Osinubi, 2003). The reduction in liquid limit from 56.8 % for the untreated soil to a minimum value of 43.8 % was recorded at 8 % lime / 6 % IOT treatmenr. This corresponds to a decrease of 22.9 %.

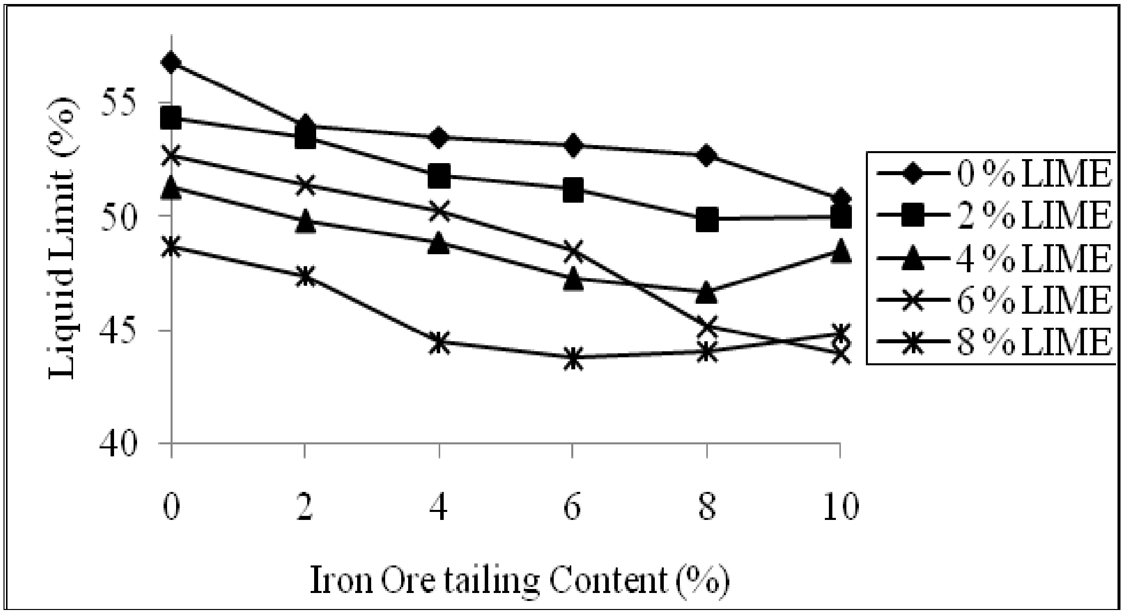


Fig. 4.9: Variation of liquid limit of black cotton soil -lime mixtures with iron ore tailing content

The results of the two-way analysis of variance (ANOVA) on liquid limit results (see Table 4.5) were statistically significant with lime having a more pronounced effect.

4.3.2 Plastic limit (PL)

The variation of the plastic limit (PL) of the black cotton soil-lime mixtures with IOT content is shown in Fig. 4.10. The plastic limit decreased with increasing IOT content for all lime content. The results are not consistent with the findings of Ovuarume (2011) who reported the increase in plastic limit of soil - lime - LBWA mixtures due to highly plastic nature of lime and the soil-lime reaction (Osula, 1991). In this study it was observed that the highly non-plastic nature of IOT may have had significant effect in reducing the plastic limit in agreement with the findings of Ramesh et al. (2013). The decrease may be due to cation exchange reaction that liberated adsorbed water particles in the soil leading to the flocculation and aggregation of the soil (Osinubi, 1995).

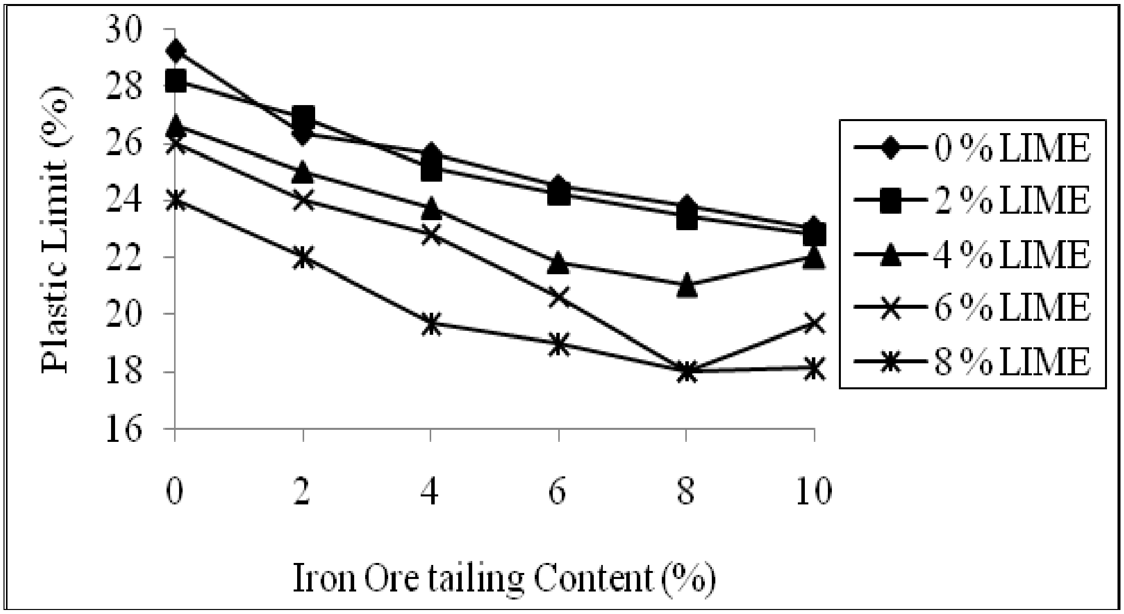


Fig. 4.10: Variation of plastic limit of black cotton soil-lime mixtures with iron ore tailing content

The results of the two-way analysis of variance (ANOVA) on plastic limit results (see Table 4.5) were statistically significant with lime having a more pronounced effect.

4.3.3 Plasticity index

The variation of plasticity index (PI) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.11. Generally plasticity index of black cotton soil – lime – iron ore tailing mixture increased with higher iron ore tailing content the plasticity index of the soil increase from its natural value of 27.6 % to a maximum value of 28.9 % at 0 % lime / 8 % IOT treatment.

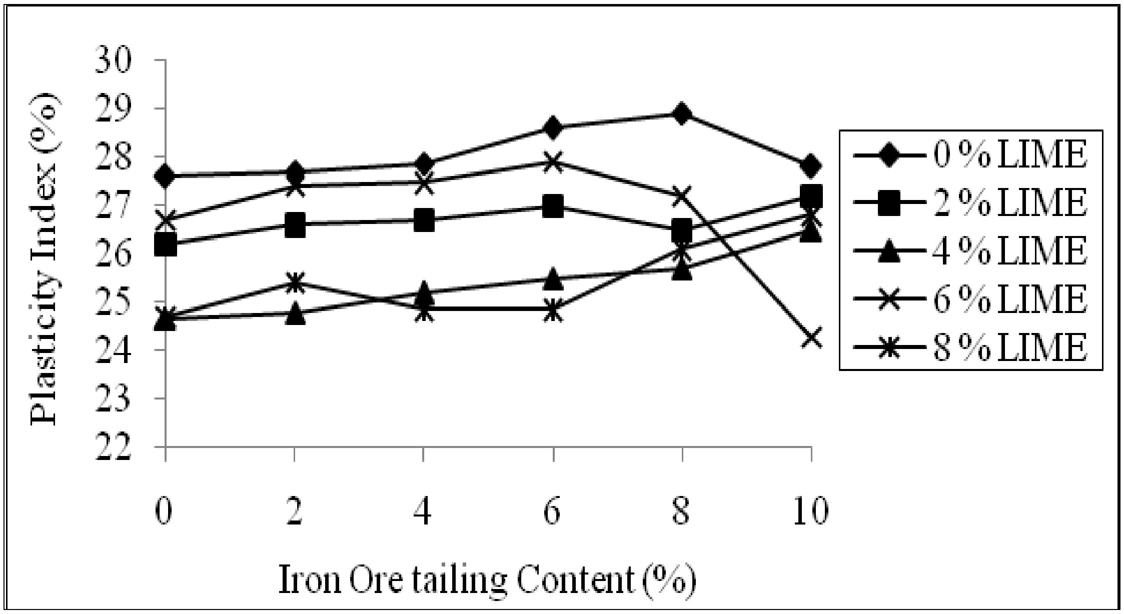


Fig. 4.11: Variation of plasticity index of black cotton soil-lime mixtures with iron ore tailing content

The two-way analysis of variance (ANOVA) on plasticity index results (see Table 4.5) shows that the effect of lime on black cotton soil was statistically significant. On the other hand the effect of IOT was not statistically significant.

4.3.4 Linear shrinkage

The variation of linear shrinkage of black cotton soil-lime mixture with iron ore tailing content is shown in Fig. 4.12: The linear shrinkage result shows a steady decrease in the linear shrinkage from 18.1 % for the natural soil to 11.0 % at 10 % IOT content. On treatment with 2, 4, 6 and 8 % lime and up to 10 % IOT content the linear shrinkage progressively decreased. This trend is in conformity with the report of (Ola 1991; Osinubi 1995, 1999; Buhler and Cerato 2007). This decrease suggests that the use of lime in conjunction with IOT resulte in a soil of lesser shrinkage when compared with IOT treatment alone. It was observed that specimens which were not treated with lime (i.e., specimens treated with IOT alone) yielded shrinkage values that are higher than the values obtained for specimens treated with lime and IOT blend.

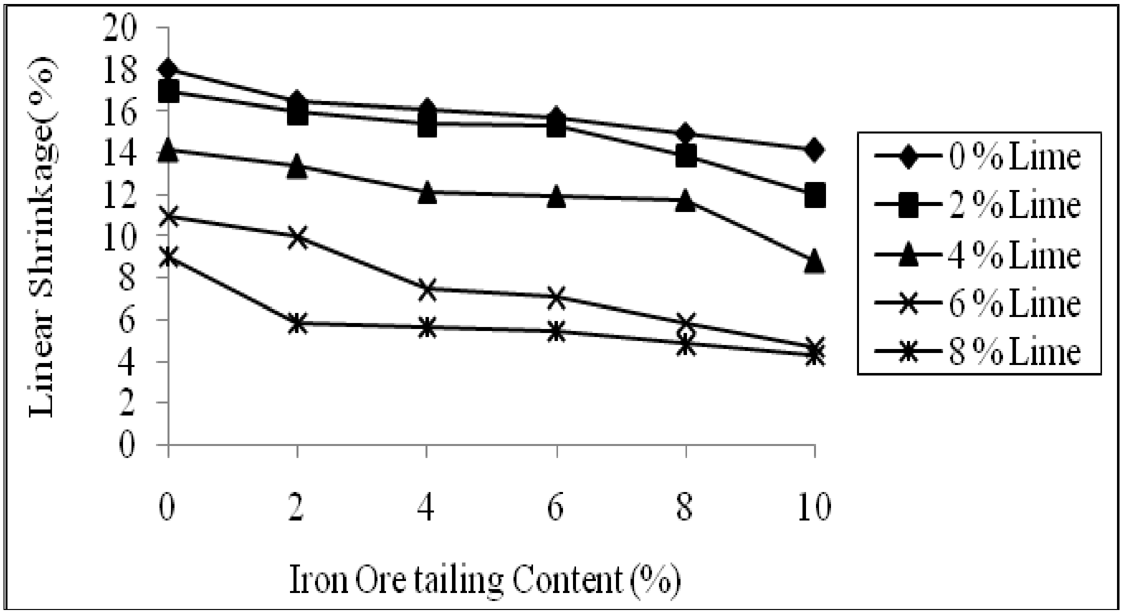


Fig. 4.12: Variation of linear shrinkage of black cotton soil-lime mixture with iron ore tailing content

The results of the two-way analysis of variance (ANOVA) on plastic limit results (see Table 4.5) were statistically significant with lime having a more pronounced effect.

Table 4.5: Two -way analysis of variance for Atterberg limits of black cotton soil-lime-iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
Liquid Limit	Lime	4	58.86	8.85E-11	2.87	F_{CAL}>F_{CRIT}, Significant effect
	IOT	5	16.03	2.12E-06	2.71	F_{CAL}>F_{CRIT}, Significant effect
Plastic Limit	Lime	4	77.24	7.17E-12	2.87	F_{CAL}>F_{CRIT}, Significant
	IOT	5	61.35	1.92E-11	2.71	F_{CAL}>F_{CRIT}, Significant
Plasticity Index	Lime	4	19.38	1.18E-06	2.87	F_{CAL}>F_{CRIT}, Significant
	IOT	5	2.11	1.07E-01	2.71	F_{CRIT}>F_{CAL}, Not significant
Linear Shrinkage	Lime	4	260.35	6.10E-17	2.87	F_{CAL}>F_{CRIT}, Significant
	IOT	5	33.37	4.81E-09	2.71	F_{CAL}>F_{CRIT}, Significant

Detailed test results are given in Table A4.22 - A4.25 in the Appendix.

4.4 Compaction Characteristics

4.4.1 Maximum dry density

The variation of maximum dry density (MDD) of black cotton soil – lime mixtures with IOT content for BSL, WAS and BSH compactions are shown in Fig. 4.13a-c. Generally MDD values increased with increasing IOT content for all lime contents considered. For the British Standard light (BSL) compaction, it was observed that MDD increased generally with increase in IOT content (see Fig. 4.13a) from a value of 1.55 Mg/m^3 for the natural soil to a peak value of 1.65 Mg/m^3 for 8 % lime / 8 % IOT treatment. It was also observed that all peak values were recorded at 8 % IOT content for the various lime contents considered.

The trend observed for BSL compaction was recorded for WAS and BSH compactions. For WAS and BSH compactions, MDD values increased from 1.60 and 1.70 Mg/m^3 for the natural soil to peak values of 1.72 amd 1.82 Mg/m^3 for 6 % lime / 8 % IOT (see Fig. 4.13b) and 8 % lime / 8 % IOT (see Fig. 4.13c) treatments, respectively. The observed trends are similar to the findings reported by Phanikumar and Sharma (2004), Jadhao and Nagarnik (2008) as well as Kumar and Puri (2013).

The increase in MDD recorded for all the compactive efforts, may not be unconnected with the flocculation and agglomeration of the clay particles primarily due to cation exchange in addition to the particles filling the voids within the soil matrix (O'Flaherty, 1988; Osinubi, 2000a: Moses, 2008: Oriola and Moses, 2010).

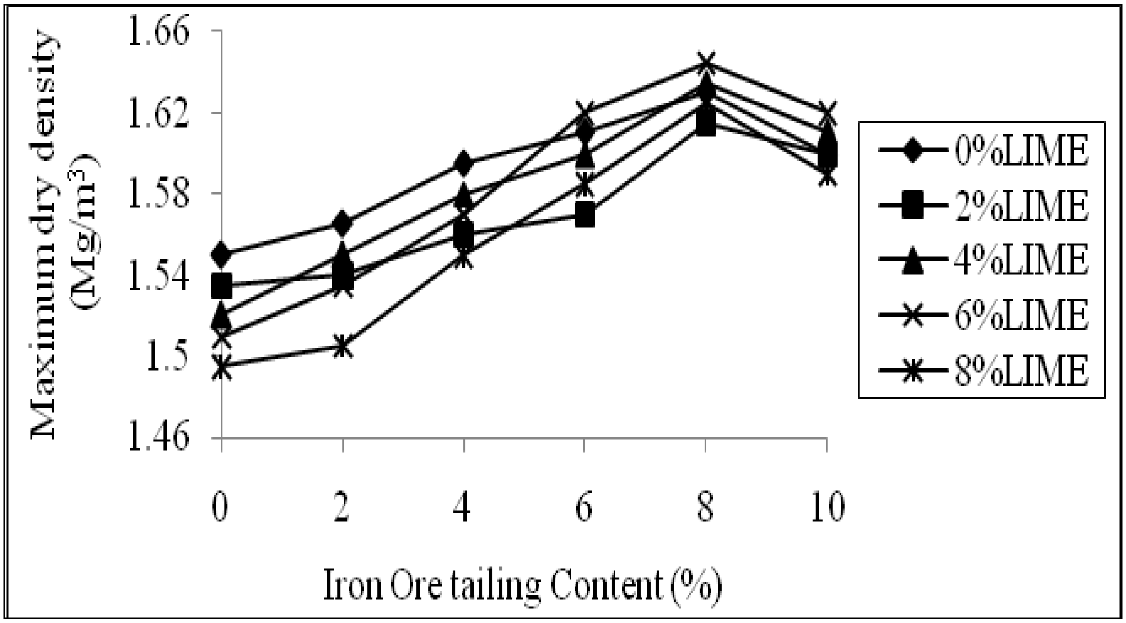


Fig. 4.13a: Variation of maximum dry density of black cotton soil–lime mixtures with iron ore tailing content (BSL compaction)

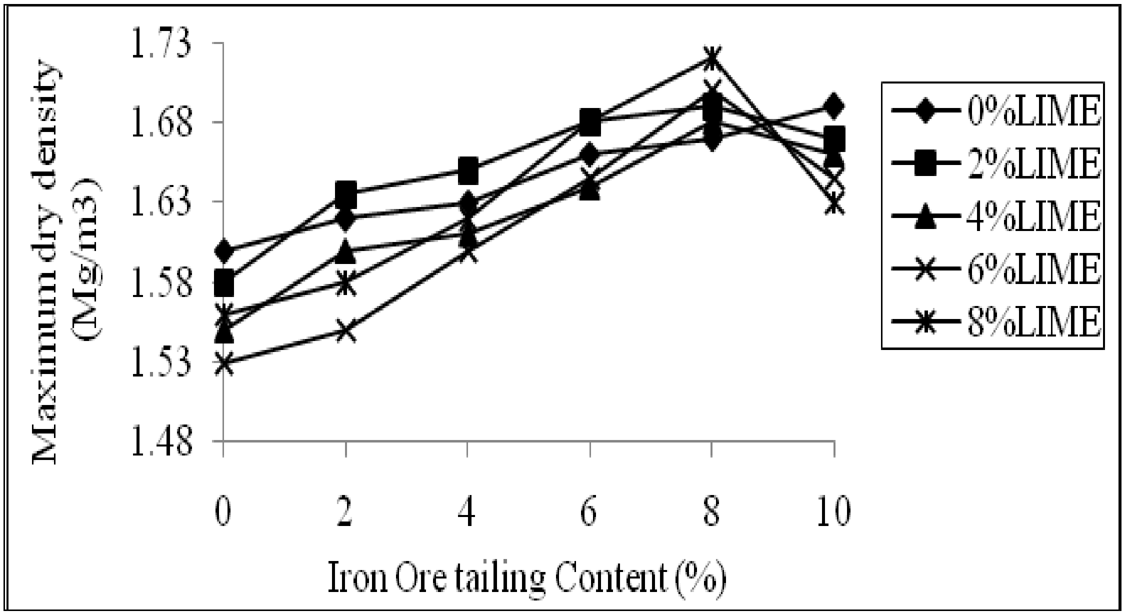


Fig. 4.13b: Variation of maximum dry density of black cotton soil–lime mixtures with iron ore tailing content (WAS compaction)

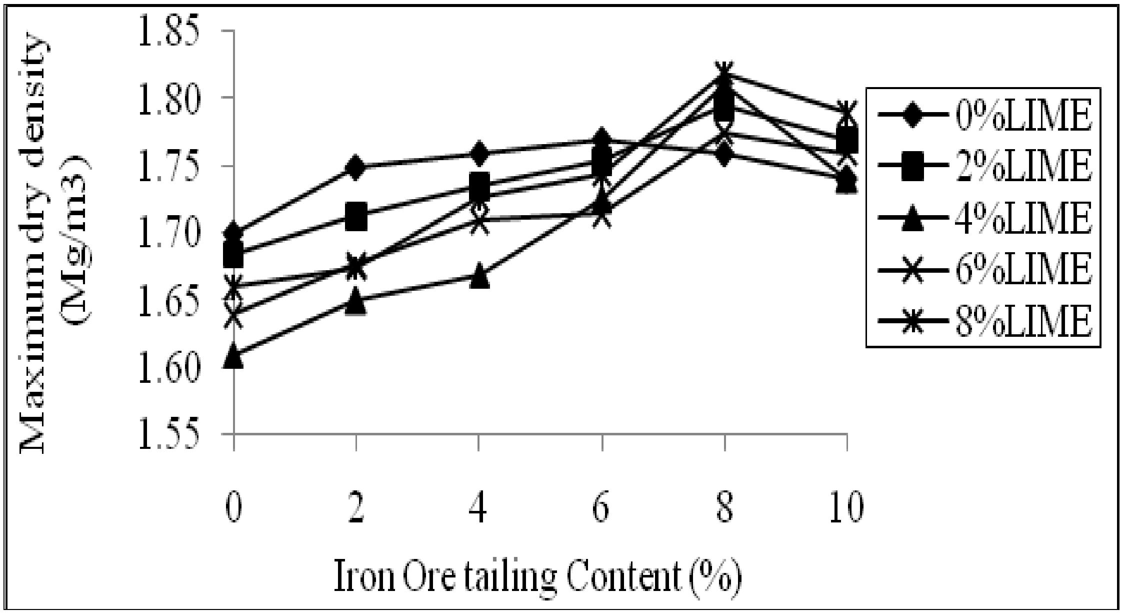


Fig. 4.13c: Variation of maximum dry density of black cotton soil–lime mixtures with iron ore tailing content (BSH compaction)

Furthermore, there was a possibility that the increase in MDD could be as a result of IOT which has a higher specific gravity (3.29) replacing the soil particles which has a lower specific gravity of 2.48 thus resulting in the formation of a mixture with higher specific gravity and higher MDD as reported by Ishola (2014).

The reduction in MDD beyond 8 % IOT content may be due to flocculated and agglomerated particles occupying larger spaces leading to corresponding decrease in dry density (Ola, 1991; Lees *et al*., 1982: Sani, 2012), it could also be due to the minimal effect of IOT (with little calcium) on the workability of the stabilized soil. The decrease in

MDD was also probably due to the fact that for any soil - additive mixture, there is always a water content that produces maximum strength (Osinubi, 1999).

The two - way analysis of variance (ANOVA) test on the MDD result for BSL, WAS and BSH compaction (see Table 4.6) shows that the effects of lime and IOT on black cotton soil were statistically significant for lime (F_{CAL} = 5.79, 3.87, 3.82 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 47.81, 28.39, 18.34 > F_{CRIT} = 2.71).

Table 4.6: Two-way analysis of variance for maximum dry density of black cotton soil - lime – iron ore tailing mixtures

Property		Source of variation	Degree of freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	MDD	Lime	4	5.79	2.91E-03	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	47.81	1.91E-10	2.71	F_{CAL}>F_{CRIT}, Significant
WAS	MDD	Lime	4	3.87	1.73E-02	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	28.39	1.96E-08	2.71	F_{CAL}>F_{CRIT}, Significant
BSH	MDD	Lime	4	3.82	1.82E-02	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	18.34	7.37E-07	2.71	F_{CAL}>F_{CRIT}, Significant

Detailed test results are given in Tables A4.26 a - c in the Appendix.

4.4.1.1 Regression analysis for maximum dry density

Results of regression analysis showed that the maximum dry density was influenced by the grading properties, specific gravity and compactive effort applied. This agrees with previous statements by Gidigasu (1976) who stated that the behaviour of soil used in pavement structure has been found to depend mainly on their particle size characteristics, the nature and strength of the particles and the degree to which the soils have been compacted. The geotechnical properties considered for this analysis include the lime content, iron ore tailing content, gravel, sand and silt alongside their respective specific gravities using compactive effort as a deterministic parameter with compactive effort index values of –1, 0 and 1 for British Standard light, West African Standard and British Standard Heavy compactive efforts respectively. The regression equations (see equation 4.1) revealed the extent to which these parameters influence the maximum dry density which is a function of the coefficient of each parameter. The specific gravity and compactive effort has the most significant effect on the maximum dry density having higher coefficient than the others parameters which is similar to the report of Yohanna (2015). The positive coefficient for lime content, iron ore tailing content, gravel, sand and silt could be associated with the reduction in the voids within the soil matrix leading to the increase in the maximum dry density. The correlation coefficient values (R^2) shows a strong relationship between maximum dry density and the parameters with R^2 value of 86.3%.

The regression equations is

$$\mathrm{MDD} = 0.92 + 0.00053\mathrm{L} + 0.00774\mathrm{IOT} + 0.00368\mathrm{Gc} + 0.00011\mathrm{Sa} + 0.000686\mathrm{Si} + 0.254\mathrm{Gs} + 0.0753\mathrm{CE} \tag{4.1}$$

R^2= 86.3%

Where MDD = Maximum dry density, L= Lime content, IOT = Iron ore tailing content, Gc = Gravel content, Sa = Sand, Si = Silt, Gs = Specific gravity, CE = Compactive effort.

The two – way analysis of variance (ANOVA) test for MDD is given in Table 4.7. The analysis shows that the IOT (F_{CAL} = 15.846 > F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 455.036 > F_{CRIT} = 3.156) significantly affected MDD values of the treated soil.

However, the effect of Compactive effort on the MDD of black cotton soil was much more significant.

Table 4.7: Two-way analysis of variance for regression analysis on maximum dry density of black cotton soil-lime-IOT mixtures

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
MDD	IOT	29	15.846	2.61E-18	1.663	$F_{CAL}>F_{CRIT}$, Significant effect
	Compactive effort	2	455.036	3.53E-36	3.156	$F_{CAL}>F_{CRIT}$, Significant effect

4.4.2 Optimum moisture content

The variation of optimum moisture content (OMC) of black cotton soil - lime mixtures with iron ore tailing contents for BSL, WAS and BSH compactive efforts is shown in Fig. 4.14a-c. It was observed that there was a general decrease in OMC with increased IOT treatment for specimens compacted with BSL, WAS and BSH energy levels. This observed decrease in OMC could be probably due to self – desiccation in which all the water was used up thus resulting in low hydration. When there was no water movement to or from black cotton soil – lime - IOT matrix the available moisture was used up in the hydration reaction until too little was left to saturate the solid surfaces and hence the relative humidity within the paste decreased (Osinubi, 1998c; Okonkwo, 2009 Moses *et al.*, 2012). The subsequent increase in OMC could be that the soil-lime-IOT mixtures require more moulding water to achieve effective bonding. It was also observed that OMC decreased with higher compactive effort because it was easier to breakdown flocculated aggregates, destroy shear planes and eliminate large pores, at higher compactive efforts. (Osinubi, 1999).

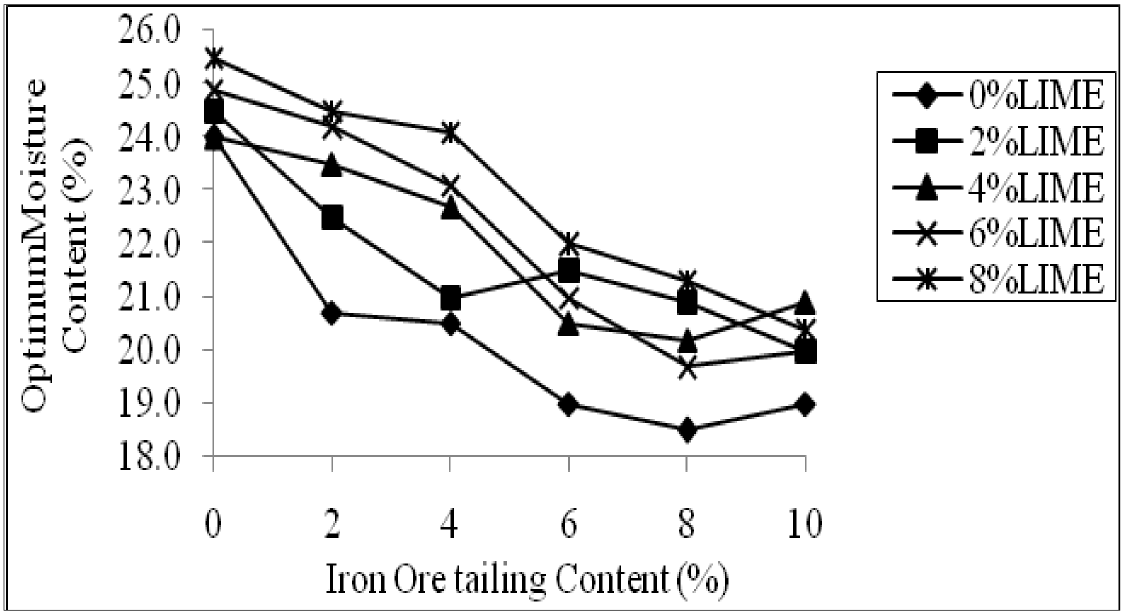


Fig. 4.14a: Variation of optimum moisture content of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

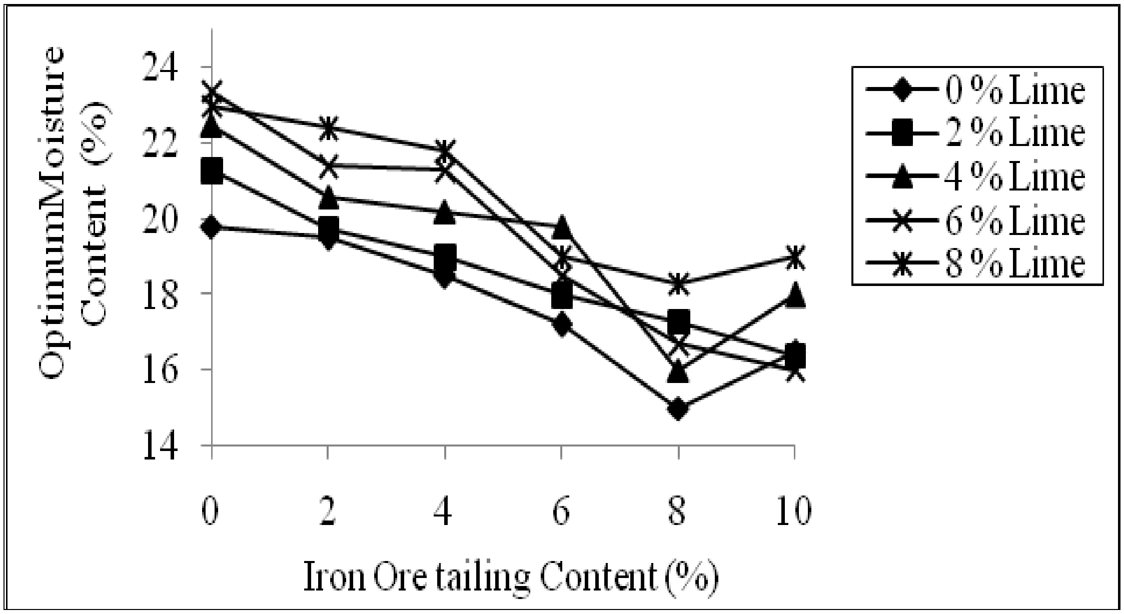


Fig. 4.14b: Variation of optimum moisture content of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

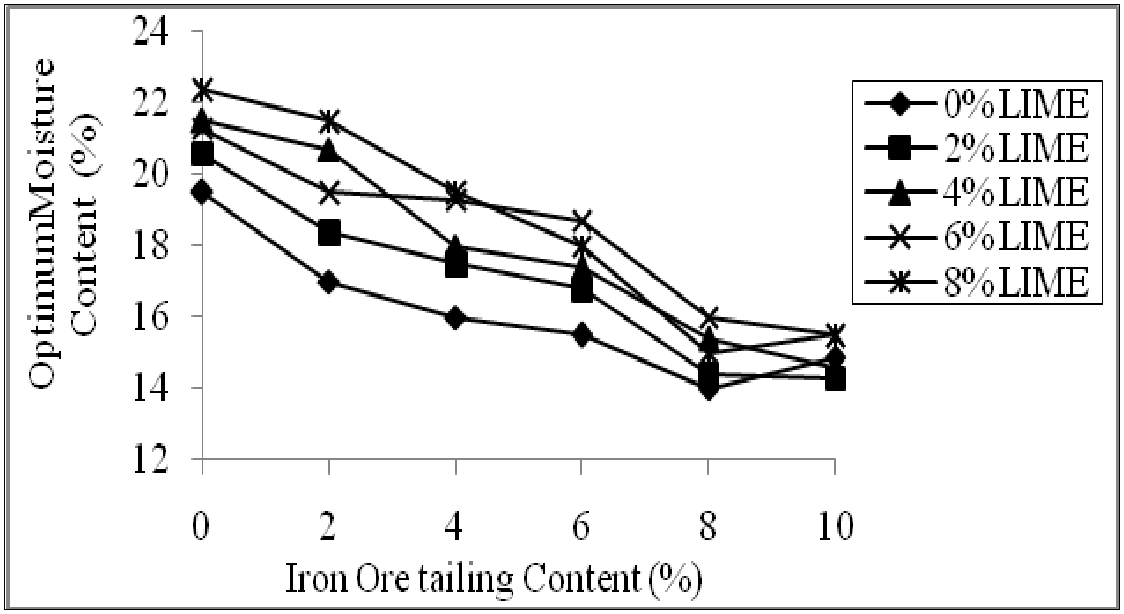


Fig. 4.14c: Variation of optimum moisture content of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

The two - way analysis of variance (ANOVA) test on OMC results for BSL, WAS and BSH compactions (see Table 4.8) shows that the effects of lime and IOT on black cotton soil were statistically significant for lime (F_{CAL} = 12.41, 11.85, 13.37 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 35.67, 38.27, 61.39> F_{CRIT} = 2.71).

Table 4.8 Two-way analysis of variance for optimum moisture content of black cotton soil – lime – iron ore tailing mixtures

Property		Source of variation	Degree of freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	OMC	Lime	4	12.41	3.10E-05	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	35.67	2.66E-09	2.71	F_{CAL}>F_{CRIT}, Significant
WAS	OMC	Lime	4	11.85	4.24E-05	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	38.27	1.43E-09	2.71	F_{CAL}>F_{CRIT}, Significant
BSH	OMC	Lime	4	13.37	1.85E-05	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	61.39	1.91E-11	2.71	F_{CAL}>F_{CRIT}, Significant

Detailed test results are given in Tables A4.27a - c in the Appendix.

4.4.2.1 Regression analysis for optimum moisture content.

Results of regression analysis for optimum moisture content are as shown in equation 4.2. The optimum moisture content was influenced by the grading properties, specific gravity and compactive effort applied. This agrees with previous statements by Gidigasu (1976) who stated that the behaviour of Laterite in pavement structure has been found to depend mainly on their particle size characteristics, the nature and strength of the gravel particles and the degree to which the soils have been compacted. The geotechnical properties considered for these analyses include the percentages of gravels, sand, and silt alongside their respective specific gravities. The regression equation showed that the optimum moisture content of the treated soil is much more influenced by the lime content and silt present in the soil. The iron ore tailing content, gravel, sand, specific gravity and compactive effort has no significant effect on the optimum moisture content having negative coefficients. The positive coefficient of lime content and silt present in the soil could be due to self - desiccation of the mixture during which all the water was used, resulting in low hydration and hence the relative humidity within the paste decreases (Osinubi, 2001; Moses *et.al.*, 2012).

The correlation coefficient values (R^2) shows a strong relationship between optimum moisture content and the parameters with R^2 value of 90.9%. Generally the correlation coefficient values (R^2) of 86.3% for maximum dry density and 90.9% for optimum moisture content shows that the parameters are more correlated to the maximum dry density than optimum moisture content.

The regression equation for optimum moisture content is

$$\mathrm{OMC} = 6.3 + 0.308\mathrm{L} - 0.608\mathrm{IOT} - 0.160\mathrm{Gc} - 0.0177\mathrm{Sa} + 0.0297\mathrm{Si} + 7.0\mathrm{Gs} - 2.10\mathrm{CE} \tag{4.2}$$

$R^2 = 90.9\%$

Where OMC=Optimum moisture content, L= Lime content, IOT= Iron ore tailing content, Gravel= Gc, Sa= Sand, Si= Silt Gs= Specific gravity, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for OMC is given in Table 4.9. The analysis shows that the IOT ($F_{CAL} = 29.082 > F_{CRIT} = 1.663$) and Compactive effort ($F_{CAL} = 271.775 > F_{CRIT} = 3.156$) significantly affected OMC values of the treated soil.

However, the effect of Compactive effort on the OMC of black cotton soil was much more significant.

Table 4.9: Two-way analysis of variance for regression analysis on optimum moisture content of black cotton soil-lime-IOT mixtures

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
OMC	IOT	29	29.082	5.3E-25	1.663	$F_{CAL}>F_{CRIT}$, Significant effect
	Compactive effort	2	271.775	3.47E-30	3.156	$F_{CAL}>F_{CRIT}$, Significant effect

4.5 Strength Characteristics

4.5.1 Unconfined compressive strength

The general test recommended for use in the determination of the additive to be used in the stabilization of soil is the unconfined compressive strength (UCS) test (Singh, 1991). It is an important factor in the evaluation of the design criteria for the use of soil as a pavement material (Ola, 1983).

4.5.1.1 7 days curing period

The variation of UCS of black cotton soil – lime – iron ore tailing IOT mixtures cured for 7 days with BSL, WAS and BSH compactive efforts is shown in Fig. 4.15a-c. The UCS values for the BSL compaction increased from 107 kN/m^2 for the natural soil to 1074.54 kN/m^2 for 8 % lime / 8 % IOT treatment. Subsequent addition of IOT did not increase UCS value, rather a slight decrease to a value of 849.95 kN/m^2 for 8 % lime / 10 % IOT treatment because of insufficient water to take the pozzolanic reaction to completion and the IOT occupying greater fraction of the soil matrix.

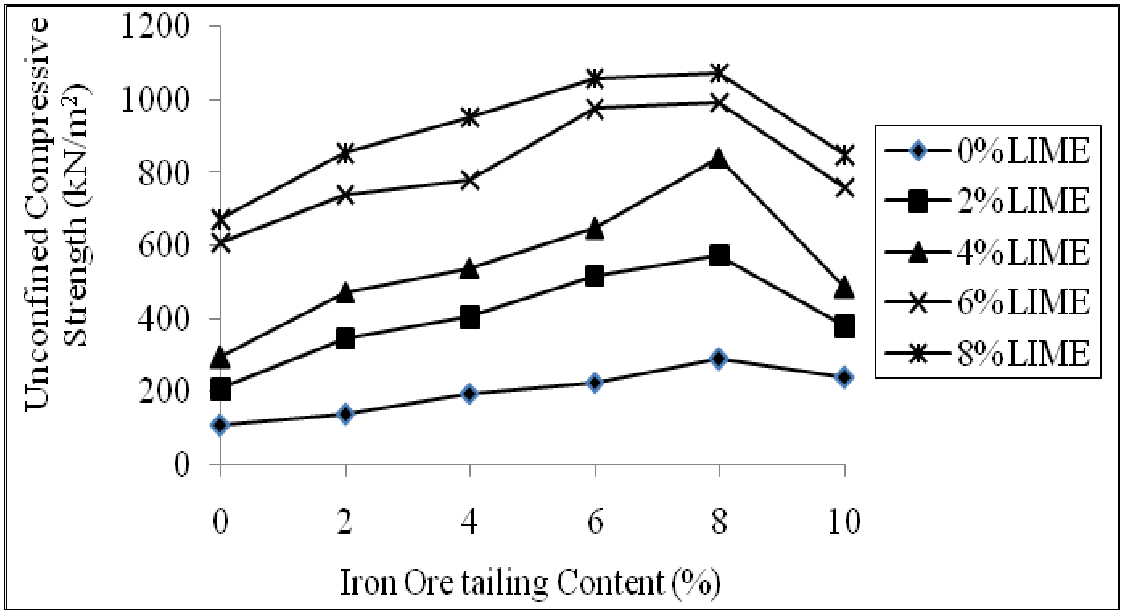


Fig. 4.15a: Variation of unconfined compressive strength (7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

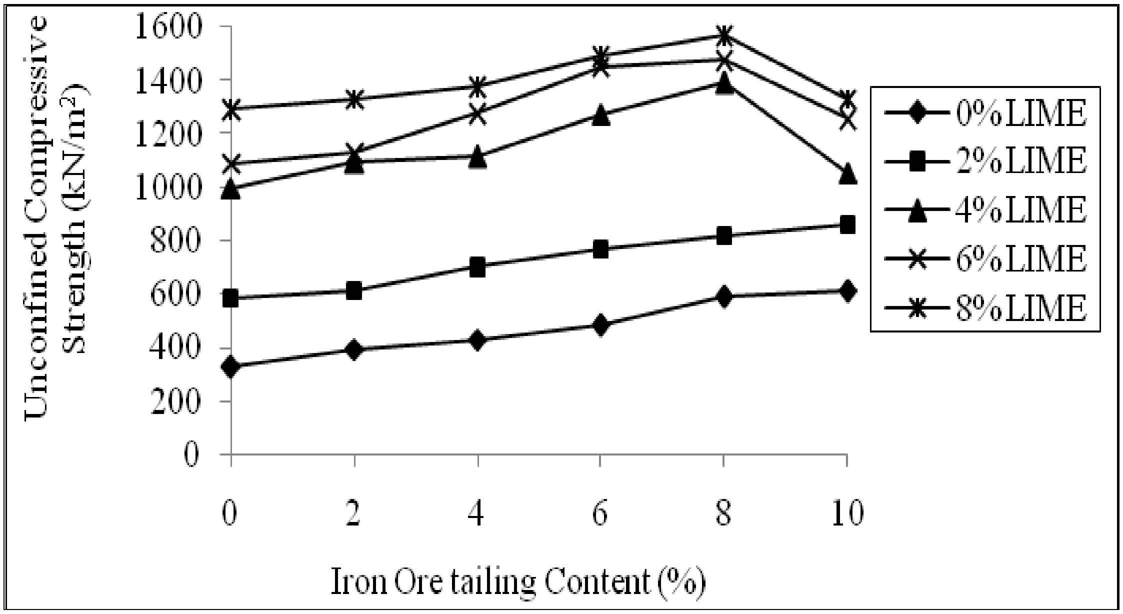


Fig. 4.15b: Variation of unconfined compressive strength (7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

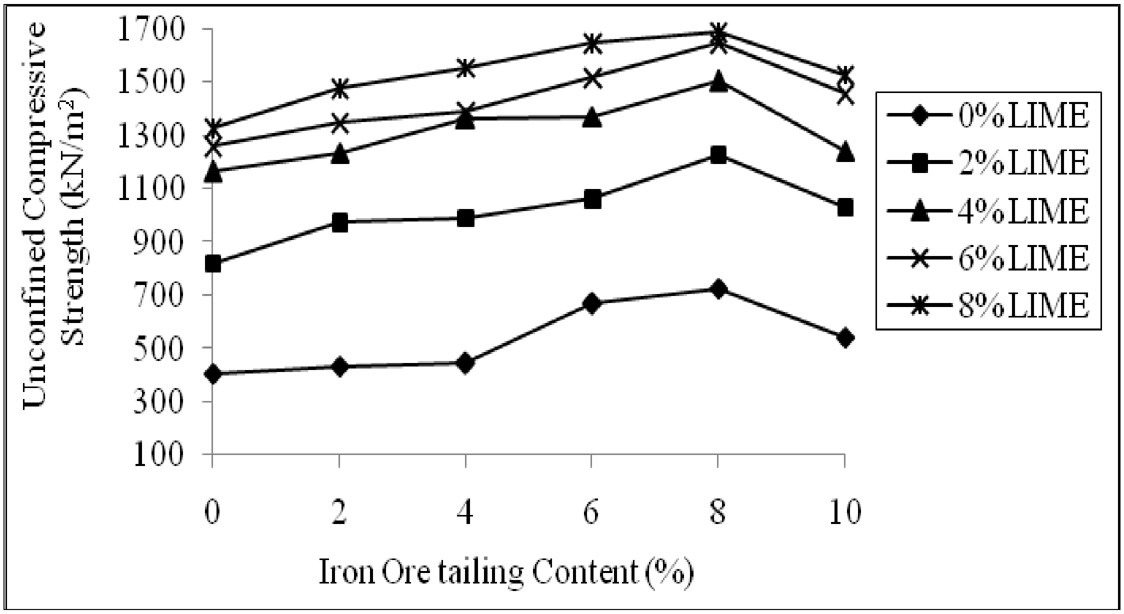


Fig. 4.15c: Variation of unconfined compressive strength (7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

For specimen compacted with WAS energy, the UCS value increased from an initial value of 326 to 1569.02 kN/ m^2 for 8 % lime / 8 % IOTtreatment. Further treatment of the soil did not produce a positive effect because the UCS value reduced to a minimum 1053.94 kN/ m^2 for 4 % lime / 10 % IOT treatment. The UCS for BSH compaction increased from 408.35 kN/ m^2 for no additive to 1688.76 kN/ m^2 for 8 % lime / 8 % IOT treatment. Additional IOT treatment reduced the UCS value to 1243.83 kN/m^2 for 4 % lime / 10 % IOT treatment.

The increase in UCS values (or the gain in strength) was primarily due to the formation of various compounds such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) and micro fabric changes, which are responsible for strength development (Ingles and Metcalf, 1972; Ola, 1983; Negi *et al*., 2013). The exact products, however, vary with the kind of clay mineralogy and the reactions, including temperature, moisture and curing conditions (Mitchell and Hooper, 1961). The UCS values of specimen compacted with BSL, WAS and BSH energies met the 7-day 1034.25 kN/ m^2 normally specified as criterion for adequate lime stabilization (Ola, 1983; Osinubi, 1998a; 1999). The decrease in UCS values beyond 8 % IOT content for all lime contents and compactive efforts considered was due to insufficient water required to complete the pozzolanic reaction (Osinubi, 1999).

The two – way analysis of variance (ANOVA) of the 7-day UCS results (see Table 4.10) shows that for BSL, WAS and BSH compactive efforts, the effects of lime (F_{CAL} =

172.19, 200.77, 619.63 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 29.85, 14.39, 50.38 > F_{CRIT} = 2.71) on black cotton soil were statistically significant.

Table 4.10: Two-way analysis of variance for unconfined compressive strength (7 days curing period) of black cotton soil-lime-iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	7 Days curing	Lime	4	172.19	3.43E-15	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	29.85	1.27E-08	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	7 Days curing	Lime	4	200.77	7.72E-16	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	14.39	4.84E-06	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	7 Days curing	Lime	4	619.63	1.18E-20	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	50.38	1.19E-10	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are given in Tables A4.28 a - c in the Appendix.

4.5.1.2 14 days curing period

The variation of unconfined compressive strength (14 days curing period) of black cotton soil - lime mixtures with iron ore tailing content is shown in Fig. 4.16a-c. For BSL, WAS and BSH compactions UCS values increased from 258.72, 452 and 900 kN/m^2 for the natural soil to peak values of 1893.59, 2228.04 and 2658.46 kN/m^2 for 8 % lime /8 % IOT, 6 % lime / 8 % IOT and 6 % lime / 8 % IOT treatments, respectively.

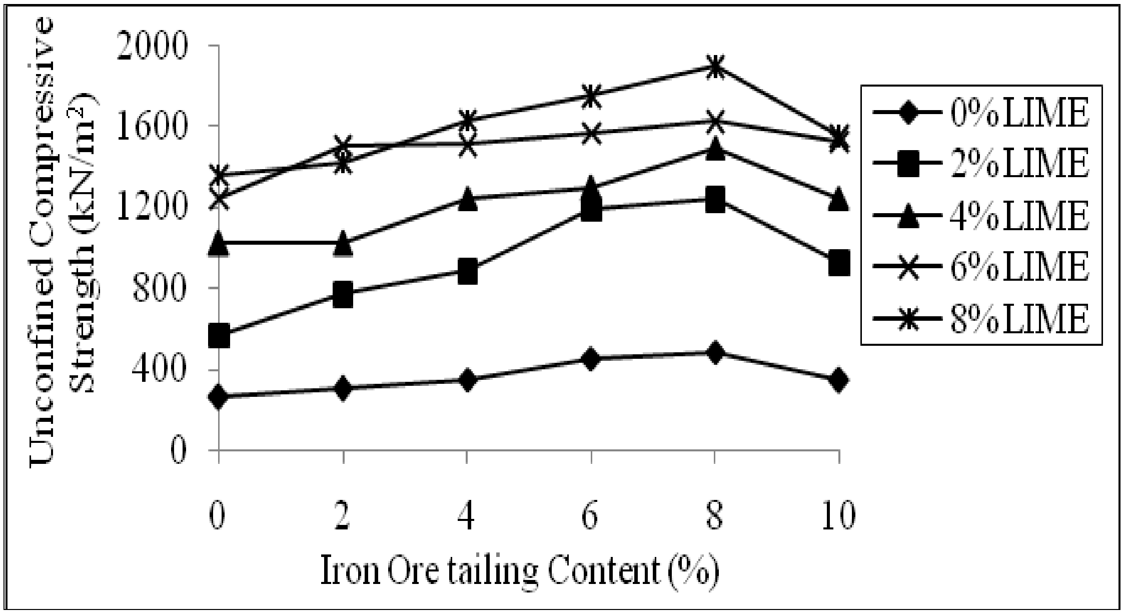


Fig. 4.16a: Variation of unconfined compressive strength (14 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

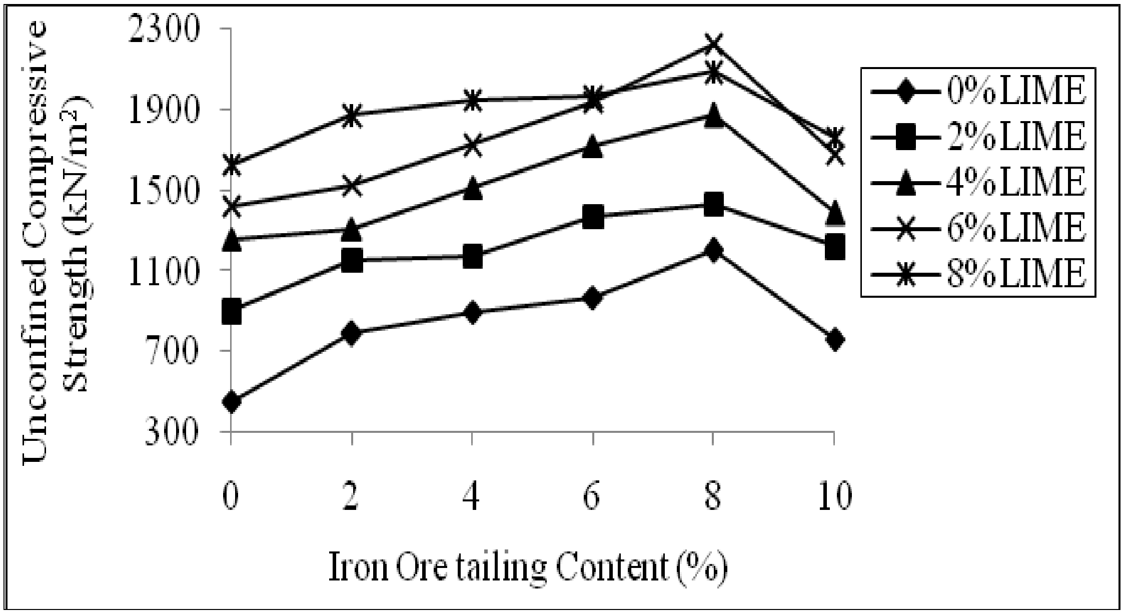


Fig. 4.16b: Variation of unconfined compressive strength (14 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

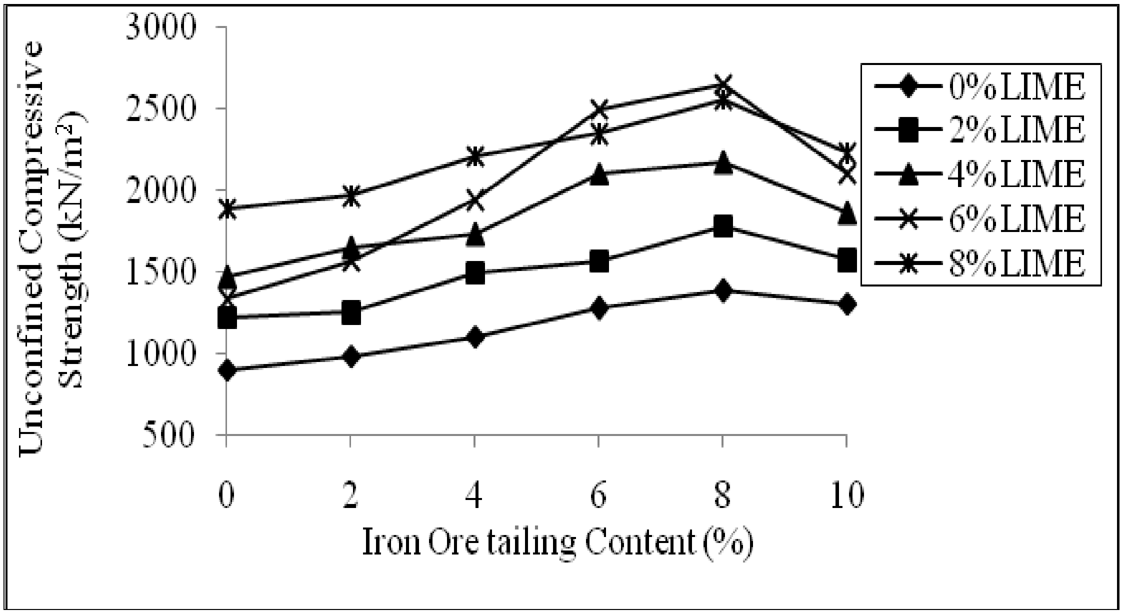


Fig. 4.16c: Variation of unconfined compressive strength (14 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction).

The observed trend of increase in UCS value with curing period can be attributed to time dependent strength gain of the mixture due to pozzolana reaction. The strength gain was due to the availability of water that enhanced hydration reaction between lime liberated from the hydration reaction of lime and the IOT to form secondary cementation compounds (Diamond *et al*., 1964; Sloane, 1965; Ormsby and Kinter, 1973a, b; Choquette *et al*., 1987; Osinubi and Medubi, 1997; Mohammed and Anita 1998; Mohammed et al 2001).

The two – way analysis of variance (ANOVA) of the 14-days UCS results (see Table 4.11) shows that for BSL,WAS and BSH compactions, the effects of lime (F_{CAL} = 220.16, 162.38, 52.77 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 20.04, 37.13, 20.00 > F_{CRIT} = 2.71), respectively, on black cotton soil were statistically significant.

Table 4.11: Two - way analysis of variance for unconfined compressive strength (14 days curing period) of black cotton soil - lime – iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	14 days curing	Lime	4	220.16	3.14E-16	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	20.04	3.61E-07	2.71	F_{CAL}>F_{CRIT}, Significant
WAS	14 days curing	Lime	4	162.38	6.06E-15	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	37.13	1.87E-09	2.71	F_{CAL}>F_{CRIT}, Significant
BSH	14 day curing	Lime	4	52.77	2.39E-10	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	20	3.66E-07	2.71	F_{CAL}>F_{CRIT}, Significant

Detailed test results are given in Tables A4.28 d - f in the Appendix.

4.5.1.3 28 days curing period

The variation of unconfined compressive strength (28 days curing period) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.17a-c. The same trend of increase in UCS values recorded for specimens cured for 7 and 14 days was also observed for 28 days curing period except that the UCS values increased with the curing periods and higher compactive efforts. For BSL, WAS and BSH compactive efforts the UCS for 28 days curing period increased from 528.37, 995.87 and 1124.9kN/m^2 for the natural soil to 2042.37, 2456.32 and 2732.12kN/ m^2, respectively, for 8 % lime / 8 % IOT treatment.

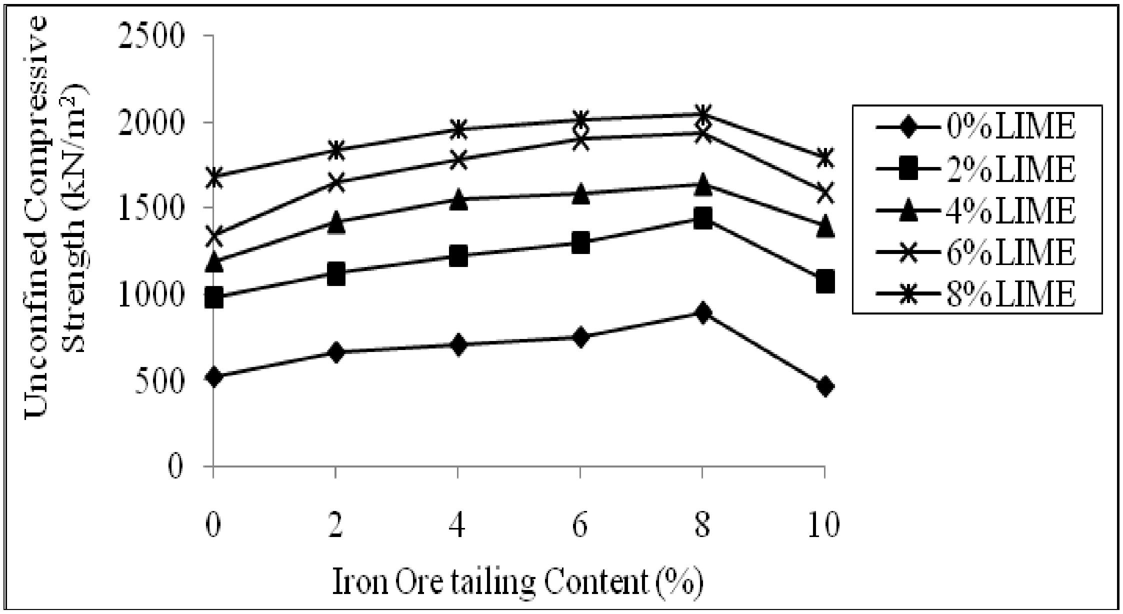


Fig. 4.17a: Variation of unconfined compressive strength (28 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

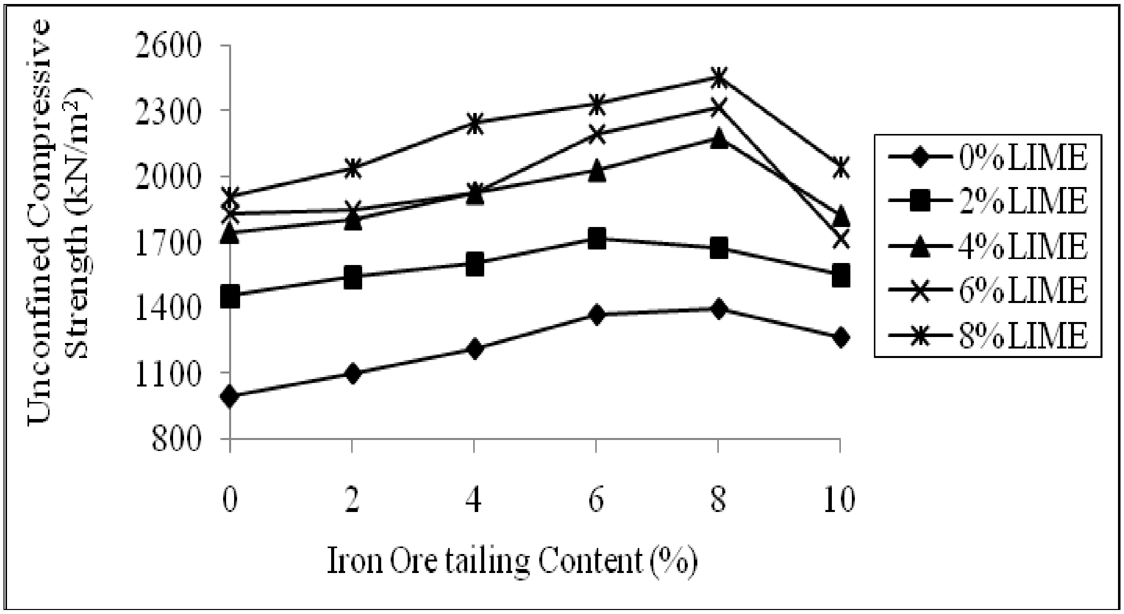


Fig. 4.17b: Variation of unconfined compressive strength (28 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

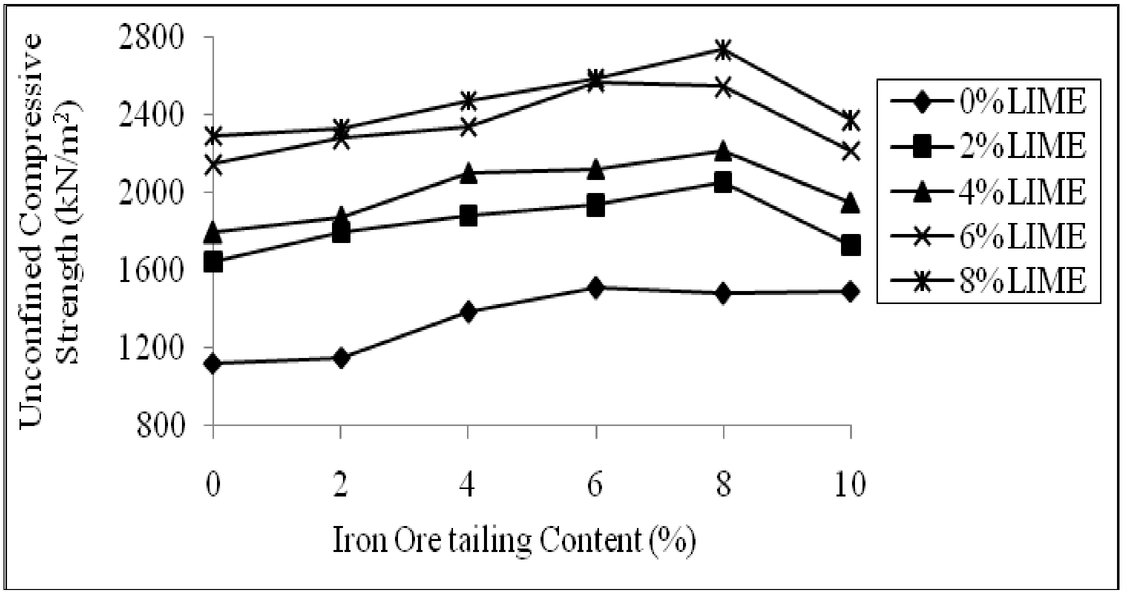


Fig. 4.17c: Variation of unconfined compressive strength (28 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

The two – way analysis of variance (ANOVA) of the 28-day UCS results for BSL, WAS and BSH compactions (see Table 4.12) shows that the effects of lime (F_{CAL} = 489.04, 136.32, 258.44 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 48.44, 21.82, 26.44 > F_{CRIT} = 2.71), respectively, on black cotton soil were statistically significant.

Table 4.12: Two-way analysis of variance for unconfined compressive strength (28 days curing) of black cotton soil-lime – iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	28 days curing	Lime	4	489.04	1.23E-19	2.87	F_{CAL}>F_{CRIT}, Significant
		IOT	5	48.44	1.70E-10	2.71	F_{CAL}>F_{CRIT}, Significant

WAS	28 day curing	Lime	4	136.32	3.27E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	21.82	1.80E-07	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	28 day curing	Lime	4	258.45	6.56E-17	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	26.44	3.60E-08	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are given in Tables A4.28 g - i in the Appendix.

4.5.1.3.1 Regression analysis for unconfined compressive strength.

A regression analysis was performed for unconfined compressive strength as a dependant variable and four geotechnical properties as independent variables. The geotechnical properties considered for these analyses include the lime content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter.

The regression equations (see equation 4.3) revealed the extent to which these parameters influence the unconfined compressive strength after 7 days curing of the stabilized soil which is a function of the coefficient of each parameter. The regression equations showed that the unconfined compressive strength of the treated soil is much more influenced by the lime content, iron ore tailing content, percentage fine in the soil and compactive effort all having positive coefficients. The plasticity index has no significant effect on the unconfined compressive strength having negative coefficients. The compactive effort has the most significant effect on the unconfined compressive strength having the highest positive coefficient. The correlation coefficient value (R^2) shows a strong relationship between UCS of the treated soil and the parameters with R^2 value of 88.2%. Similar correlation was obtained for unconfined compressive strength for 28 days curing period (see equation 4.4) because formation of crystalline product of pozzolanic reactions responsible for strength gain in lime stabilized soil is time dependent and may continue for a long period of time as reported by (Mallela et al., 2004; Osinubi and Medubi, 1997a).

$$\mathrm{UCS(7)} = 711 + 107.35\mathrm{L} + 25.71\mathrm{IOT} + 0.04\mathrm{PF} - 13.44\mathrm{PI} + 296.85\mathrm{CE} \quad (4.3)$$

$R^2 = 88.2\%$

$$\mathrm{UCS(28)} = 1164 + 131\mathrm{L} + 24.2\mathrm{IOT} + 1.1\mathrm{PF} - 6.7\mathrm{PI} + 310\mathrm{CE} \quad (4.4)$$

$R^2 = 87.3\%$

Where

UCS(7)= Unconfined compressive strength after 7 days curing

UCS(28)= Unconfined compressive strength after 28 days curing

L= Lime content, IOT= Iron ore tailing content, PF=Percentage fine, Pl= Plasticity index, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for unconfined compressive strength after 7 days curing period is given in Table 4.13. The analysis shows that the IOT (F_{CAL} = 41.594 > F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 325.096 > F_{CRIT} = 3.156) has significant affect on unconfined compressive strength of the stabilized soil. However, Compactive effort has a more pronounced effect.

Table 4.13: Two-way analysis of variance for regression analysis on unconfined compressive strength after 7 days curing period of black cotton soil-lime-IOT mixtures.

Property	**Source of Variation**	**Degree of freedom**	**F_{CAL}**	**p-value**	**F_{CRIT}**	**Remark**
UCS(7)	IOT	29	41.594	3.75E-29	1.663	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	325.096	3.06E-32	3.156	F_{CAL}>F_{CRIT}, Significant effect

The two – way analysis of variance (ANOVA) test for unconfined compressive strength after 28 days curing period is given in Table 4.14. The analysis shows that the IOT (F_{CAL} = 64.912 > F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 362.971 > F_{CRIT} = 3.156) has significant affect on unconfined compressive strength after 28 days curing of the stabilized soil. However, Compactive effort has a more pronounced effect.

Table 4.14: Two-way analysis of variance for regression analysis on unconfined compressive strength after 28 days curing period of black cotton soil-lime-IOT mixtures.

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
UCS(28)	IOT	29	64.192	2.55E-34	1.663	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	362.971	1.6E-33	3.156	F_{CAL}>F_{CRIT}, Significant effect

4.5.1.4 7 days curing and 7 days soaking periods

The variation of unconfined compressive strength (7 days curing + 7 days soaking) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.18a-c. Generally, the UCS values increased with higher compactive effort and additive content. The UCS values recorded for BSH compaction increased from 89.7 kN/m^2 to a peak value 1370.37 kN/m^2 at 6 % lime / 8 % IOT treatment and thereafter reduced to 860.83 kN/m^2 for 6 % lime/10 % IOT treatment. For BSL and WAS compaction the UCS value increased from 27.41 and 32.41 kN/m^2 to 711.26 and 654.79 kN/m^2, respectively, for 8 % lime/ 8 % IOT treatment. Beyond this treatment no significant increase in UCS values as explained earlier. It is pertinent to state that the UCS values for the soaked specimens are far too low compared to those obtained for 7 and 14 days curing periods probably due to the ingress of water that resulted in loss of strength.

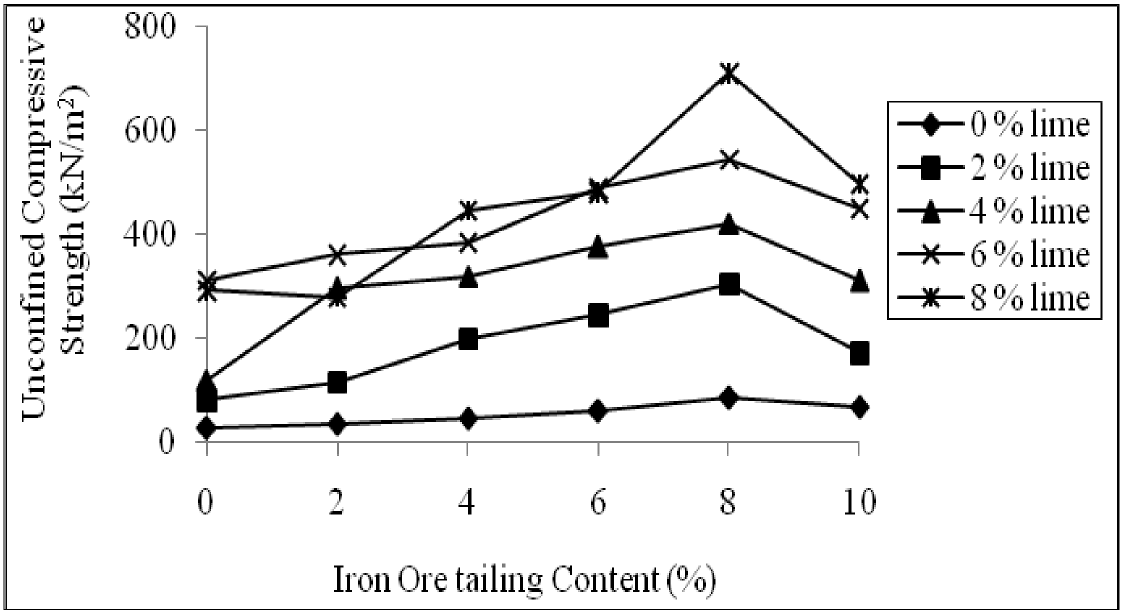


Fig. 4.18a: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of black cotton soil - lime mixtures with iron ore tailing content (BSL compaction)

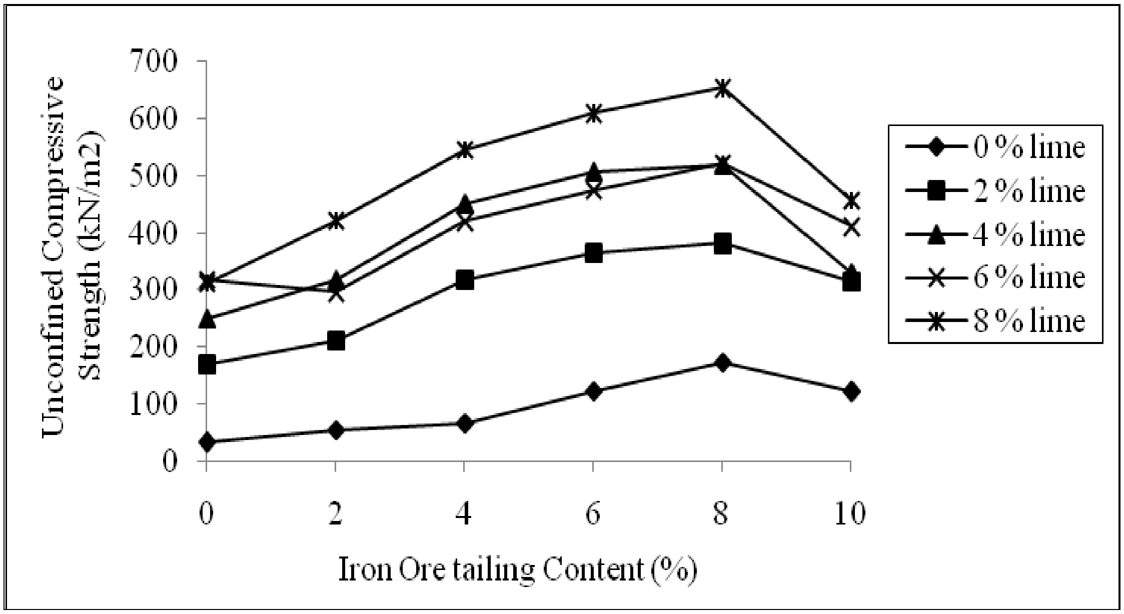


Fig. 4.18b: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of black cotton soil - lime mixtures with iron ore tailing content (WAS compaction)

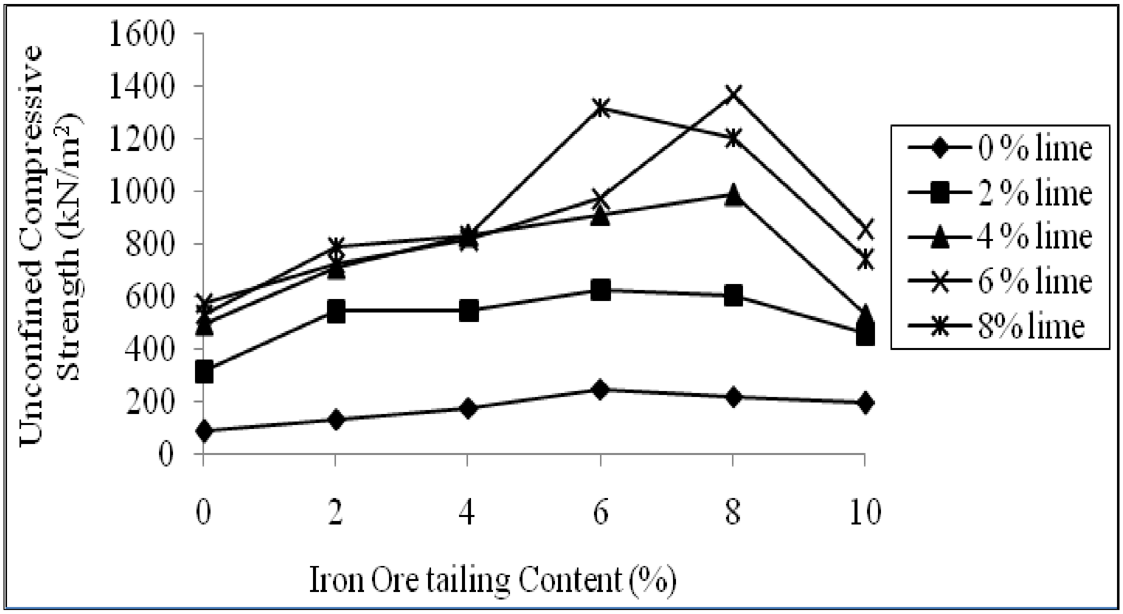


Fig. 4.18c: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of black cotton soil - lime mixtures with iron ore tailing content (BSH compaction)

The two – way analysis of variance (ANOVA) of the 7-day curing and 7 days soaking UCS results for BSL,WAS and BSH compaction (see Table 4.15) shows that the effects of lime (F_{CAL} = 51.20, 90.50, 34.29 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 11.51, 25.23, 9.44 > F_{CRIT} = 2.71), respectively, on black cotton soil were statistically significant.

Table 4.15: Two - way analysis of variance for unconfined compressive strength (7 days curing + 7 days soaking) of black cotton soil-lime – iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	7c + 7s	Lime	4	51.20	3.14E-10	2.87	Fcal>Fcrit, significant
		IOT	5	11.51	2.48E-05	2.71	Fcal> Fcrit, significant
WAS	7c + 7s	Lime	4	90.50	1.62E-12	2.87	Fcal> Fcrit, significant
		IOT	5	25.23	5.35E-08	2.71	Fcal> Fcrit, significant
BSH	7c + 7s	Lime	4	34.29	1.08E-08	2.87	Fcal> Fcrit, significant
		IOT	5	9.44	9.62E-05	2.71	Fcal> Fcrit, significant

7c + 7s - 7 days curing + 7 days soaking

Detailed test results are given in Tables A4.28a - A4.28j in the Appendix.

4.5.1.5 Ratio of 28 days to 7 days curing periods

The variation of unconfined compressive strength ratio of 28 days to 7 days curing periods of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.19a-c. Generally, the UCS ratio of 28 days to 7 days decreased with increase in iron ore tailing content. Detailed test results are given in Tables A4.31a - A4.31c in the Appendix.

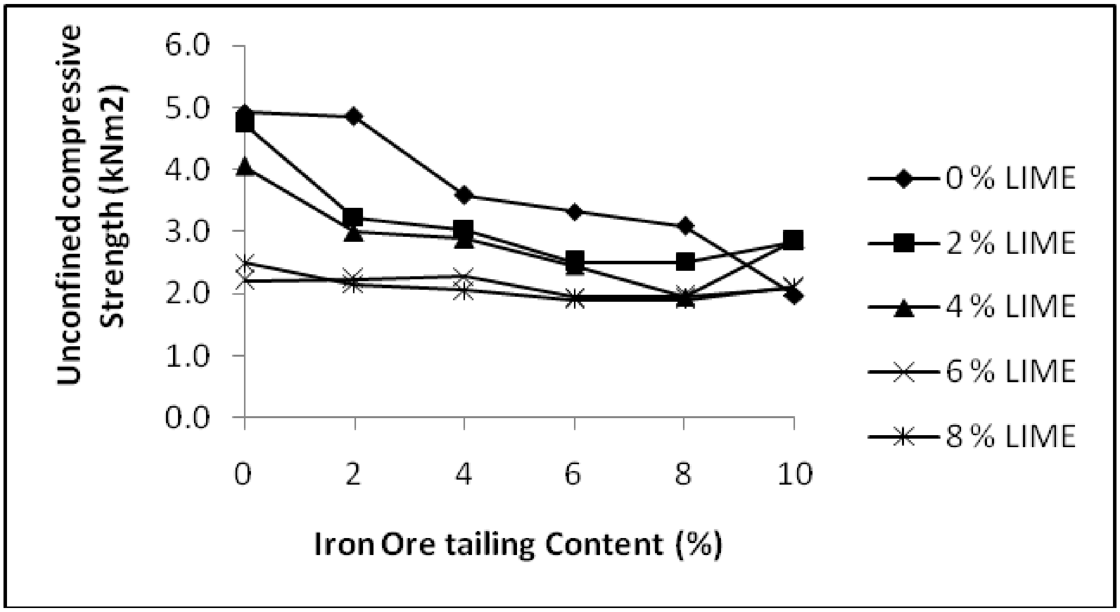


Fig. 4.19a: Variation of unconfined compressive strength (ratio of 28 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

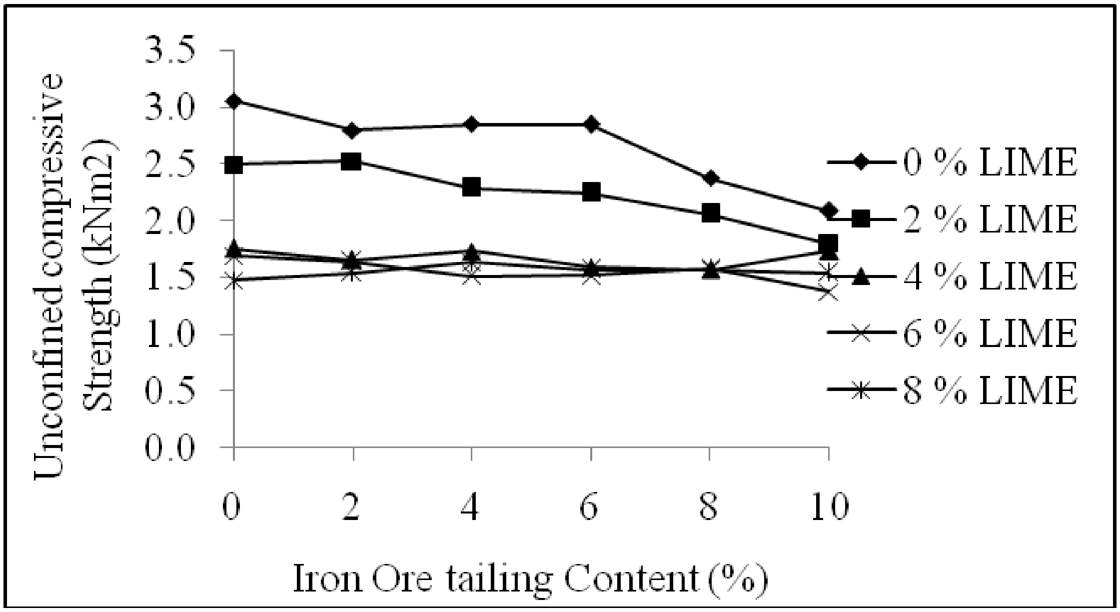


Fig. 4.19b: Variation of unconfined compressive strength (ratio of 28 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

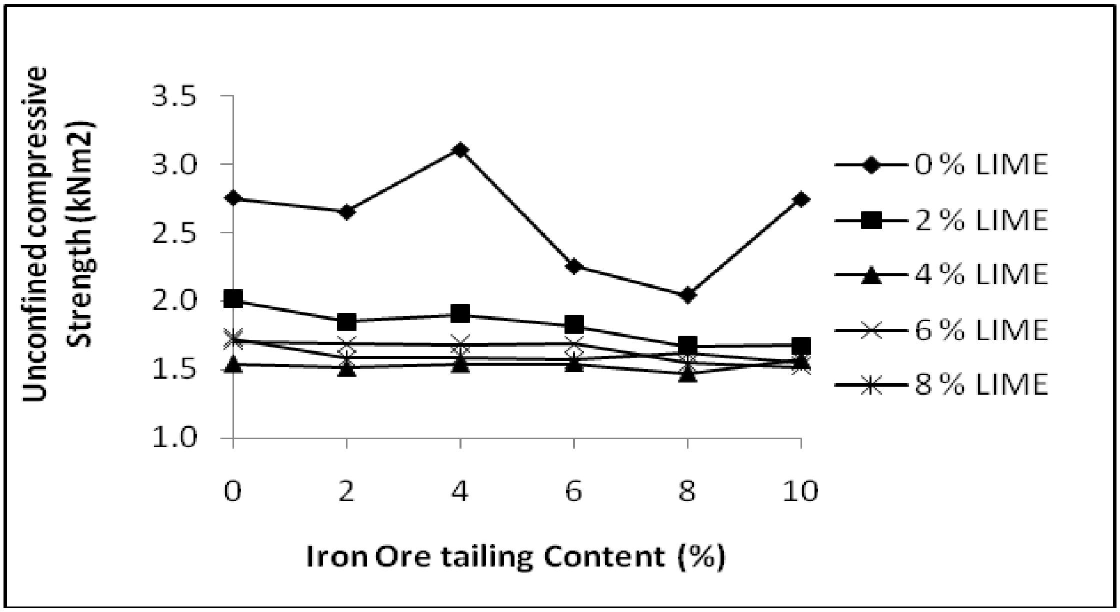


Fig. 4.19c: Variation of unconfined compressive strength (ratio of 28 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

4.5.1.6 Ratio of 14 days to 7 days curing periods

The variation of unconfined compressive strength ratio of 14 days to 7 days curing periods of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.20a-c. Generally, the UCS ratio of 28 days to 7 days decreased with increase in iron ore tailing content for British standard light compactive effort and decreased for West Africa standard and British standard heavy compactive effort respectively. Detailed test results are given in Tables A4.32a - A4.32c in the Appendix.

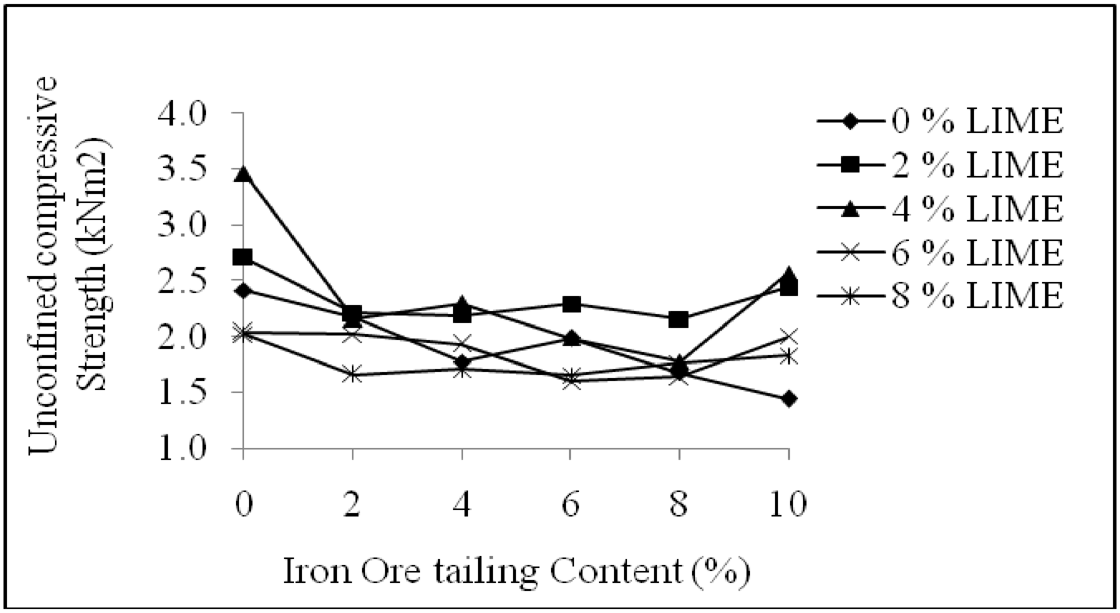


Fig. 4.20a: Variation of unconfined compressive strength (ratio of 14 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

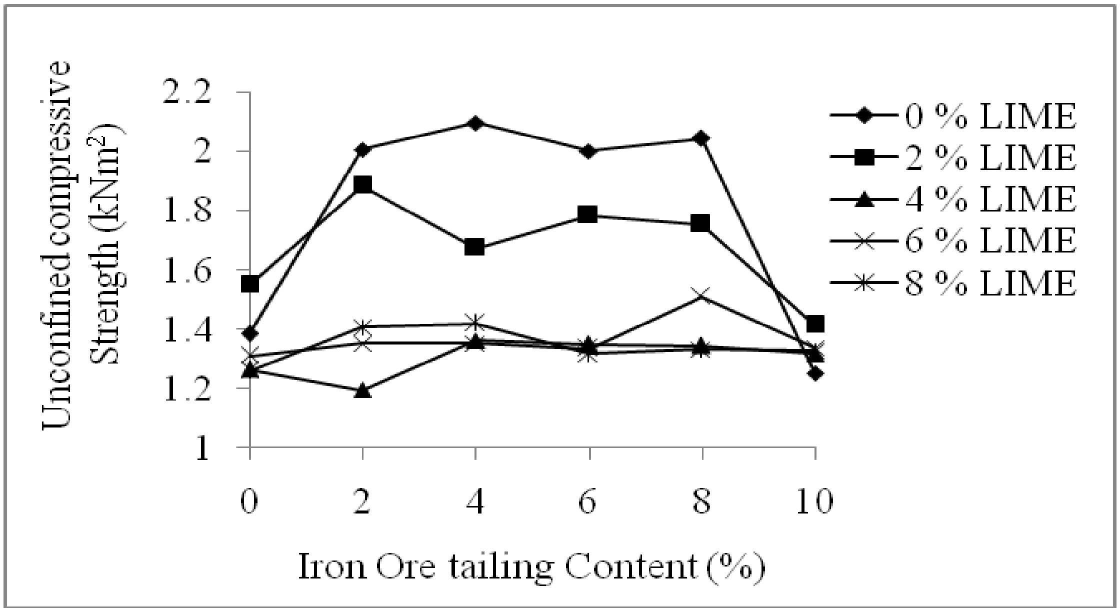


Fig. 4.20b: Variation of unconfined compressive strength (ratio of 14 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

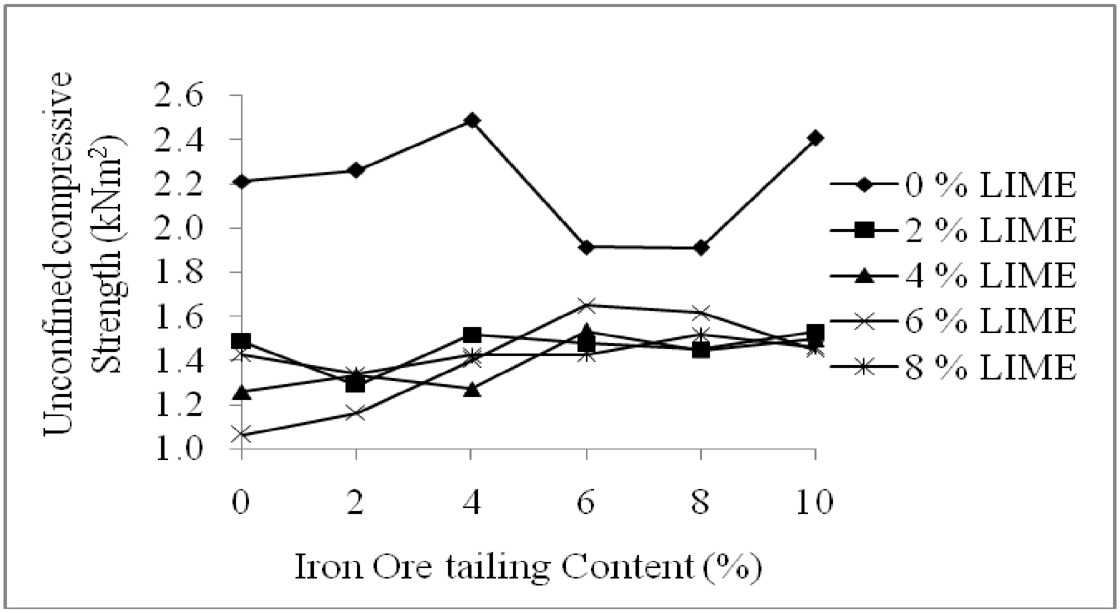


Fig. 4.20c: Variation of unconfined compressive strength (ratio of 14 to 7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

4.5.1.7 Ratio of 14 days curing to (7 days curing + 7 days soaked)

The variation of unconfined compressive strength ratio of 14 days curing to (7 days curing + 7 days soaked) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.21a-c. Generally, the UCS ratio of 28 days to 7 days decreased with increase in iron ore tailing content. Detailed test results are given in Tables A4.33a - A4.33c in the Appendix.

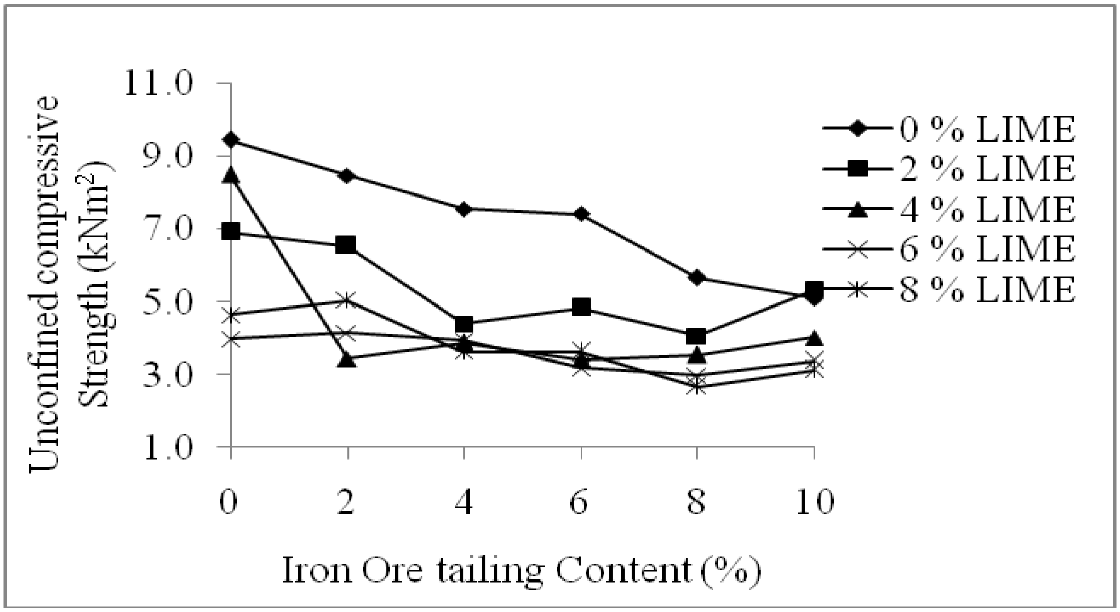


Fig. 4.21a: Variation of unconfined compressive strength (ratio of 14 to 7+7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

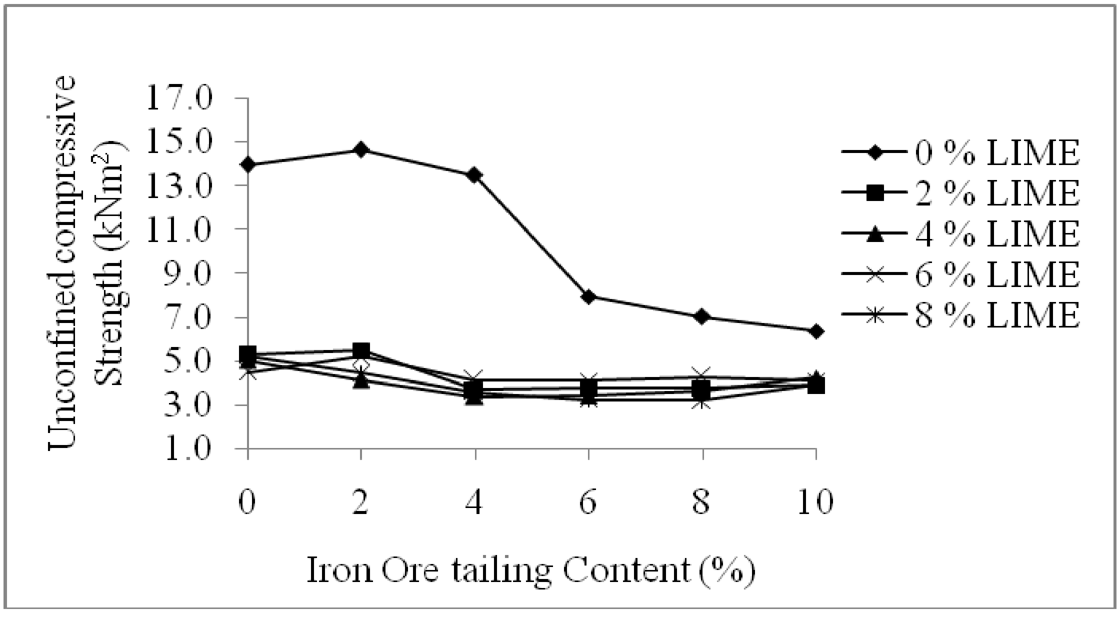


Fig. 4.21b: Variation of unconfined compressive strength (ratio of 14 to 7+7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

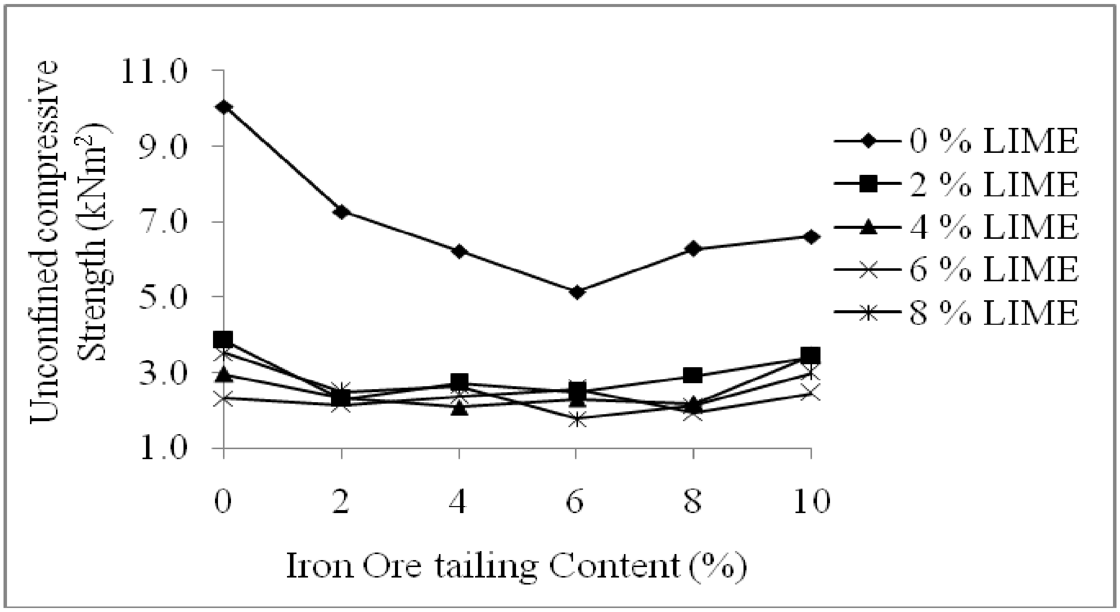


Fig. 4.21c: Variation of unconfined compressive strength (ratio of 14 to 7+7 days curing period) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

4.5.2 California bearing ratio

The California bearing ratio (CBR) value of a soil/stabilized soil is an important parameter used to indicate its strength and bearing capacity for base and sub-base in pavement structure. Lime stabilized soils are often used for the construction of these pavement layers and also for embankment. The CBR is therefore a familiar test used to evaluate the strength of soils for these applications.

4.5.2.1 *Unsoaked condition*

The variation of CBR (unsoaked) values of black cotton soil-lime mixtures with iron ore tailing content for the three energy levels used is shown in Fig. 4.19a-c. The unsoaked CBR value for BSL compaction increased from 5 % for the natural soil to a peak value of 55 % for 8 % lime / 8 % IOT treatment. For WAS and BSH compactions, the CBR value increased from 8 and 13 % to 85 and 90 %, respectively at 8 % lime / 6 % IOT treatment. It was observed that although CBR values increased with higher additive contents however, higher compactive effort did not have any appreciable effect on the values recorded.

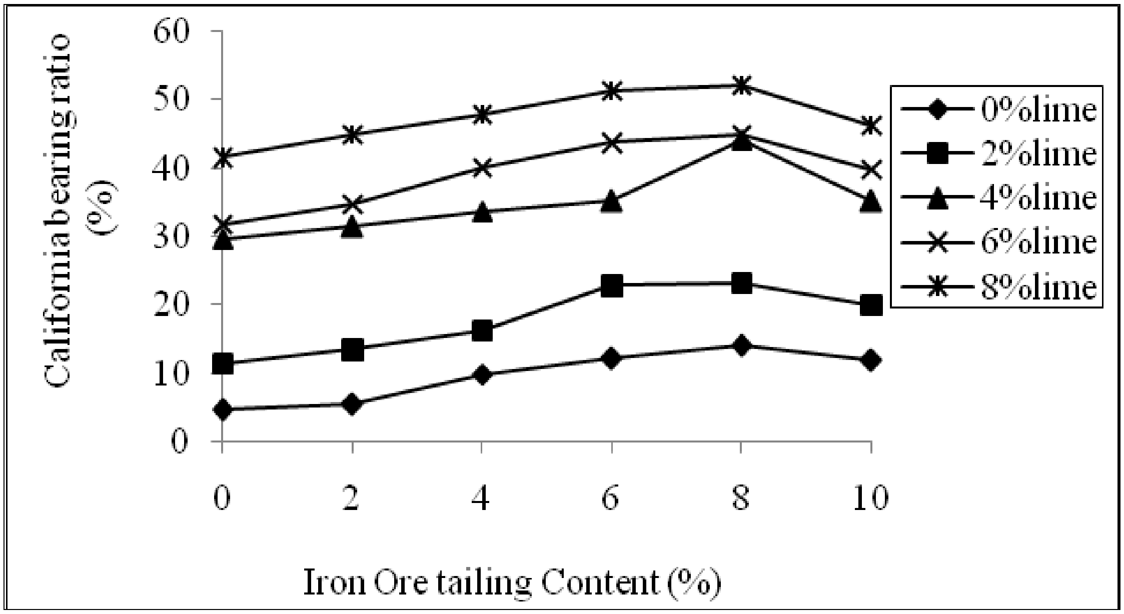


Fig. 4.22a: Variation of California bearing ratio (unsoaked condition) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

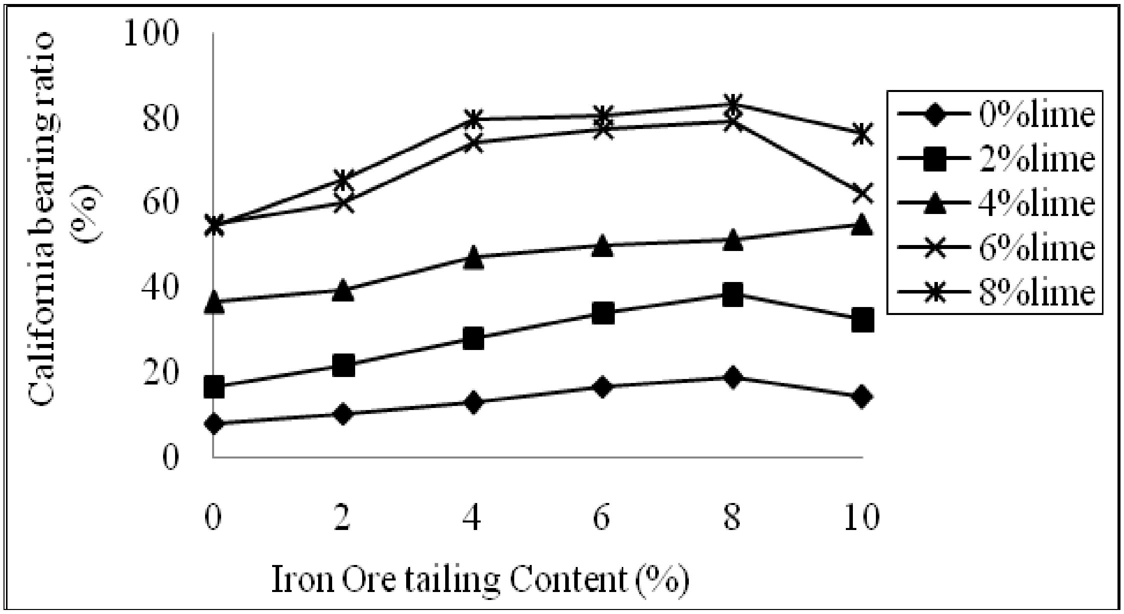


Fig 4.22b: Variation of California bearing ratio (unsoaked condition) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

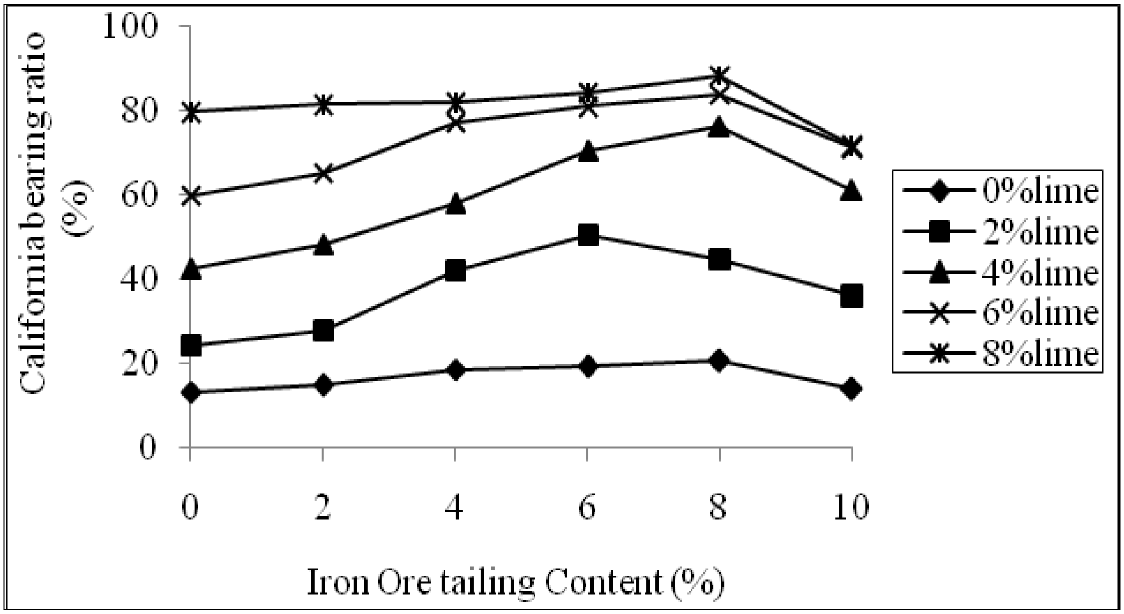


Fig 4.22c: Variation of California bearing ratio (unsoaked condition) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

The Nigerian General Specifications (1997) recommends a CBR value of 180 % to be attained in the laboratory for cement stabilized material to be constructed by mix-in place method, while it did not state the value for lime-treated soil. Usually, a minimum CBR value of 60 - 80 % is required for bases and from 20 – 30 % for sub-base both when compacted at optimum moisture and 100 % West African Standard (Gidigasu,1982). However, the minimum conventional CBR values for lime-treated soils of 40, 80, and 100 % (standard Proctor or British Standard light) for sub-base, base (lightly trafficked roads) and base (heavily trafficked roads), respectively, were adopted by Osinubi (2006) to evaluate the strength of soil-lime mixtures.

Based on the criteria adopted for lime-treated soil it can be inferred that at 8 % lime/ 8 % IOT treatment the soil-lime-IOT mixture can be used for sub-base of lightly trafficked road when compacted with any of the three energies considered. However, if the pozzolanic nature of soil-lime reaction is taken into consideration then the same mixture can be said to be adequate for base course of lightly trafficked roads when compacted takes with WAS and BSH energies.

The two – way analysis of variance (ANOVA) test on the unsoaked CBR result for BSL,WAS and BSH compaction (see Table 4.16) shows that the effects of lime and IOT on black cotton soil were statistically significant (F_{CAL} = 601.42, 237.28, 149.70 > F_{CRIT} = 2.87) for lime and (F_{CAL} = 39.56, 17.86, 10.09 > F_{CRIT} = 2.71) for IOT respectively.

Table 4.16 Two-way analysis of variance for California bearing ratio (unsoaked condition) of black cotton soil-lime-iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Unsoaked	Lime	4	601.42	1.59E-20	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	39.56	1.06E-09	2.71	$F_{CAL} > F_{CRIT,}$ significant
WAS	Unsoaked	Lime	4	237.28	1.51E-16	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	17.86	9.08E-07	2.71	$F_{CAL} > F_{CRIT,}$ significant
BSH	Unsoaked	Lime	4	149.70	1.33E-14	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	10.09	6.16E-05	2.71	$F_{CAL} > F_{CRIT,}$ significant

Detailed test results are given in Tables A4.29 a - c in the Appendix.

4.5.2.2 Soaked condition

The variation of California bearing ratio (24 hours soaking) of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.20a-c. For BSL, WAS and BSH compactive efforts CBR values increased with higher additive contents and peak values of 45, 65 and 70 %, respectively, at 8 % lime / 8 % IOT treatment.

The lower values recorded in comparison to the unsoaked CBR values were due to the ingress of water into the specimen that reduced their strength. The results show that the CBR values did not decrease very significantly when soaked. However, based on the earlier adopted criteria for lime-treated soil, the soaked CBR values fall short of the specification required for base courses but meet the requirement for sub-base when compacted using the three energy levels for 8 % lime / 8 % IOT treatment.

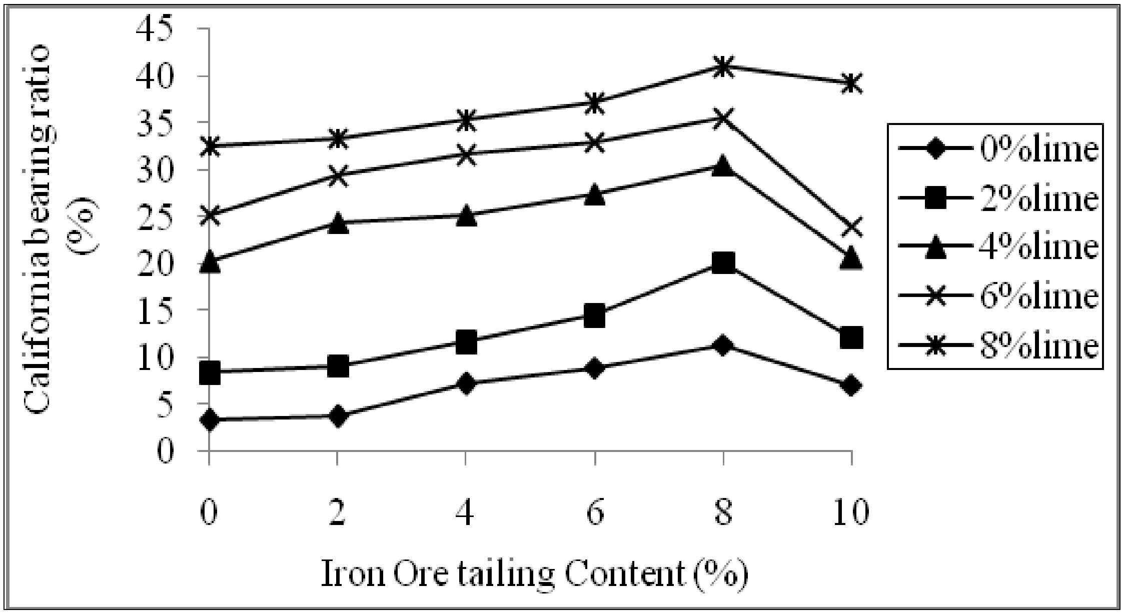


Fig. 4.23a: Variation of California bearing ratio (24 hours soaking) of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

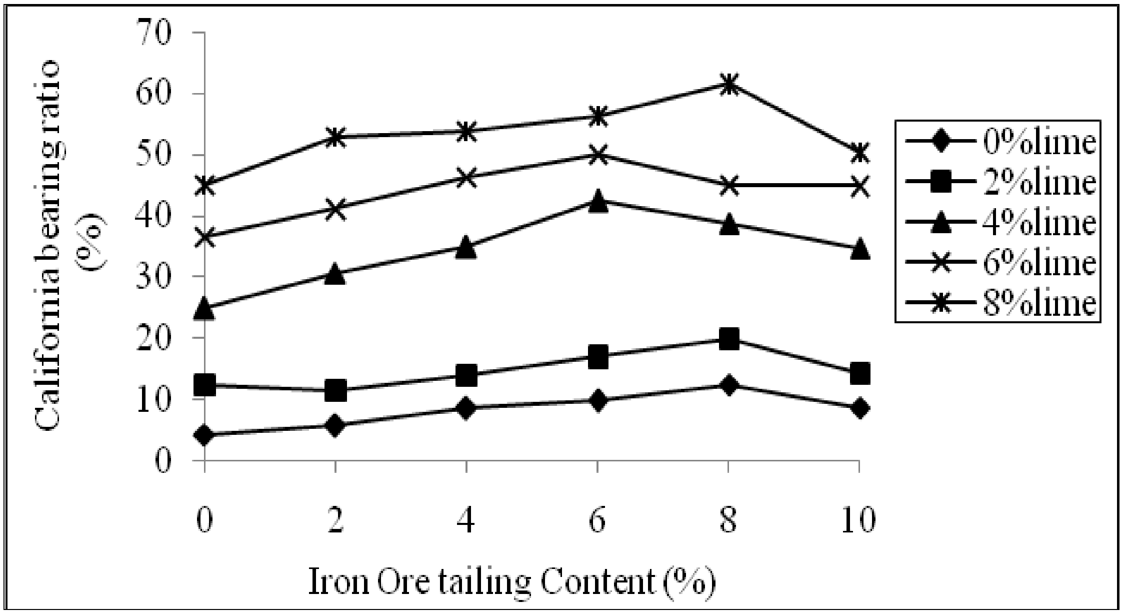


Fig. 4.23b: Variation of California bearing ratio (24 hours soaking) of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

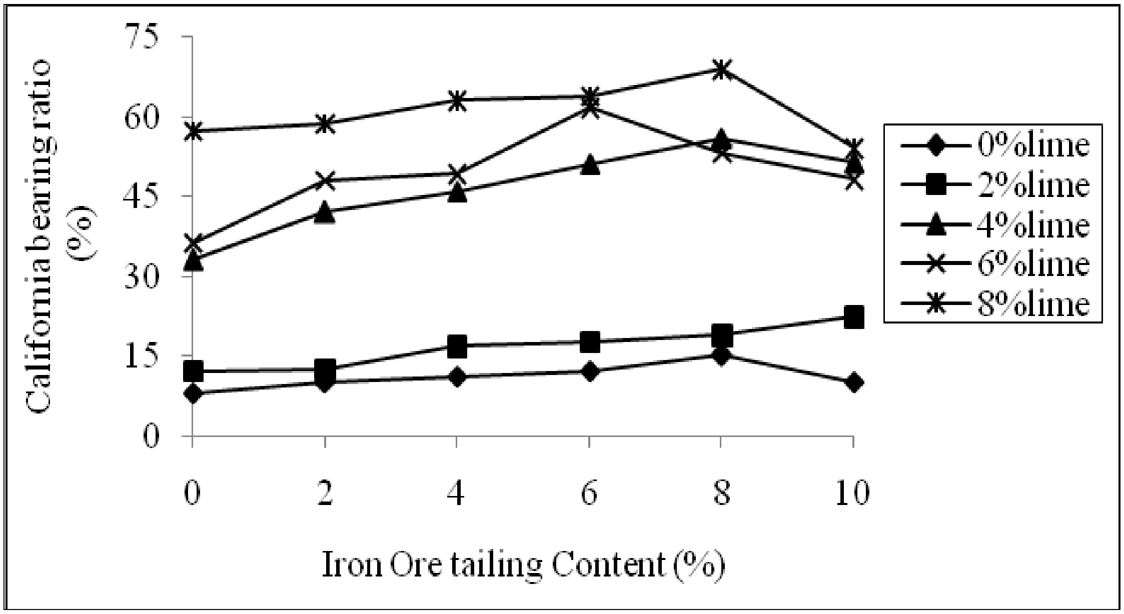


Fig. 4.23c: Variation of California bearing ratio (24 hours soaking) of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

The two – way analysis of variance (ANOVA) test on the soaked CBR result for BSL,WAS and BSH compaction (see Table 4.17) shows that the effects of lime and IOT on black cotton soil were statistically significant for lime (F_{CAL} = 241.05, 380.29, 162.05 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 16.22, 14.91, 6.43 > F_{CRIT} = 2.71).

Table 4.17: Two - way analysis of variance for California bearing ratio (24 hours soaking) of black cotton soil - Lime – iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Soaked	Lime	4	241.05	1.30E-16	2.87	Fcal > Fcrit, significant
		IOT	5	16.22	1.93E-06	2.71	Fcal > Fcrit, significant
WAS	Soaked	Lime	4	380.29	1.47E-18	2.87	Fcal > Fcrit, significant
		IOT	5	14.91	3.69E-06	2.71	Fcal > Fcrit, significant
BSH	Soaked	Lime	4	162.05	6.18E-15	2.87	Fcal > Fcrit, significant
		IOT	5	6.43	1.03E-03	2.71	Fcal > Fcrit, significant

Detailed test results are given in Tables A4.29 d - f in the Appendix.

4.5.1.3.1 Regression analysis for California bearing ratio.

A regression analysis was performed for California bearing ratio as a dependant variable and four geotechnical properties as independent variables. The geotechnical properties considered for these analyses include the lime content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter.

The regression equations (see equation 4.5) revealed the extent to which these parameters influence the California bearing ratio of unsoaked condition of treated soil which is a function of the coefficient of each parameter. The regression equation (see equation 4.5) showed that the CBR(US) of the treated soil is much more influenced by the lime content, iron ore tailing content, plasticity index and compactive effort all having positive coefficients. The percentage fine in the soil has no significant effect on the CBR(US) having negative coefficients. The compactive effort has the most significant effect on the CBR(US) having the highest positive coefficient. The correlation coefficient value (R^2) shows a strong relationship between CBR of the treated soil and the parameters with R^2 value of 88.2%. Similarly, correlation was obtained for California bearing ratio after six days curing and soaked for 24 hours (see equation 4.6). The correlation coefficient value (R^2) shows a strong relationship between CBR of the treated soil and the parameters with R^2 value of 87.4%. Generally the correlation coefficient values (R^2) of 88.2% for CBR of unsoaked treated soil and 87.4% for CBR of soaked treated soil shows the parameters are more correlated to the unsoaked than soaked of CBR.

The regression equation is

$$CBR(US) = 8.7 + 7.11L + 1.2IOT - 0.12PF + 0.38PI + 12CE \qquad (4.5)$$

$R^2 = 88.2\%$

$$CBR(S) = -0.2 + 5.42L + 0.814IOT + 0.111PF - 0.166PI + 7.44CE \qquad (4.6)$$

$R^2 = 87.4\%$

Where

CBR (US) = California bearing ratio of unsoaked treated sample

CBR(S) = California bearing ratio of soaked treated samples

L= Lime content, IOT= Iron ore tailing content, PF=Percentage fine, Pl= Plasticity index, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for CBR of unsoaked test samples is given in Table 4.18. The analysis shows that the IOT (F_{CAL} = 27.344 > F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 90.044 > F_{CRIT} = 3.156) has significant affect on CBR of unsoaked test samples of treated soil. However, Compactive effort has a more pronounced effect.

Table 4.18: Two-way analysis of variance for regression analysis on California bearing ratio of unsoaked samples of black cotton soil-lime-IOT mixtures.

Property	**Source of Variation**	**Degree of freedom**	**F_{CAL}**	**p-value**	**F_{CRIT}**	**Remark**
CBR(US)	IOT	29	27.344	2.67E-24	1.663	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	90.044	1.64E-18	3.156	F_{CAL}>F_{CRIT}, Significant effect

The two – way analysis of variance (ANOVA) test for CBR of soaked test samples is given in Table 4.19. The analysis shows that the IOT ($F_{CAL} = 28.173 > F_{CRIT} = 1.663$) and Compactive effort ($F_{CAL} = 57.511 > F_{CRIT} = 3.156$) has significant affect on CBR soaked test samples of treated soil. However, Compactive effort has a more pronounced effect.

Table 4.19: Two-way analysis of variance for regression analysis on California bearing ratio of soaked samples of black cotton soil-lime-IOT mixtures.

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
CBR(US)	IOT	29	28.173	1.22E-24	1.663	$F_{CAL}>F_{CRIT}$, Significant effect
	Compactive effort	2	57.511	1.72E-14	3.156	$F_{CAL}>F_{CRIT}$, Significant effect

4.6 Durability

Durability assessment of soil samples involves the simulation of some of the worst conditions that could be experienced in the field. It was evaluated by the immersion of specimens in water to determine resistance to loss in strength which is more acceptable for tropical regions like Nigeria (Ola, 1974). The resistance to loss in strength determined as the ratio of the unconfined compressive strength of specimen wax-cured for 7 days, de-waxed top and bottom to allow absorption of water and later immersed in water for 7 days, to those cured for 14 days. Conventionally, an allowable 20 % loss in strength (i.e., 80 % resistance to loss in strength) is recommended for a specimen cured for 7 days and immersed in water for 4 days (Ola, 1974; Osinubi, 1998a; 1999).

The variation of resistance to loss in strength of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.21a - c, For BSL, WAS and BSH compactions the resistance to loss in strength increased from 11.79, 7.17 and 19.85 % for the natural soils to peak values of 37.56, 31.3 and 67.17 % for 8 % lime / 8 % IOT, 8 % lime / 8 % IOT and 8 % lime /6 % IOT treatments, respectively.

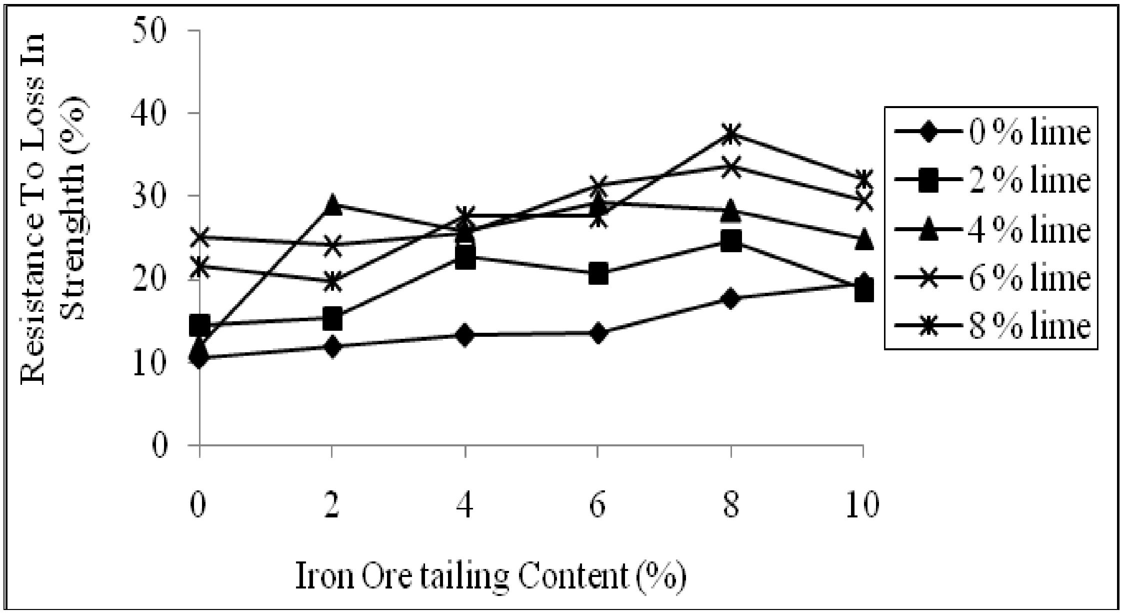


Fig. 4.24a: Variation of resistance to loss in strength of black cotton soil – lime mixtures with iron ore tailing content (BSL compaction)

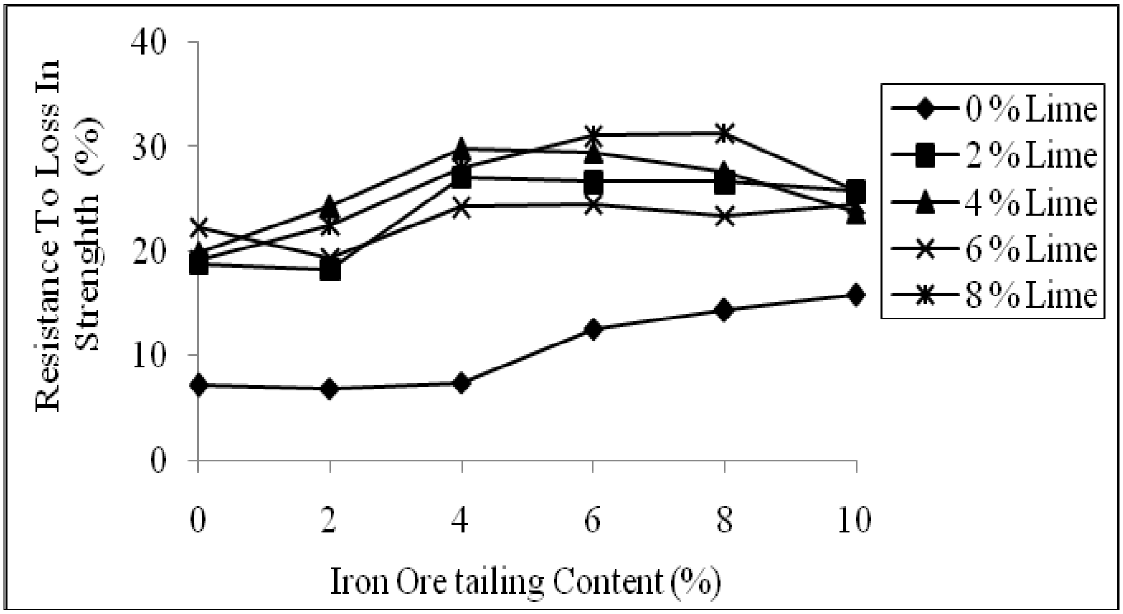


Fig. 4.24b: Variation of resistance to loss in strength of black cotton soil – lime mixtures with iron ore tailing content (WAS compaction)

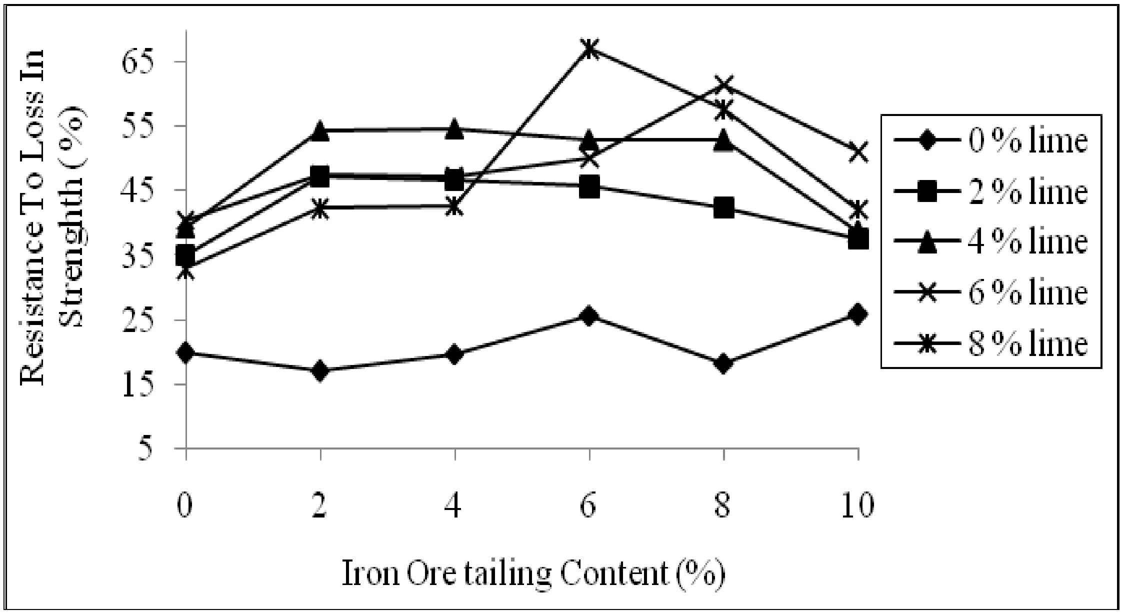


Fig. 4.24c: Variation of resistance to loss in strength of black cotton soil – lime mixtures with iron ore tailing content (BSH compaction)

The recorded peak resistance to loss in strength values for the various compactive efforts considered fell short of the 80 % criterion stated earlier. However, the 67.17 % resistance to loss in strength for 8 % lime / 6 % IOT treatment of soil when compacted with BSH energy may be acceptable since the limiting value reported by Ola (1974) is based on 4 day soaking and not the 7 days soaking to which the specimens were subjected.

The two – way analysis of variance (ANOVA) test on the durability assessment result for BSL, WAS and BSH compaction (see Table 4.20) shows that the effects of lime and IOT on black cotton soil were statistically significant for lime (F_{CAL} = 17.49, 44.20, 21.50 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 6.97, 9.35, 3.51 > F_{CRIT} = 2.71).

Table 4.20: Two-way analysis of variance for resistance to loss in strength of black cotton soil – lime – iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Lime	4	17.49	2.59E-06	2.87	Fcal > Fcrit, Significant
	IOT	5	6.97	6.40E-04	2.71	Fcal > Fcrit, Significant
WAS	Lime	4	44.20	1.17E-09	2.87	Fcal > Fcrit, Significant
	IOT	5	9.35	1.00E-04	2.71	Fcal > Fcrit, Significant
BSH	Lime	4	21.50	5.20E-07	2.87	Fcal > Fcrit, Significant
	IOT	5	3.51	1.94E-02	2.71	Fcal > Fcrit, Significant

Detailed test results are given in Tables A4.30 a - c in the Appendix.

4.4.1.1 Regression analysis for durability

Results of regression analysis showed that the durability was influenced by the lime content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter with compactive effort index values of –1, 0 and 1 for British Standard light, West African Standard and British Standard Heavy compactive efforts respectively. The regression equations (see equation 4.7) revealed the extent to which these parameters influence the durability which is a function of the coefficient of each parameter. The equation depict that lime content, iron ore tailing content and compactive effort has positive effect on the durability while percentage fine and plasticity index has a negative effect on the durability. The correlation coefficient values (R^2) shows a partial relationship between durability and the parameters with R^2 value of 59.1%.

The regression equations is

$$\mathrm{DURABILITY} = 87.4 + 1.60\mathrm{L} + 0.914\mathrm{IOT} - 0.260\mathrm{PF} - 1.83\mathrm{PI} + 9.51\mathrm{CE} \qquad (4.7)$$

R^2= 59.1%

The two – way analysis of variance (ANOVA) test for durabilty is given in Table 4.21. The analysis shows that the IOT (F_{CAL} = 7.973 > F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 140.923 > F_{CRIT} = 3.156) significantly affected durabilty values of the treated soil. However, the effect of Compactive effort on the durability of black cotton soil was much more significant.

Table 4.21: Two-way analysis of variance for regression analysis on durability of black cotton soil-lime-IOT mixtures

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
MDD	IOT	29	7.973	1.43E-11	1.663	$F_{CAL}>F_{CRIT}$, Significant effect
	Compactive effort	2	140.923	5.4E-23	3.156	$F_{CAL}>F_{CRIT}$, Significant effect

4.7 Microanalysis of Specimens

4.7.1 Scanning electron microscope

Materials evaluation using scanning electron microscope (SEM) includes grain size, surface roughness, porosity, particle size distributions, material homogeneity inter-metallic distribution and diffusion. Micro-structural studies are increasingly used to improve understanding of the macroscopic behaviour and physical properties of compacted and natural soils. Micro-structural studies involve the use of techniques at particle/aggregation scale (<100 µm) to analyse the arrangement and distribution of particles, particle assemblies and pores and their contacts and connectivity in different soils (Collins and McGowan 1974; Delage and Lefebvre, 1984; Delage *et al*., 1996, Al-Rawas and McGown, 1999; Mitchell and Soga 2005). A finely focused electron beam scanned across the surface of the sample generates secondary electrons, backscattered electrons, and characteristic X-rays. These signals are collected by detectors to form images of the sample displayed on a cathode ray tube screen.

4.7.1.1 Micrograpsh of specimens cured for 7days

The scanning electron micrographs of specimens of natural black cotton soil and black cotton soil optimally treated with 8 % lime / 8 % IOT after 7 days curing period are shown on Plate 4.1a-d. The micrograph of natural black cotton soil indicates a scaly-like surface morphology with a well develop network of cracks. It shows an inter-grain porosity induced by drying and microstructure alteration. This result is similar to the report of Romero and Simms (2008) and Zhang *et al*., (2005). It could also be that no significant pozzolanic and ionic reaction might have taken place during the curing period. Similar behaviour was observed by Azige (2012) and Ishola (2014). The micrograph of optimally stabilized black cotton soil indicates that changes caused by cation exchange, flocculation-agglomeration, pozzolanic reaction, and carbonation affected the soil particles. The micrograph shows the development of cementitious products of calcium silicates hydrates, calicium aluminate hydrates and calcium aluminosilicate hydrates covering the soil grains and filling the inter-aggregate pores. These compounds were responsible for the strength gain. Similar results were reported by Lambe and Martin (1954), Mallela *et al*., (2004) and Deneele *et al*., (2010),

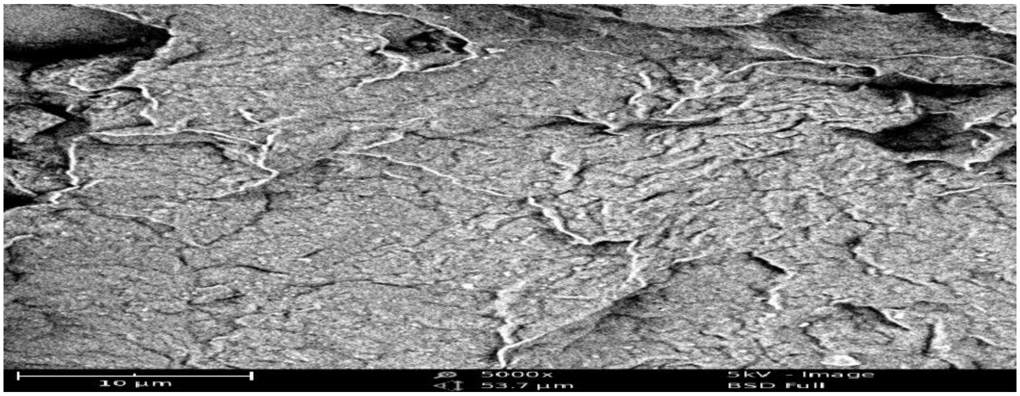


Plate 4.1a: Micrograph of natural black cotton soil after 7 days curing at 10 µm magnification

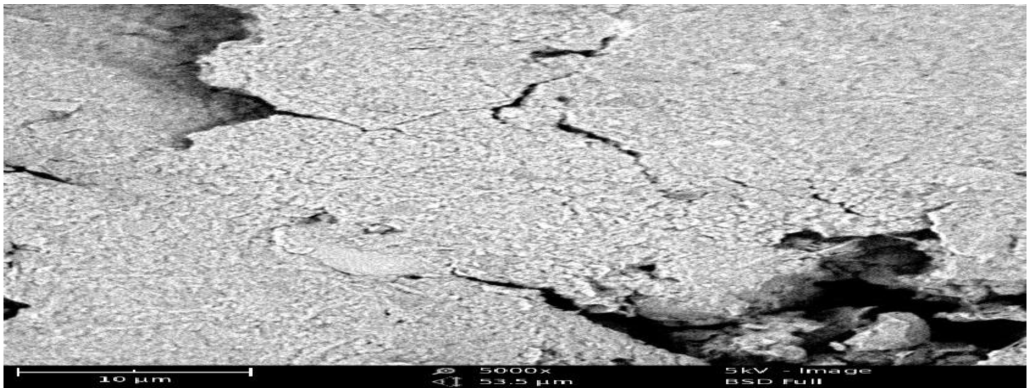


Plate 4.1b: Micrograph of black cotton soil optimally stabilized with 8 %lime / 8 % iron ore tailing blend after 7 days curing at 10 µm magnification

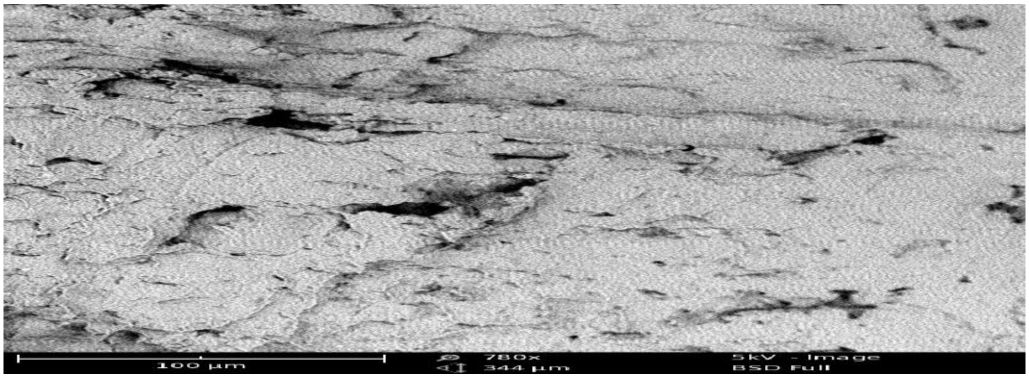


Plate 4.1c: Micrograph of natural black cotton soil after 7 days curing at 100 µm magnification

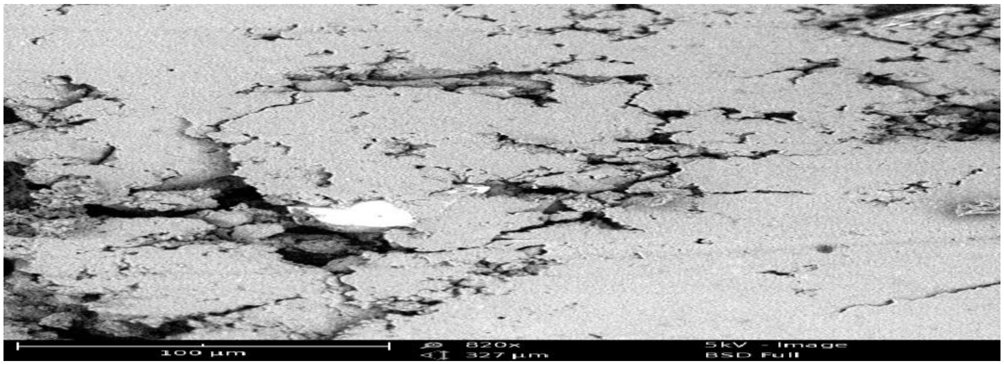


Plate 4.1d: Micrograph of black cotton soil optimally stabilized with 8 %lime / 8 % iron ore tailing blend after 7 days curing at 10 0µm magnification

4.7.1.2 Micrograph of specimens cured for 28 days

The micrographs of specimens of the natural and stabilized black cotton soil cured for 28 days is shown in Plate 4.2a-d. The micrograph for the natural black cotton soil show changes in the micro-structural particle orientations which appeared to be different from those of specimens cured for 7 days. This could be attributed to the insignificant inter-surface activity/reaction within the untreated sample during curing. However, the orientation changes indicate that flocculation of clay probably occurred through simple electrostatic attraction between positively charged particles edges and negative particle surface.

The micrograph of stabilized black cotton soil after 28 days curing period shows a floppy-like aggregated structure. It indicates that the clay particles and the flocs, were grown within the pore. The stabilization reaction in the soil-lime-iron ore tailing mixture might have taken place with complete flocculation and agglomeration, cation exchange and gain in strength that contributed to the inter-particle bonding of the mixture. Also, the curing period enhanced the formation of cementitious compounds that precipitated in the soil matrix because of the high pH of the medium caused by lime and IOT (see Plate 4.1a - d).This finding is consistent with the findings reported by Okonkwo (2009) and Negi *et al.*, (2013).

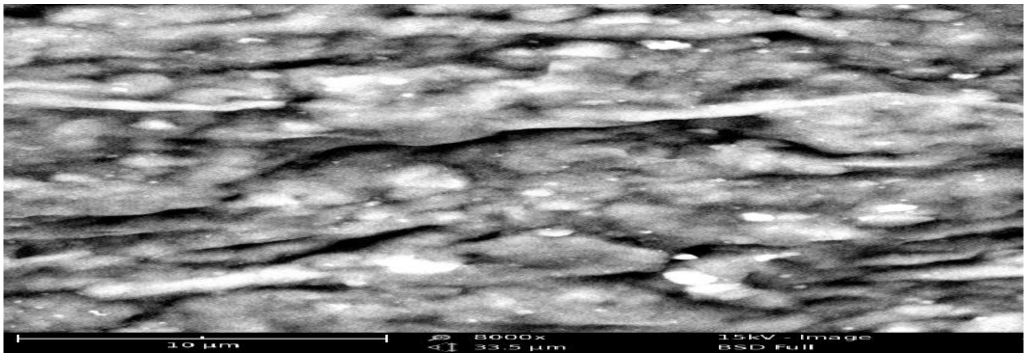


Plate 4.2a: Micrograph of natural black cotton soil after 28 days curing at 10µm magnification

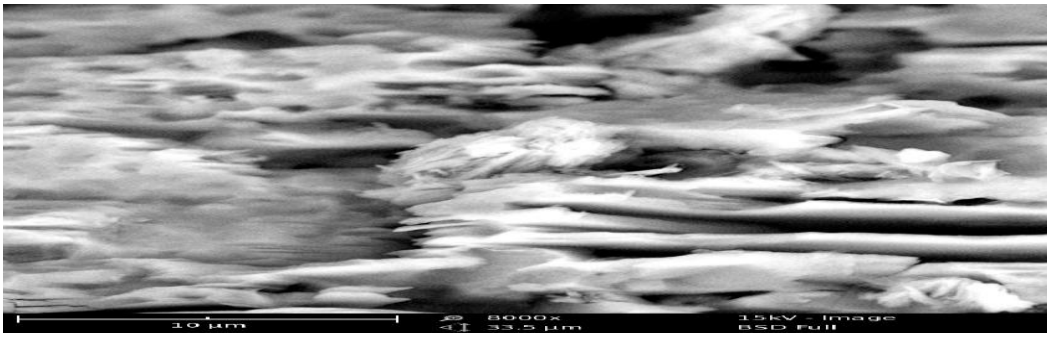


Plate 4.2b: Micrograph of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 28 days curing at 10 µm magnification

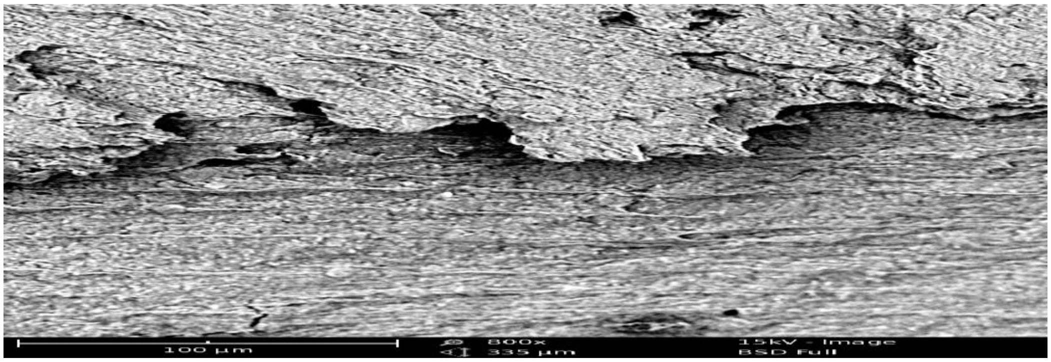


Plate 4.2c: Micrograph of natural black cotton soil after 28 days curing at 100µm magnification

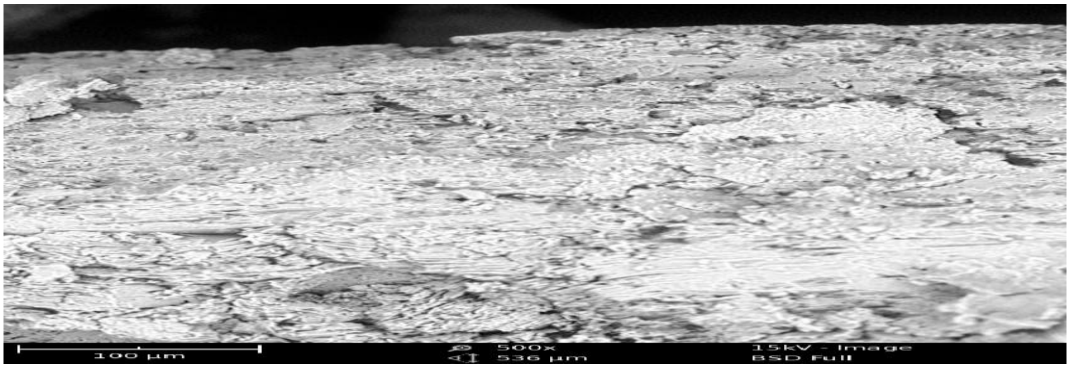


Plate 4.2d: Micrograph of stabilized black cotton soil optimally blend at 8 % lime / 8 % iron ore tailing after 28 days curing at 100µm magnification

4.7.2 Energy-Dispersive X-Ray Spectroscopy

Energy-dispersive x-ray spectroscopy (EDS) identifies the elemental composition of materials imaged in a scanning electron microscope (SEM) for all elements with an atomic number greater than boron. The nature of these compositional differences can be investigated further through the individual element maps and the targeted point analysis of different surface chemical phases (Clare, 2012). Most elements are detected at concentrations in the order of 0.1 %. EDS is used in materials evaluation and identification of contaminants, elemental diffusion profiles and multiple spot analyses of areas from 1 micron to 10 cm in diameter (Neeraj *et al*., 2012). As the electron beam of the SEM is scanned across the sample surface, it generates X-ray fluorescence from the atoms in its path. The energy of each X-ray photon is characteristic of the element which produced it. The EDS microanalysis system collects the X-rays, sorts and plots them by energy, and automatically identifies and labels the elements responsible for the peaks in this energy distribution. The EDS data are typically compared with either known or computergenerated standards to produce a full quantitative analysis showing the sample composition.

4.7.2.1 Spectroscopy of specimens cured for 7 days

The EDS of natural black cotton soil and soil optimally stabilized with 8 % lime /8 % iron ore tailing cured for 7 days is shown on Plate 4.3a-b. The results of EDS elemental analyses of the natural soil shows that it is composed of alumino silicates minerals as reported by Reyes et al., (2007). It was observed that the natural black cotton soil had a higher silicon content of 64.8% than the optimally stabilized black cotton soil with a value of 62.6 %. This difference in silicon content might be due to silicon involved in hydration reaction with the calcium present in the lime and IOT. It was also observed aluminium and bromine were detected in the natural and optimally stabilized black cotton soil. The spectrum of silicon and aluminium detected from the EDS confirms the dissolution of silica and alumina present in the soil-lime-IOT mixture where cementitious compounds such as hydrated calcium silicates or hydrated calcium aluminates (C-S-H and C-A-H) were formed. However, the nature of these compositional differences can be investigated further through the individual element maps and the targeted point analysis of different surface chemical phases through the scanning electron microscope backscattered images (see Plate 4.3 e - f).

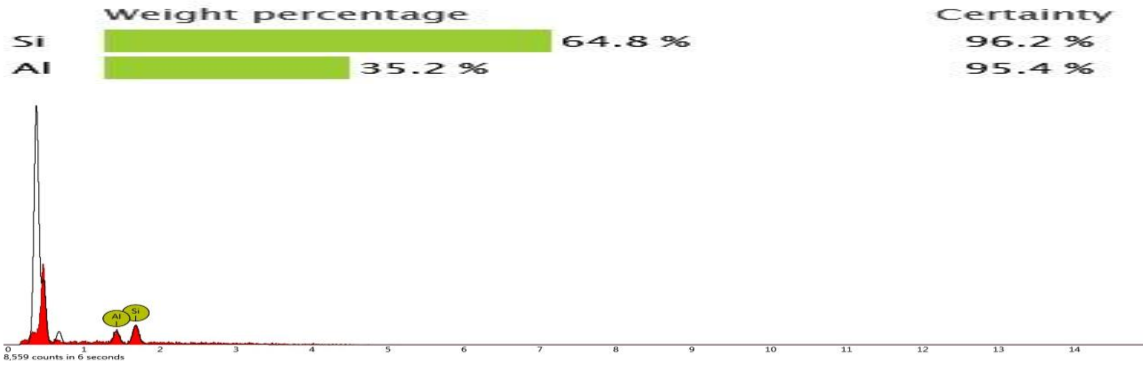


Plate 4.3a: Energy-dispersive x-ray spectroscopy of natural black cotton soil after 7 days curing period (Point 1)

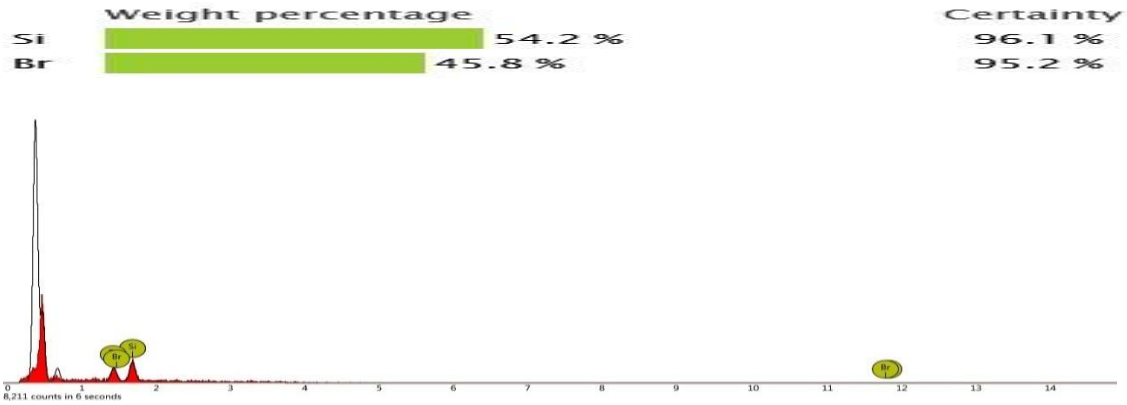


Plate 4.3b: Energy-dispersive x-ray spectroscopy of natural black cotton soil after 7 days curing period (Point 2)

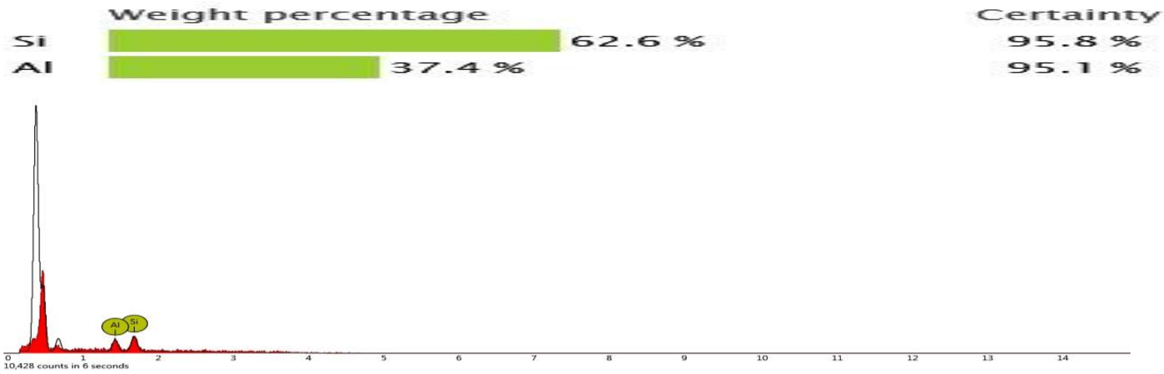


Plate 4.3c: Energy-dispersive x-ray spectroscopy of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 7 days curing period (Point 1)

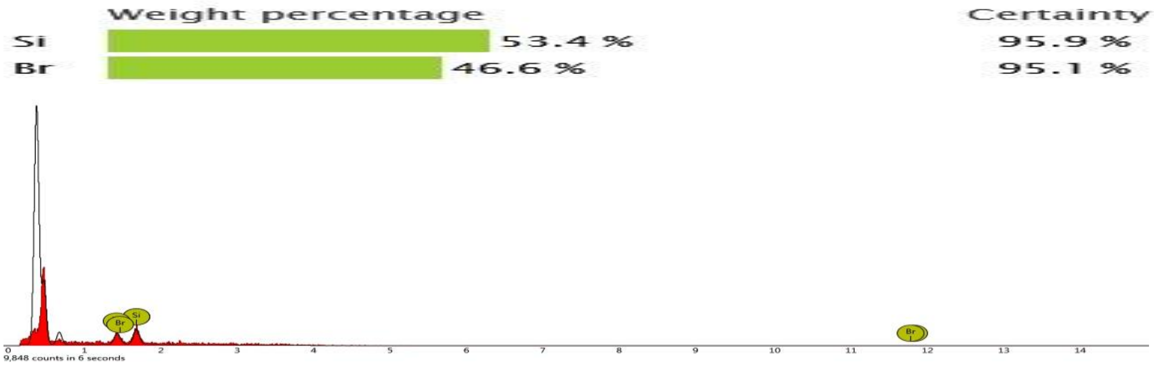
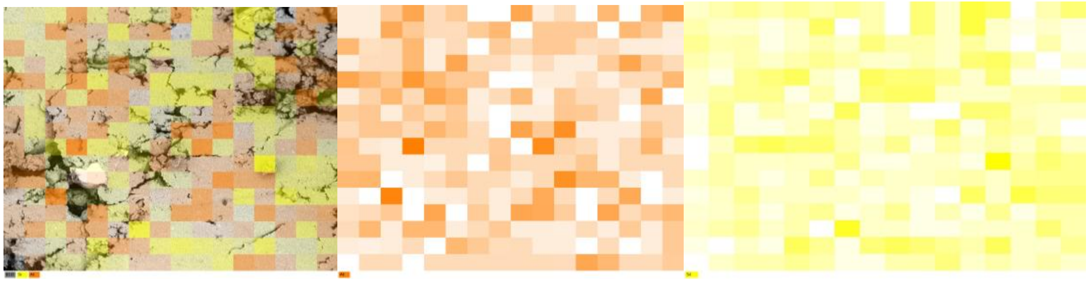
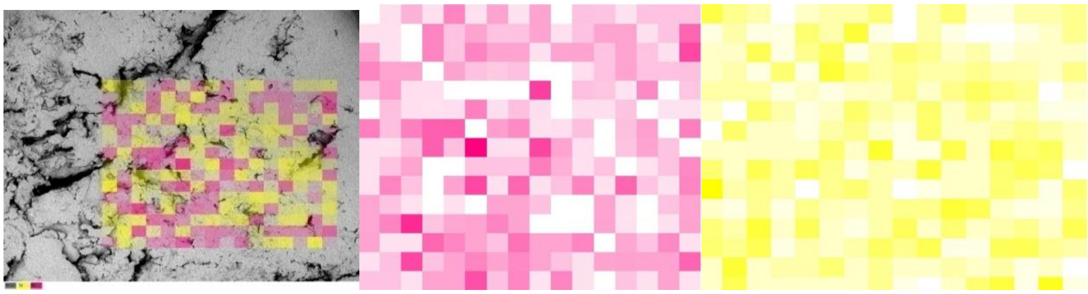


Plate 4.3d: Energy-dispersive x-ray spectroscopy of black cotton soil optimally stabilized with 8 % lime /8 % iron ore tailing blend after 7 days curing period (Point 2)



BSD Image Al Si

Plate 4.3e: Scanning electron microscope backscattered images and Al and Si distribution maps for the natural soil and stabilized black cotton soil cured for 7days (Point 1)



BSD Image Br Si

Plate 4.3f: Scanning electron microscope backscattered images and Br and Si distribution maps for the natural soil and stabilized black cotton soil cured for 7days (Point 2)

The SEM Backscattered Electron (BSE) image and distribution maps of Al, Si and Br for 7 days natural and stabilized black cotton soil for Points 1 and 2 show spatial heterogeneity in their distributions. However their distributions appear to be disjointed in some sections.

4.7.2.2 Spectroscopy of specimens cured for 28 days

The EDS elemental analysis of specimens cured for 28 days are similar to those of specimens cured for 7 days (see Plate 4.4a - d. However, elemental traces of O, N, Mo, Sb, and Rb were detected besides Si, Al and Br that were detected after the 7 days curing period.

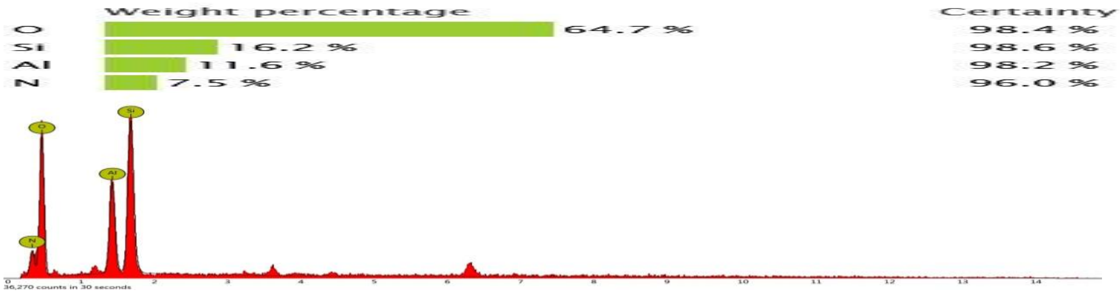
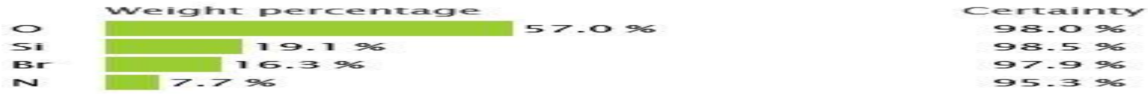


Plate 4.4(a): Energy-dispersive x-ray spectroscopy of natural black cotton soil after 28 days curing period (Point 1)



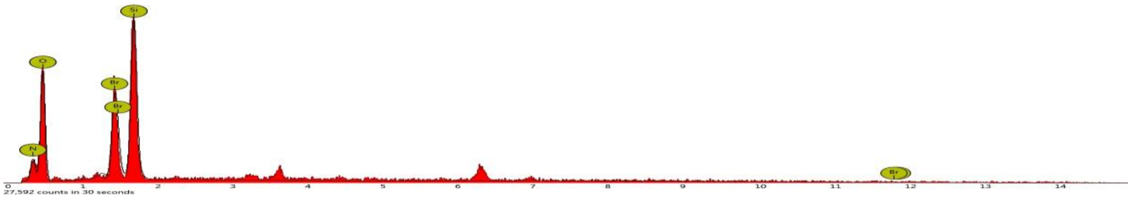


Plate 4.4b: Energy-dispersive x-ray spectroscopy of natural black cotton soil after 28 days curing period (Point 2)

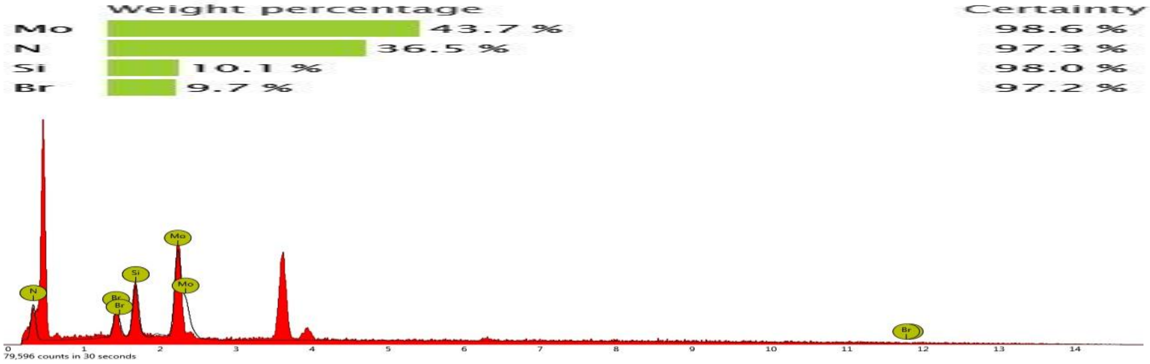


Plate 4.4c: Energy-dispersive x-ray spectroscopy of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 28 days curing period (Point 1)

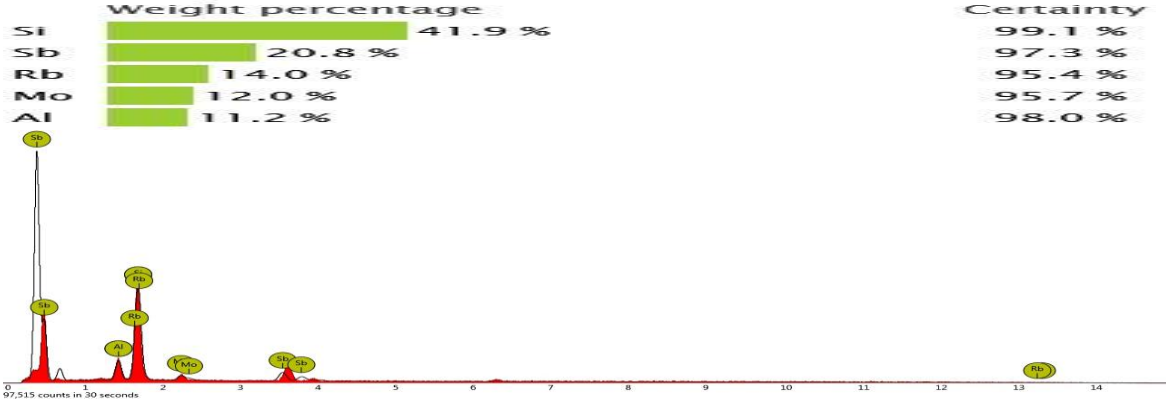


Plate 4.4d: Energy-dispersive x-ray spectroscopy of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 28 days curing period (Point 2)

4.7.3 Fibermetric analysis

The fibermetric application is a statistical package incorporated in SEM that generates all the statistical data needed for analysis. It automatically analyses hundreds of data points that provide solid statistical analysis. This data is displayed in various formats like an interactive fiber and pore size distribution histogram. The Fiber metric application can be used on fibers ranging from 40 µm to 100 nm. It can be used for a wide range of applications, like investigation of filtration materials, diaper paddings, fiber research, and fiber and filter production control. This techniques could be used to make qualitative and quantitative inferences about unsaturated behaviour of soils such as water retention and water permeability properties, evolution of pore size density functions along different hydro-mechanical paths, macroscopic volume change behavior, micro and macro scale interactions, and so on (Romero and Simms, 2008).

Plate 4.5a-d shows the PHENOMWORLD desktop screen shot obtained from fiber and pore image measurement (fibermetric analysis) of the natural black cotton soil and optimally stabilized black cotton soil cured for 7 and 28 days respectively. The red patches/spots indicate data points from which the fibermetric analysis was achieved.

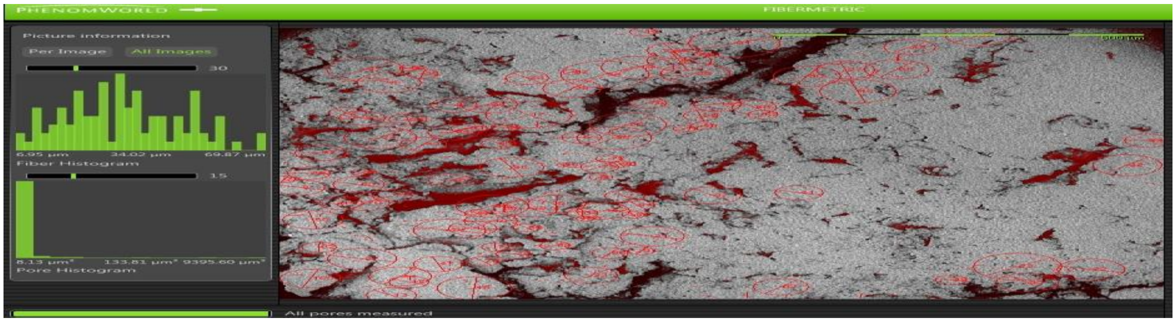
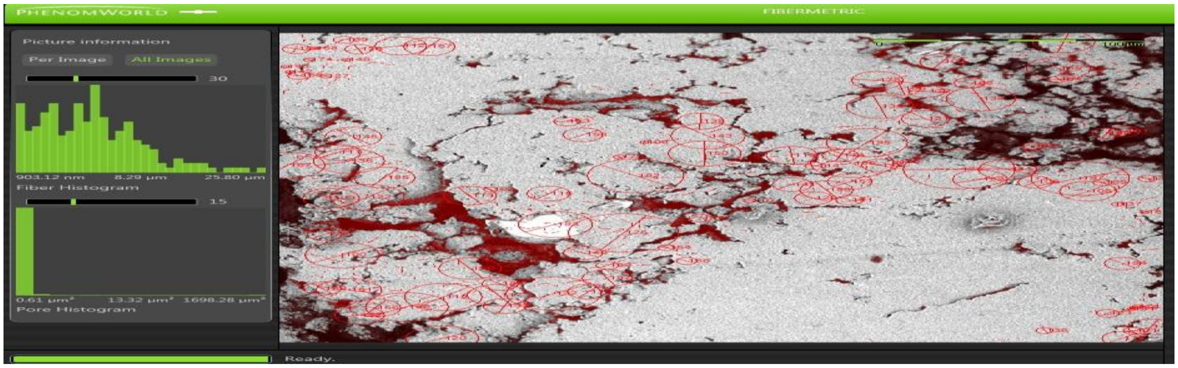
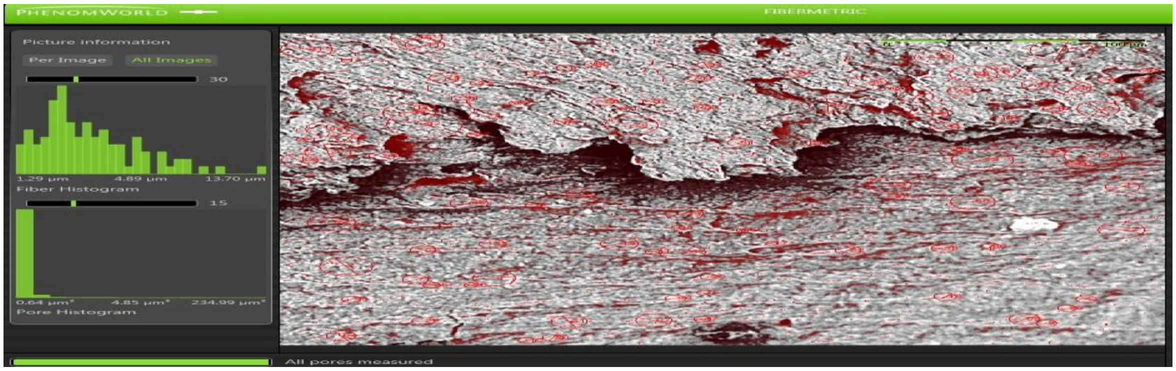


Plate 4.5a: Fiber and pore image measurements of natural black cotton soil cured for 7 days



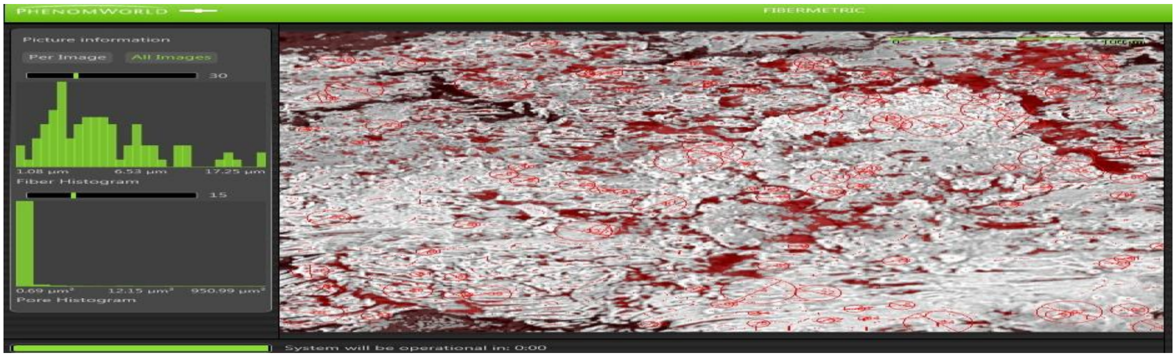
Ready.

Plate 4.5b: Fiber and pore image measurements of optimally stabilized black cotton soil treated with 8 % lime / 8 % iron ore tailing blend after 7 days curing period



All pores measured

Plate 4.5c: Fiber and pore image measurements of natural black cotton soil cured for 28 days



System will be operational in: 0:00

Plate 4.5d: Fiber and pore image measurements of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 28 days curing period

4.7.3.1 Fiber histogram of specimens cured for 7 days

The histograms of fabrics of the untreated natural BCS soil and the stabilized black cotton soil optimally treated with 8 % lime / 8 % IOT blend and cured for 7 days was determined using SEM are shown on Plate 4.6a-b. It was observed that the length of soil fiber/sizes decreased from 6.95 µm for the natural soil to 903.12 nm for the stabilized soil. The decrease in length of soil fiber could be due to the flocculent nature of IOT and also as a result of cation ion exchange reaction that resulted in the formation of calcium silicate. This technique could be used to make qualitative and quantitative inferences about unsaturated behaviour of soils such as water retention and water permeability properties, evolution of pore size density functions along different hydro-mechanical paths, macroscopic volume change behavior, micro and macro scale interactions, and so on (Romero and Simms, 2008).

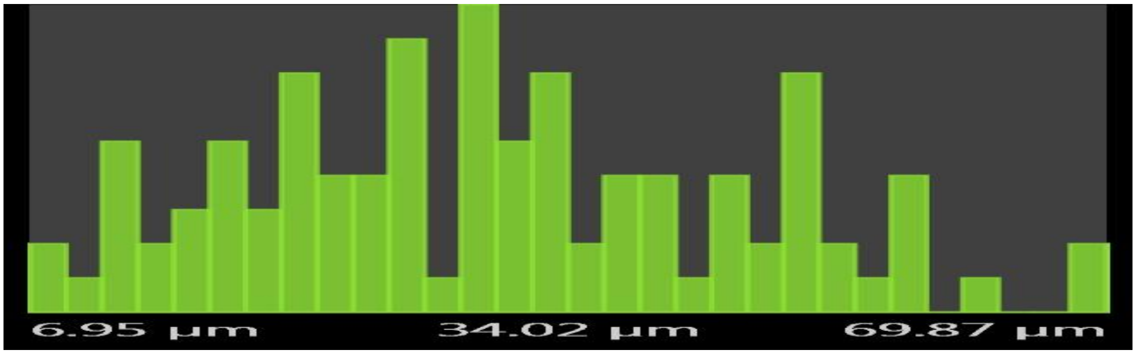


Plate 4.6a: Fibre histogram of natural black cotton soil after 7 days curing period

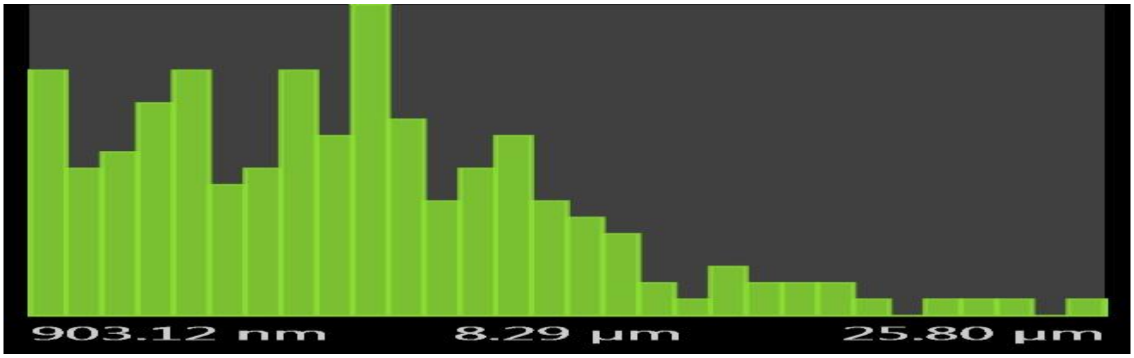


Plate 4.6b: Fibre histogram of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing blend after 7 days curing period

4.7.3.2 Fiber histogram of specimens cured for 28 days

Fiber analysis for specimens cured for 28 days is similar to those of specimens cured for 7 days (see Plate 4.7a-b).

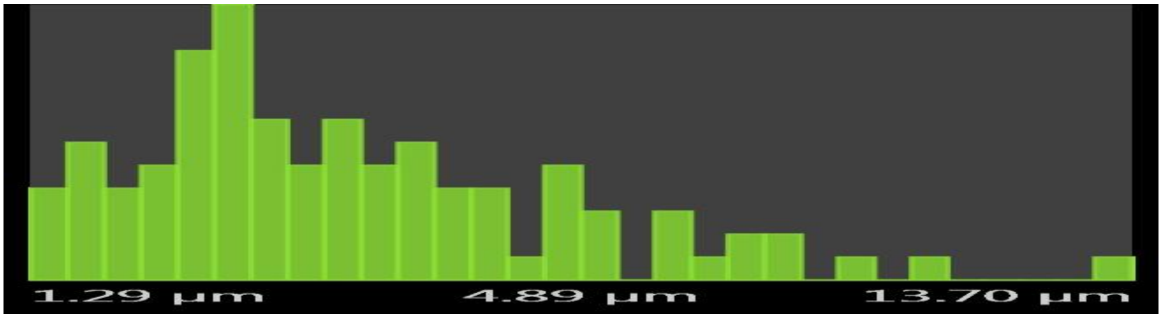


Plate 4.7a: Fiber histogram of natural black cotton soil after 28 days curing period

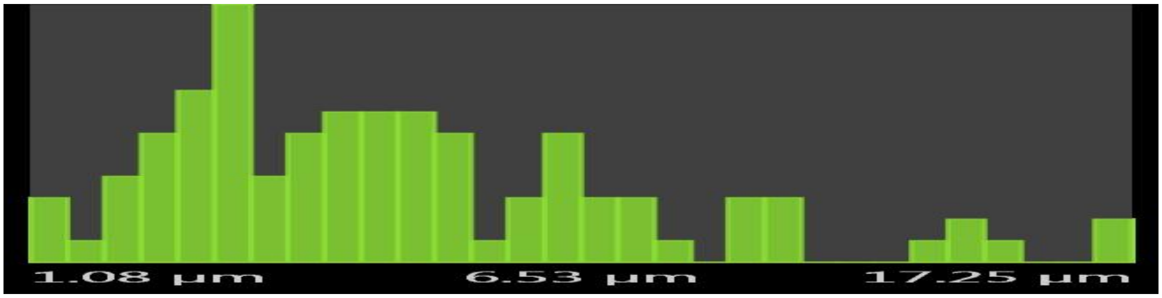


Plate 4.7b: Fibre histogram of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing after 28 days curing period

4.7.3.3 Pore histogram of specimens cured for 7 days

The variation of surface area of pores of the natural black cotton soil and black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing after 7 days curing period is shown in Plate 4.8a-b. It was observed that the surface area of pores within soil-lime-IOT mixtures considered decreased from the value of 8.13 µm^2 for the natural soil to a value of 0.61 µm ^{2} for the optimally stabilized soil. The decrease in pores spaces was due to the formed calcium silicates hydrates that covered the soil grains and filling the inter-aggregate porosity similar to the findings reported by Deneele *et al*., (2010). From the micro-structural point of view, the lime-IOT treatment reduced the proportion of the bigger pores, while the cementation products stabilize the surface state of the soil grains.

In addition, this techniques gives further information on the relationship between the dominant pore sizes observed directly with SEM and the pore size distribution (PSD) measured as shown on the histogram. The decrease in pores was due to the re-arrangement and distribution of particles, particle assemblies and pores and their contacts and connectivity in different soils. Similar behaviour was observed by Collins and McGowan (1974), Delage and Lefebvre (198)4; Delage *et al*., (1996), Al-Rawas and McGown 1999) as well as;Mitchell and Soga (2005).

Plate 4.8a): Pore histogram of natural black cotton soil after 7 days curing period

Plate 4.8b: Pore histogram of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing after 7 days curing period

4.7.3.4 Pore histogram of specimens cured for 28 days

Pore analysis of specimens after 28 days curing period also follows similar trend like that of seven days curing period. (see Plate 4.9a-b). However, there was no significant difference between the pore sizes of the untreated and optimally treated black cotton soil which could be as a result of complete dryness caused hydration and pozollanic reaction.

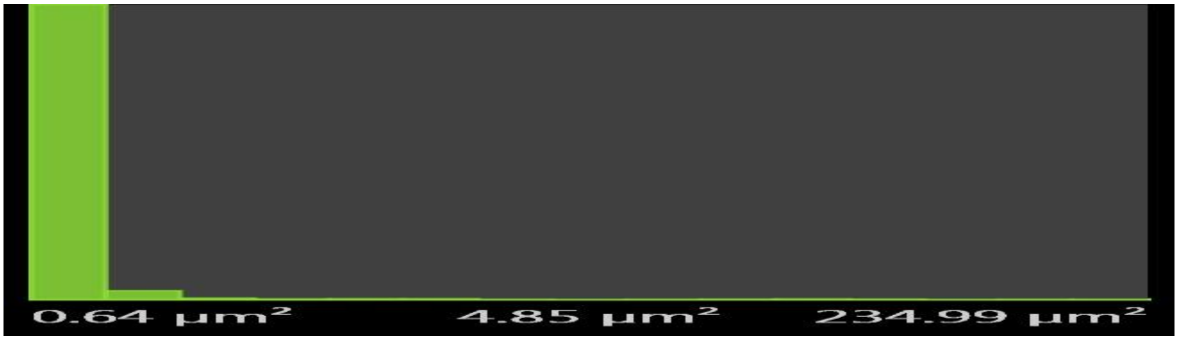


Plate 4.9a: Pore histogram of natural black cotton soil after 28 days curing period

Plate 4.9b: Pore histogram of black cotton soil optimally stabilized with 8 % lime / 8 % iron ore tailing after 28 days curing period

4.7.4 Leaching Potential of Iron to the Environment

4.7.4.1 Effect of pH

The variation of pH of black cotton soil-lime mixtures with iron ore tailing content is shown in Fig. 4.22a

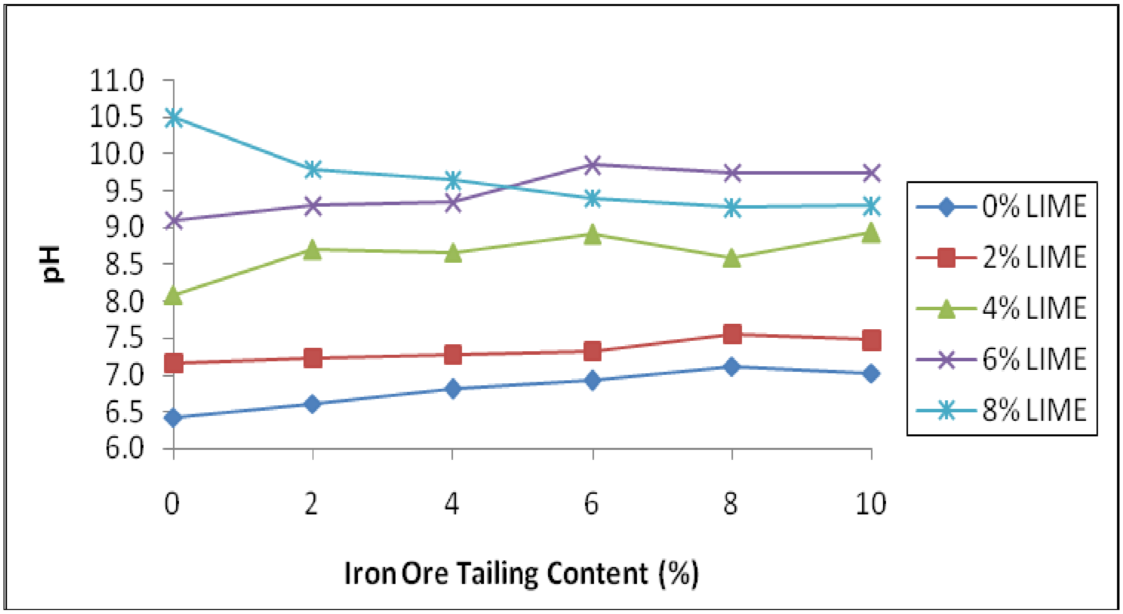


Fig 4.25: variation of pH of black cotton soil-lime mixtures with iron ore tailing content

It was observed that the pH of the black cotton soil - lime-IOT mixtures considered increased from a value of 6.42 for the natural soil to 9.75 for 6 % lime / 0 % IOT treatment and thereafter no increased for higher IOT content. The increase in pH with increase in IOT content could be as a result of increase in free lime present in the soil with higher IOT treatment that that led to increase in the pH alkalinity values (Osinubi *et al*., 2010). It has been reported by Amadi (2010) that the increase in pH level observed in specimens containing industrial waste may be due to hydroxides which were created by the dissolution of oxides in the waste. Similar finding was reported by Neeraj *et al*., (2012).

The increase in pH could also be due to high alkaline properties of IOT with pH of 9.72 which caused the increase in pH of the acidic soil. The acid neutralization property may have arisen from the high CEC of IOT (24.6 Cmol/kg) that exchanged the solution proton (H^+) with Ca^{2+} ion present in the clay structure. This is in consistent with the findings of Liu and Lal (2012b).

However, it was observed that the pH decreaseds rom a value of 10.5 at 8% lime 0 % IOT to 9.28 for 8 % lime 10 % IOT treatment. The decrease is attributed to decrease in the CEC of soil-lime-IOT mixture at higher lime and IOT content. Similar observation was reported by Huang and Petrovic (1994) , Katz et al. (1996), Liu and Lal,(2012a,b). pH is extremely important to the mobility of contaminant, especially metals and metalloids. Low pH correlates closely with high dissolved metals and low metal content in the soil. High pH correlates with low dissolved metals and high metals content in the soil (Vogel and Kasper, 2002). However, the pH value 9.3 for the optimum blend at 8 % lime 8 % IOT is above the permissible range of 6.5-8.5 for drinking water recommended by APHA (1989), WHO (2006) and NIS (2007).

4.7.4.1 Batch equilibrium adsorption test

Results of chemical analyses using Atomic Absorption Spectrophotometry (AAS) were used to obtain desorbed concentration of Iron (Fe^{2+}) at various lime-Iron ore tailing (IOT) contents as shown in Fig. 4.23. It was observed that the desorbed values increased with higher IOT content in the range of 0.004 mg/l for the natural soil to a peak value of 0.204 mg/l for 0 % lime/ 10 % IOT treatment. The increase could be attributed to increase in the Fe^{2+} concentration with increase in IOT which has a desorbed value of 10.552 mg/l for 10 % IOT content. The same trend of increase in the desorbed values of Fe^{2+} was observed for the stepped concentrations (i.e., 2, 4, 6 and 8 %) of lime content ranging between 0.016 mg/l to 0.181 mg/l at 2% lime 0% IOT up to 10%IOT, 0.016 mg/l to 0.152 mg/l at 4% lime 0% IOT up to 10% IOT, 0.10 to 0.242 mg/l at 6% lime 0% IOT up to 10%IOT and 0.063 mg/l to 0.292 mg/l at 8% lime 0% IOT. This implies that more Fe^{2+} was released by the treated soil with higher IOT content. This trend of increase in the desorbed values may not be unconnected with the increasing pH of the solution. (Ijimdiya and Osinubi, 2011). The possible explanation for the increase desorption capacity of the soil-lime-IOT mixtures with higher IOT content is that the high pH value made the surfaces to become more negatively charge. An increase in pH created a condition for the establishment of attractive electrostatics forces that enhance the desorption of cation species (Shackelford 1993; Osinubi and Amadi, 2003). However, the desorbed value 0.272 mg/l Iron(Fe^{2+}) concentration for the optimum 8 % lime 8 % IOT blend falls within the permissible value of not more than 0.3 mg/l Iron (Fe^{2+}) concentration for drinking water recommended by WHO (2006) and NIS (2007).

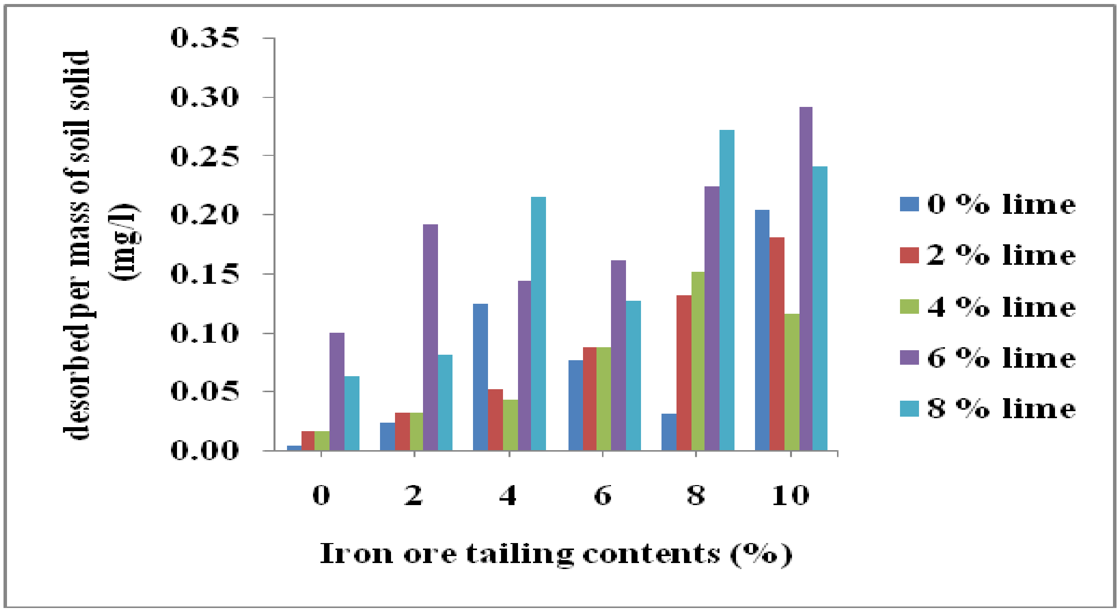


Fig.4.26: Variation of desorbed Iron (Fe^{2+}) of black cotton soil – lime mixtures with iron ore tailing content

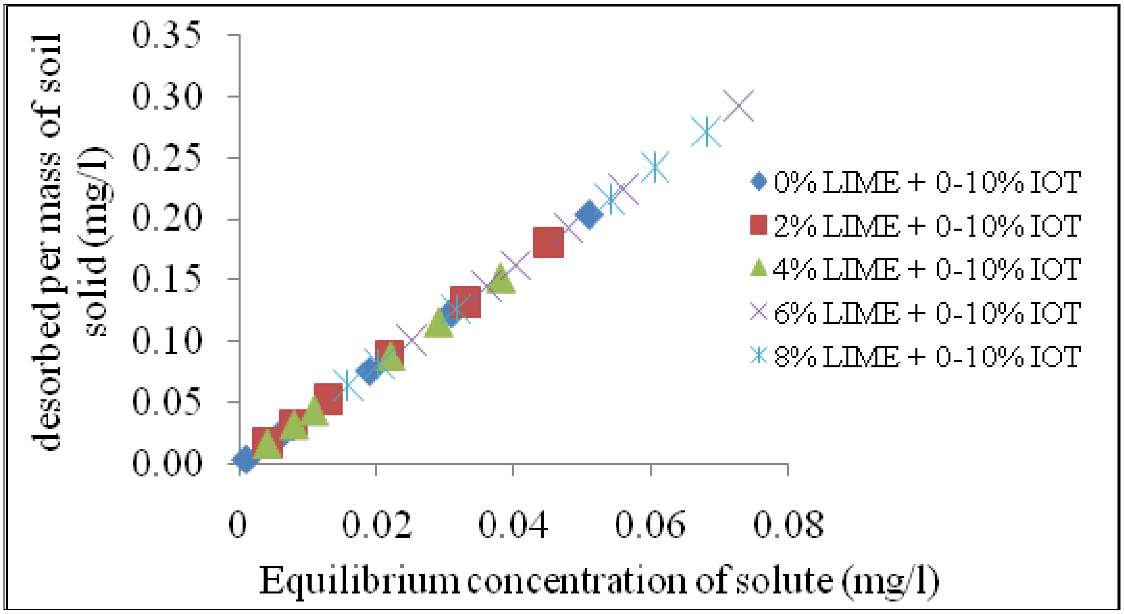


Fig.4.27: Variation of desorbed Iron (Fe^{2+}) of black cotton soil - lime – iron ore tailing mixtures at various concentrations with equilibrium concentration of solute (desorption isotherms)

The desorption isotherms were all linear from the origin, (see Fig. 4.24). This is in agreement with the report of Shackelford and Daniel (1991); that desorption isotherms can be linear and non-linear.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

An expansive soil (also known as black cotton soil) belonging to the CH group in the Unified Soil Classification System, USCS or A-7-6(26) soil group of the American Association of State and Transportation Officials (AASHTO) soil classification system was collected from Deba L.G.A, Gombe state. According to NBRRI classification it classifies as soil of medium swell potential .The soil is greyish black in colour (from wet to dry states) with a liquid limit of 56.8 %, plastic limit of 27.2 % , plasticity index of 28.6 %, free swell of 52.5 % , linear shrinkage of 18.1 %, specific and gravity of 2.48. All these values indicated that the soil is highly plastic with about 80.7 % passing the BS. No. 200 sieve (0.075 mm aperture). The soil was treated with blends of lime (i.e., 0, 2, 4, 6, and 8 %) and IOT (i.e., 0, 2, 4, 6, 8, and 10 %) by dry weight of black cotton soil

Results of tests carried out show that the liquid limit of the natural black cotton soil decreased from 56.8 % to a minimum value of 43.8 % when treated with 8 %lime / 6 % IOT blend. The PL decreased from a value of 29.2 % for the natural soil to a minimum value of 18 % for 8 % lime / 8 % IOT treatment, while the plasticity index decreased from a value of 27.6 % to 24.3 % for 6 % lime / 10 % IOT treatment. The plasticity indices for all the test samples were within the 30 % value prescribed for sub-grade by Clause 6122 of Nigeria General Specifications.

The MDD values increased with higher compactive effort and IOT content. The MDD values of the natural black cotton soil increased from 1.55, 1.60 and 1.70 Mg/m^3 to peak values of 1.65,1.72 and 1.82 Mg/m^3 when treated with 8 % lime / 8 % IOT, 6 % lime / 8 % IOT and 8 % lime / 8 % IOT blends for specimens compacted with BSL, WAS and BSH energies, respectively. The corresponding OMCs decreased from 24, 19.8 and 19.5Mg/m^3 to 19, 16.7 and 15Mg/m^3 with higher compactive efforts and IOT content. Based on Clause 6201 of the Nigerian General Specifications requirements, the treated soil did not meet the value of not more than 35 % passing sieve No. 200 sieve (0.075 mm aperture) and 12 % maximum plasticity index value for use as sub grade material .

The unconfined compressive strength (UCS) values for natural soil compacted with BSL, WAS and BSH energies at 7 days curing period are 107.24, 326.25 and 408.35 kN/m^2, respectively; increased to 1074.54, 1569.02 and 1688.76 kN/m^2 at 8 % lime/8 % IOT treatment respectively. The UCS values compacted using BSL, WAS and BSH energy all met the 7 day 1034.25 kN/m^2 normally utilized/specified as criterion for adequate stabilization using lime.

The unsoaked CBR values increased from 3, 4 and 8 % for the natural soil compacted with BSL, WAS and BSH energies efforts, respectively, increased to 55, 80 and 90 % at 8 % lime /8 % IOT treatment. The 24 hour soaked CBR values for BSL, WAS and BSH compactive effort recorded peak values of 45, 65 and 70 % at 8% lime/8% IOT treatment, respectively. Based on the minimum conventional CBR values for lime-treated soils of 40, 80, and 100% (standard proctor/British Standard Light) for sub-base, base (lightly trafficked roads) and base (heavily trafficked roads) respectively it can be inferred that at 8 % lime and 8% IOT treated black cotton soil can be used for sub-base of lightly trafficked road when compacted at the three energy levels. However, if the pozzolanic nature of soil-lime reaction is taken into consideration then the same mixture can be said to be adequate for base course of lightly trafficked roads when compaction takes place at WAS and BSH.

The resistance to loss in strength of the soil increased from 10.59, 7.17, and 19.85% for the natural soil to peak values of 37.56, 31.3 and 67.17 % for BSL, WAS and BSH energies at 8 % lime/8 % IOT, 8 % lime/8 % IOT and 8 % lime/6 % IOT, respectively. These peak values fell short of the limiting value of 80 % requirement but the 67 % resistance to loss in strength can be used as subgrade since the specimen was subjected to a more hasher condition of 7 days soaking as against the 4 days by Ola(1983).

SEM micrographs revealed that crystalline hydration products were present in the lime-IOT treated soil, and these hydration products were presumed to be the major factors that contributed to strength improvement.

Results of leaching potential of iron (Fe^{2+}) from the soil - lime-iron ore tailing mixtures into the environment using batch equilibrium test suggested that the desorbed value 0.272 mg/l of Iron (Fe^{2+}) concentration for the optimum 8 % lime 8 % IOT blend falls within the permissible value of not more than 0.3mg/l Iron (Fe^{2+}) concentration for drinking water recommended by World Health Organization (WHO) and Nigerian Industrial Standard (NIS).

5.2 Recommendation

Based on the test results obtained an optimal 8 % lime / 8 % iron ore tailing treatment of black cotton soil is recommended for use as sub-base material for the construction of lightly trafficked roads when compacted with British Standard heavy energy.

REFERENCES

(AASHTO), AASHTO (1986). *Standard Specifications for Transport Materials and Methods of Sampling and Testing*. 14th Edition, American Association of State Highway and Transport Officials Washington, D.C

Adeniji, F. A. (1991). "Recharge function of vertisolic Vadose zone in sub-sahelian Chad Basin." *Proceedings 1st International Conference on Arid Zone Hydrology and Water Resource,* Maiduguri, pp. 331-348.

Adepoju, S. O. and Olaleye, B. M., (2001). Gravity concentration of silica sand from Itakpe iron-ore tailings by tabling operation. *Nigerian Journal of Engineering Management.* Vol. 2, No. 2, 51-55.

Adesunloye, M.O. 1987. Investigating the problem soils of Nigeria. 9th regional conf. on soil mech. & found. Eng. for Africa, Vol.1 A.A. Balkema/Rotterdam/Boston. pp 103-112.

Aitken, D. H. (1971). "Transportation of geomechanics to roads and bridges." *Proceedings of the 1st Australia-New Zealand Conference on Geomechanics,* Melbourne. Vol. 2, p. 489.

Ajaka E. O. (2009) Recovering Fine Iron Minerals from Itakpe Iron Ore Process Tailing. Asia- Pacific Research Network *Journal of Engineering and Applied Sciences. Asian Research.* Vol. 4, No. 9, pp. 17-28.

Akawwi, E. and Al-Kharabsheh, A. (2002) "Lime stabilization Effects on Geotechnical properties of Expansive soils in Amman, Jordan". Electronic Journal of Geotechnical Engineering.www.ejge.com/2000 ppr0020.

Akinmade, O. B., (2008). Stabilization of black cotton soil with locust bean wast ash. Unpublished M.Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Ali, M. S. and Koranne, S. S. (2011), "Performance Analysis of Expansive Soil Treated With Granite dust and Fly ash", *EJGE,* Vol. 16, Bund. I, pp. 973-982.

Al-Rawas, A.A. and McGown, A. (1999) Microstructure of Omani expansive soils. Can Geotech J 36: 272 – 290.

Amadi, A. (2010). "Evaluation of Changes in Index Properties of Laterite Soil Stabilized with Fly Ash.'' Leonardo Electronic *Journal of Practices and Technologies*. pp. 69-78.

APHA. (1989) *Standard methods for the examination of water and wastewater,* 17th ed. American Public Health Association Washington, DC.

ASTM C618-12a (2013). Specification for Fly Ash and Raw or Calcined Natural Pozzolanas for Use as a Mineral Admixture in Portland cements Concrete. American Society for Testing and Materials, Philadelphia.

ASTM (1992). *Annual Book of Standards* Vol. 04.08, American Society for Testing and Materials, Philadelphia.

Azige, P (2012) Locust Bean Waste Ash Modification of Black Cotton soil using Cement Kiln Dust as an Activator. Unpublished M.Sc. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria.

B.S. 1377 (1990). *Methods of Testing Soil for Civil Engineering Purposes*. British Standards Institute, London.

B.S. 1924 (1990). *Methods of Tests for Stabilized Soils.* British Standards Institute, London.

Bairwa R , Saxena A. K, Arora T.R. (2013) "Effect of lime and fly ash on Engineering Properties of Black Cotton soil" International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 11, 535-541

Balogun, L. A. (1991). "Effect of sand and salt additives on some geotechnical properties of lime stabilized black cotton soil." *The Nigeria Engineer*, Vol 26, No 2, pp. 15-24.

Ben Rhaim H, Tessier D, Pons C.H, Amara B.H (1998) Evolution of the Microstructure of Interstratified Ca-saturated Clays during Dehydration: SAXS and HRTEM analysis. *Journal of Clay Miner* vol 33:pp619–628.

Bennett, R. H., Bryant, W. R. and Keller. G. H. (1981). Clay Fabric of selected submarine sediment:Fundamental properties and models. *Journal of Sedimentary Petrology* vol 51: 127-152.

Bhatia, S., and Soliman, A. 1990. Frequency distribution of void ratio of granular materials determined by an image analyzer, *Soils and Foundations*, Vol. 30, No. 1, pp. 1–16.

Bhuyan, S., (2010). "Stabilization of blast furnace slag and fly ash using lime and RBI grade 81." A Published Report submitted in partial fulfillment of the requirements for the degree of B.Tech Civil Engineering, National Institute of Technology Rourkela.

Bolt, G. H. (1956). Physico-Chemical Analysis of the Compressibility of Pure Clays. *Geotechnique* vol6: pp86-93.

Bowles, J. E. (1979). *Physical and Geotechnical Properties of Soils*. McGraw Hill International Books Company. New York.

Brian, J.B. (2013). "*Automated SEN/EDS analysis and classification of forensic samples"*. Forensic magazine, February/March 2013.

Bryant, W. R., Bennett, R. H., Burkett, P. J. and Rack, F. R.(1991). Microfabric and Physical Properties Characteristics of a Consolidated Clay Cection: ODP site 697. Weddell Sea. Pp.

Buhler, R. and Cerato, A. B. (2007). Stabilization of Oklahoma Expansive Soils Using lime and Class C Fly ash. GeoDenver 2007, GSP-162: Problematic Soils and Rocks and In Situ Characterization, February, Denver, Colorado, 1-10. proceedings

Butcher, F. and Sailie, E. L (1984) "Swelling behaviour of tropical black clays." *Proceedings of the 8th Regional Conference for Africa on Soil Mechanics and Foundation Engineering,* Harare. 81 – 86.

CEBTP (1980). "Guide pratique de dimension emenldes chausses pour les pays Tropican X." Centre Experimental de Recherchies et D'Etudes du Batiment et des Travanx, publics Paris.

Chen, F. H. (1988). *Foundation on Expansive Soils.* Elsevier Scientific Publication Company, Amsterdam.

Choquette M., Berube M.A.,and Locat J. (1987): Mineralogical and microtextural changes associated with lime stabilization of marine clays from Eastern Canada, *Applied Clay Science*.

Clare, K. E and Cruchley, A. E (1957) "Laboratory Experiments on the stabilization of clays with hydrated lime" *Geotechnique,* Vol. 7, pp. 97 – 100.

Clare, W. (2012), SEM – EDS analysis of particles from dalgety bay. Environmental radioactivity laboratory school of biological and environmental sciences. University of Stirling Scotland.

Cokca E (2001), "Use of class C fly ashes for the stabilization- of an expansive soil", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, pp. 568-573.

Collins, K and McGown, A (1974) The Form and Function of Microfabric Features in a Variety of Natural soils.*Ge'otechnique* vol 24(2) pp223-254.

Collins, R. J. and Ciesiellski, S. K. (1993). "Recycling and use of waste materials or by products in highway construction." Vols 1 and 2, pp 1-20.

Cui, Y. A., Loiseau C. and Delage P (2002) “Microstructure changes of confines swelling soil due to suction controlled hydration”. Proceedings of 3rd International Conference on Unsaturated Soils, Recife, Brazil,. In: Juca JFT. De Campos TMP, Marinho FAM (eds) Unsaturated Soils, vol 2. A.A. Balkema Publishers, Lisse, pp 593-598. 10-13 March 2002.

Delage ,P. Audiguier, M., Cui, Y.J, Howatt, M.D (1996) Microstructure of a Compacted Silt. *Canadian Geotechnical Journal* vol 33 pp150–158

Delage, P. and Lefebvre, G. (1984) Study of the Structure of a Sensitive Champlain Clay and of its Evolution during Consolidation. *Canadian Geotechnical Journal* vol 21,pp21–35

Demers, B., and Haile, G., (2003), Management of tailings stabilized by lime and cement at Canadian electrolytic zinc,Valleyfield, Quebec, Proc. Sudbury 2003 Mining and the Environment, May 25-28, Sudbury, Ontario.

Deneele,D., Cuisinier, O., Hallaire, V. and Masrouri, F. (2010) Microstructural evolution and physico-chemical behavior of compacted clayey soil submitted to an alkaline plume. Journal of Rock Mechanics and Geotechnical Engineering. Vol. 2 No. 2, pp. 169–177

Diamond S., White J.L., & Dolch W.L. (1964): Transportation of clay minerals by calcium hydroxide attack. Clays, *Clay Minerals*, Vol. 12, pp. 359-379.

Djeran-Maigre I, Tessier D, Grundberger D, Velde B, Vasseur G (1998) Evolution of Microstructure and of Macroscopic Properties of Some Clays during Experimental Compaction.*Mar Petrol Geol* vol 15 pp109–128

Eades, J.L., and Grim, R.E. (1960) “The reaction of hydrated lime with pure clay minerals in Soil Stabilization” U.S. Highway Research Board Buletin, Vol 262, pp 51 – 63.

Ergin, A., Ali, Y and Agrali (1986) Strength characteristics of lime-stabilized mine tailings, *Journal of Mining Science and Technicalogy* .Vol 3, pp161-16.

EuroSoilStab. (2002). *Development of Design and Construction Methods to Stabilize Soft Organic Soils: Design Guide for soft soil stabilization.* CT97-0351, European Commission, Industrial and Materials Technologies Programme (Rite-EuRam III) Brussel.

Fakiyesi, F. R. and Osinubi, K. J. (1995). “Economic utilization of a solid mineral waste resource – Phosphatic Waste.” *Abstracts Volume of 31st Annual Conference of Nigerian Mining and Geosciences Society,* 12 – 16 March, Calabar, Nigeria, pp. 37 – 38

Frost, J. D., and Jang, D. J. 2000. Evolution of sand microstructure during shear, *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 126, No. 2, pp. 116–130.

Frost, J. D., and McNeil, S. (1998). Imaging technologies; techniques and applications in civil engineering, *Proceedings of the 2nd International Conference,* ASCE, Reston, VA.

Frost, J. D., and Wright, J. R. 1993. Digital image processing; techniques and applications in civil engineering, *Proceedings,* ASCE, New York.

Garcia-Bengochea, I, Lovell, W, Altshaeffl, A.G (1979) Pore Distribution and Permeability of Silty Clays. *Journal of Geotechnical Engineering* ASCE vol 105(7)pp839–856

Gidigasu, M. D. (1982). "Importance of material selection, construction control and field performance studies in developing acceptance specification for laterite paving gravels." Solos and Rocha, Rio de Janeiro, Brazil. Vol. 5 No1.

Gillott, J. E. (1987). *Clay in Engineering Geology*. Elsevier Publishing Company Amsterdam.

Goldstein, J. I. (2003). "*Scanning Electron Microscopy and X-ray Microanalysis*", 3rd edition, Plenum Press, New York.

Grim, R. E. (1968), *Clay Mineralogy,* 2nd edition, McGraw-Hill, New York.

Haile, G., O.'Callaghan, W.B., Hartney, T.F., and Cameron, W., (2000), Experience with thickened red mud tailings (paste) stacking tropical and temperate climates and applicability of the technology to other tailings, Proc., 53 Can. Geotech. Conf., Can. Geotech.Society, Montreal, Canada.

Hetzel F, Tessier D, Jaunet A-M., Doner H (1994) The Microstructure of three Na+ Smectites: The importance of particle geometry on dehydration and rehydration. Clays Clay Miner vol 42(1)pp242–248

Hicks, R. (2002). *Alaska Soil Stabilization Design Guide.*

Holtz, W. G. and Gibbs, H. J. (1956). "Engineering properties of expansive clays." *ASCE Transaction,* Vol. 121 No 1, Paper 2814.

Hopkins, T. C., Beckham, T. L, Sun, L., Ni, B., and Butcher, B. (2002). *Long-Term Benefits of Stabilizing Soil Subgrades.* Rep. No. KTC-02-09/SPR-196-99-1F, Kentucky Transportation Center, College of Engineering, University of Kentucky.

Huang, Z. T. and Petrovic, A. M.(1994) Clinoptilolite zeolite influence on nitrate leaching and nitrogen use efficiency in simulated sand based golf greens, *Journal of Environmental Quality*, vol. 23, no. 6, pp. 1190–1194,

Ibrahim, A. (1983). “Black cotton soil in road pavement design, construction and performance.” In S. A. Ola (ed.) *Tropical Soils of Nigeria in Engineering Practice*, A. A. Balkema, The Netherlands, Rotherdam, pp. 260-278.

Ijimdiya, T.S. and Osinubi, K.J. (2011) Attenuative Capacity of Compacted Black Cotton Soil treated with Bagasse Ash. *Electronic Journal of Geotechnical Engineering*. Vol. 16,pp 419-429.

Indraratna, B.; Balasurbramama, A. S. and Khan, M. J. (1995). “Effect of fly ash with lime and cement on the behaviour of a soft clay.” *The Quarterly Journal of Geology*, Vol. 28, pp 131 – 142.

Ingles, O. G. (1968). Soil Chemistry relevant to the Engineering Behavior of Soils. Pp. 1-57 in Lee, I.K. (editor.), *Soil Mechanics*, selected topics. London: Butterworths

Ingles, O. G. and Metcalf, J. B. (1972). ‘*Soil Stabilization Principles and Practice’*, Butterworths, Sydney.

Ishola, K. (2014) *Modification Of Lateritic Soil With Iron Ore Tailing*. Unpublished M.Sc. Thesis, Civil Engineering Department, Ahmadu Bello University, Zaria.

ISRIC (1998). “World Soil Information” International Soil and Reference Information Center.

Jadhao, P.D and Nagarnaik, P. B. (2008) Influence of Polypropylene Fibers on Engineering Behavior of Soil−Fly Ash Mixtures for Road Construction *Electronic Journal of Geotechnical Engineering*. Vol. 13, pp 1-11

Jung, C., and Bobet, A. (2008). Post-Construction Evaluation of Lime-Treated Soils. Report Number: FHWA/IN/JTRP-2007/25. Joint Transportation Research Program. Indiana Department of Transportation, West Lafayette, IN.

Kamon, M. and Katsumi T (1994), “Potential utilization of waste rock powder. Proc of the First International Congress on Enviormental Geotechnics”, *biTech*, Vancouver, British

Katti, A. and Shanmugasundaram, V. (2001) Infleunce of swelling on the microstructure of expansive clays. Can Geotech J 38: 175 – 182.

Katz, L. E., Humphrey, D. N., Jankauskas, P. T. and Demascio, F. A(1996). "Engineered Soils for Low-Level Radioactive Waste Disposal Facilities: effects of additives on the adsorptive behavior and hydraulic conductivity of natural soils," *Hazardous Waste and Hazardous Materials*, vol. 13, no. 2, pp. 283–306.

Kedzi, A. (1979). *Stabilized Earth Roads*. Elsevier, Amsterdam, pp 327.

Keller Inc., (2011). *Improvement of Weak Soils by the Deep Soil Mixing Method.* Keller Bronchure, 32-01E: http://keller-foundations.co.uk/technique/deep-dry-soil-mixing.

Kim, G.Y, Yoon, H.J, Kim, J.W, Kim,D.C, Khim, B.K and kim,S.Y (2007)The Effects of Microstructure on Shear Properties of Shallow Marine Sediments. *Journal of Marine Georesources and Geotechnology,* vol 25, pp37-51

Klinkenberg, K. and Higgins, G.M., (1972). "An Outline of Northern Nigeria soils" Nigerian *Journal of Science*. Vol. 2, No. 2, pp. 99-115.

Krazynski, L. M. (1980). "Expansive soils in highway construction: Some problems and solutions." *4th International Road Federation African Highways Conference, Nairobi, Kenya.*

Kumar,B and Puri,N.(2013) Stabilization of Weak Pavement Subgrades using Cement Kiln Dust *International Journal of Civil Engineering and Technology* vol 4,Issue 1 pp26-37.

Kumar S and Prasanna M (2012), "Silica and calcium effect on geo-technical properties of expansive soil extracted from rice husk ash IPCBEE", Vol. 32.

Kumar S. (2012), "A Study on Some Geotechnical Properties of Stabilised Expansive Soil –Quarry Dust Mixes", No. 2, Vol. 1.1.

Kuo, C.-Y., Frost, J. D., and Chameau, J.-L. A. (1998). Image analysis determination of stereology based fabric tensors, *Ge'otechnique,* Vol. 48, No. 4, pp. 515–525.

Lambe, T. W. (1958). The Structure of Compacted Clay. *Journal Soil Mechanics Foundation*

Lambe, T. W., and Martin, R. T., (1954) "Composiotion and engineering properties of soil. II," Proceedings, Highway Reseacrh Board, Vol. 33

Lees, G., Addelkader, M. O. and Hamdani, S. K. (1982). "Sodium chloride as additive in lime- soil stabilization" *Journal Institute of Highway Engineers*., 29, Vo; No(11), pp.8-16.

Li, X and Zhang L.M (2009) Characterization of dual-structure pore-size distribution of soil. *Canadian Geotechnical Journal* vol 46, pp129-141

Liu, R. and Lal, R.(2012a) A laboratory study on improvement of mine soil quality for re-vegetation through various amendments," in *Proceedings of the ASA-CSSA-SSSA International Annual Meetings*, Cincinnati, Ohio, USA,

Liu, R. and Lal, R.(2012b) NanoenhancedMaterials for Reclamation of Mine Lands and Other Degraded Soils: A Review Ruiqiang Liu and Rattan Lal .*Journal of Nanotechnology* Volume 10, Article ID 461468, pp1-18

Locat, Y. Bembe, M. A. and Choquette, M. (1990). "Laboratory investigation on the lime stabilization of sensitive clays; shear strength development." *Canadian Geotechnical Journal,* Vol. 27, pp 294-304.

Maclean, D. J. (1953). "Investigation on some problems in soil stabilization". *Proceedings of the 3rd Intn'l Conference on Soil Mechanics and Foundation Engineering,* London, pp. 134-144.

Malhotra, V. M., and Mehta, P. K. (1996). Pozzolanic and cementitious materials, Gordon and Breach, Amsterdam, Netherlands.

Mallela, J., Quintus, H. V., and Smith, K. (2004). Consideration of lime-stabilized layers in mechanistic-empirical pavement design. The National Lime Association

Marshall T.J (1958) A Relation between Hydraulic Conductivity and Size Distribution of Pores. *Journal of Soil Science* vol 9pp1–8

Masad, E., and Muhunthan, B. 2000. Three-dimensional characterization and simulation of anisotropic soil fabric, *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 126, No. 3, pp. 199–207.

Matawal, D. S. and Tomarin, O. I. (1996). Response of Some Tropical Laterite to Cement Stabilization. *College of Engineering Conference Series, Kaduna Polytechnic,* Vol. 3 pp 90-95.

Medjo, E. and Riskowiski, G. (2004). " A procedure for preparing admixtures of soil, cement and sugar cane bagasse." *The Journal of Scientific Research and Development.* Agricultural Engineering International Manuscript BC` 990, VOL.III 1-5.

Mishra, J, Yadav, R.K. And Singhai A.K. (2014). "Effect of Granite Dust on Index Properties of Lime Stabilized Black Cotton Soil" *International Journal of Engineering Research and Science. & Technology 2014* ISSN 2319-5991 Vol. 3, No. 1, pp 19-23.

Mitchell, J.K. (1956) The Fabric of Natural Clays and its Relation to Engineering properties as part of Thesis Titled The importance of structure to the engineering Behaviour of Clay. Unpublished Ph.D Thesis Department of Civil Engineering Massachusett Institude of technology, Newyork USA

Mitchell, J.K and Hooper D.R. (1961) Influence of time between mixing and compaction on properties of lime-stabilised expansive clay. *Highway Res. Board Bull.* 304, 14-31.

Mitchell, J.K and Soga, K (2005) Fundamentals of soil behaviour, 3rd edition. John Wiley, Sons, Inc, New Jersey.

Mohammed A.M.O. and Anita H.E.(1998). Geoenvironmental Engineering. Elsevier, Amsterdam.

Mohammed AMO, Hossein M. and Hassani F.P (2001): Ettringite formation in lime remediated mine tailings; III rule of fly ash addition. CIM Bulletin.

Mohammedbhai, G.T.G and Baguant, B T., (1990). "Possibility of using bagasse ash and other furnace residue as partial substitute for cement in Maritiud" *Revue Agricole et Sulclriere de l`lle Maurice,* Vol. 64, No. 3, pp. 1-10.

Morin, W. J. (1971). "Properties of African tropical black clay soils.". *Proceedings 5th Regional Conference for Africa on Soil Mechanics and Foundation Engineering* Luanda, Vol. 1, pp. 51-59.

Moses, G. (2006). *Stabilization of Black Cotton Soil with Cement and Bagasse Ash.* Unpublished .Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Moses, G. (2008). *Stabilization of black cotton soil with Ordinary Portland Cement Using Bagasse ash as admixture. IRJI Journal of Research in Engrg*. Vol. 5 No. 3, pp. 107-115.

Moses, G., Saminu, A, and Oriola F.O.P. (2012).Influence of Compactive Efforts on Compacted Foundry Sand Treated with Cement Kiln Dust.'' *Civil and Environmental Research* Vol. 2, No. 5, pp 11-24.

NBRRI (1983). "Engineering properties of black cotton soils of Nigeria and related pavement design." Nigerian Building and Road Research Institute, Research Paper No 1, p. 22".

Neeraj, Sharma,S.,Umaesh,S and Sahoo (2012). Stabilisation of a Clayed Soil with Fly ash and Lime: A Micro Level Investigation. *Journal of Geotechnical and Geologica Engineering*.

Negi, A.S., Faizan, M., Siddharth, D. P. and Singh, R. (2013) Soil Stabilization Using Lime. International Journal of Innovative Research in Science, Engineering and Technology. *Vol. 2, Issue 2, PP. 448- 453.*

Nelson, D. and Miller, J. (1992). *Expansive Soils: Problems and Practices in Foundation and Pavement Engineering.* John Wiley and Sons, Inc. New York.

Neville, A. M. and Brooks J. J. (1994). *Concrete Technology*. Longman Publishers, Ltd, Singapore.

Nicholas, J. G. and Lester, A. H. (1999). *Traffic and Highway Engineering.* 2nd edition Books/Cole Publishing Company, New York, USA.

Nigerian General Specifications (1997). *Roads and Bridges*. Federal Ministry of Works, Abuja, Nigeria.

Nigerian Industrial Standard, NIS (2007) *Nigerian Standard for drinking water Quality* NIS 554:2007.

O'Flaherty, C. A. (1988). *Highway Engineering* Vol. 2, Edward Arnold, London.

O'Glesby, C. H. and Hicks, R. G. (1982). *Highway Engineering*. 4th Edition, John Wiley and Sons, New York.

Obeahon S. O. (1993). The Effect of Elapse Time After Mixing on the Properties of Modified . Unpublished M. Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Ochepo, J., (2008). The effect of elapse time on the geotechnical properties of lime-bagasse ash black cotton soil. Unpublished M.Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Okonkwo, U. N. (2009) Effects of Compaction Delay on the Properties of Cement-Bound Lateritic Soils Nigerian Journal of Technology, Vol. 28 No.2, pp. 5 – 12

Ola, S. A. (1974) "Need for estimated cement requirement for stabilizing lateritic soil." Journal of *Transportation Div.*, ASCE, Vol. 17,No 8, pp. 379-388.

Ola, S. A. (1978) "The geology and geotechnical properties of the black cotton soils of North Eastern Nigeria." *Engineering Geology*, Vol. 12, pp. 375-391.

Ola, S. A. (1983). "The geotechnical properties of black cotton soils of North Eastern Nigeria." In S. A. Ola (ed.) *Tropical Soils of Nigeria in Engineering Practice.* Balkama, Rotterdam, pp. 160-178.

Ola, S. A. (1991). "Laboratory testing and geotechnical characterization of black cotton soil and expansive shales in Nigeria", *Proceedings 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, Balkema, Rotterdam, 991 – 995.

Orazulike, D.M. (1992), "Mineralogical and Chemical composition of some Bauchi solis and their relationship to passive Earth movement" National Hazards 7, Kluwer Academic Publishers, Netherlands, 109-119.

Oriola, F., and Moses, G. (2010). "*Groundnut Shell Ash Stabilization of Black Cotton Soil".* Electronic Journal of Geotechnical Engineering, Vol. 15, pp. 415-428.

Ormsby W.C. and Kinter E.B. (1973a): Effects of dolomitic and calcitic limes on strength development in mixtures with two clay minerals. *Public Roads*, 37, pp. 149-160.

Ormsby W.C. and Kinter E.B. (1973b). Strength development and reaction products in lime-montmorillonite-water systems, Public Roads, 37 (4), 136-148.

Osinubi K. J. (1999). "Evaluation of admixture stabilization of Nigerian black cotton soil." *Nigeria Society of Engineers Technical Transactions*. Vol 34 No. 3, pp 88 – 96.

Osinubi, K. J, Oyelakin, M. A and Eberemu, A. O.(2011). Improvement of Black Cotton Soil with Ordinary Portland Cement - Locust Bean Waste Ash Blend. *Electronic Journal of Geotechnical Engineering',* Vol. 16, pp. 619-627.

Osinubi, K. J. (1995). "Lime modification of black cotton soils." *Spectrum Journal*, Vol. 2, Nos 1 and 2, pp. 112 – 122.

Osinubi, K. J. (1997). "Soil stabilization using phosphatic waste*." Proceedings of 4th Regional Conference on Geotechnical Engineering, GEOTROPIKA '97.* Johor Bahru, Malaysia, 11 – 12 Nov., pp 225 -244.

Osinubi, K. J. (1998a). "Influence of compactive efforts and compaction delays on lime treated soils". *Journal of Transportation Engineering, American Society of Civil Engineers*, Vol 124, No. 2, pp. 149 – 155.

Osinubi, K. J. (1998c). 'Influence of compaction delay on the properties of cement-stabilised lateritic soil.' *Journal of Engineering Research*, Vol. JER-6, No. 1, pp. 13 - 26.

Osinubi, K. J. (1999). "Evaluation of admixture stabilization of Nigerian black cotton soil." *Nigerian Society of Engineers Technical Transactions*, Vol. 34, No 3, pp 88-96.

Osinubi, K. J. (2000a). “Stabilization of tropical black clay with cement and pulverized coal bottom ash admixture.” In: Advances in Unsaturated Geotechnics. Edited by Cheuler D., Sandra, L.H., and Nien-Yui Chang. ASCE Geotechnical Special Publication, No. 99, pp. 289-302.

Osinubi, K. J. (2000b). Treatment of laterite with anionic bitumen emulsion and cement. A comparative study. Ife journal of technology, Obafemi Awolowo University, Ile-Ife. Vol. 9, No. 1, pp. 139-145.

Osinubi, K. J. (2006). ”Influence of Compactive Efforts on Lime-Slag Treated Tropical Black Clay” *Journal of Materials in Civil Engineering, American Society of Civil Engineers,* Vol. 18; No 2, pp 175-181

Osinubi, K. J. and Eberemu, A. O. (2006). “Effect of bagasse ash on the strength of stabilized lateritic soil.” *Book of Abstracts of the 5th Nigerian Materials Congress “NIMACON 2006”*, Abuja, Nigeria, 17-19 November. pp. 202– 208.

Osinubi, K. J. and Medubi, A. B. (1997a). “Evaluation of cement and phosphatic waste admixture on tropical black clay road foundation.” *Proceedings of 4th Intn’l. Conference on Structural Engineering Analysis and Modeling (SEAM 4),* Kumasi, Ghana, 9-11 July, Vol. 2, pp. 297-307.

Osinubi, K. J. and Medubi, A. B. (1997b) “Effect of lime and phosphatic waste admixture on tropical black clay*.” Proceedings, 4th Regional Conference on Geochemical Engineering, GEOTROPIKA ’97,* Johor Bahru, 11-12 Nov., Malaysia, pp. 257–272.

Osinubi, K. J. and Mustapha, A. M. (2008). 'Effect of compactive efforts on cement sugarcane bagasse ash – laterite mixture.’ Submitted to *Nigerian Society of Engineers Technical Transactions*. Vol. 43, No. 2, pp. 33 – 46.

Osinubi, K. J**.** and Mustapha.A. M. (2005). ‘Potentials of bagasse ash as a pozzolana.’ *Proceedings of the 4th Nigerian Materials Congress “NIMACON 2005”*, Zaria, Nigeria, 17 – 19 November, pp. 41 - 45.

Osinubi, K. J. and Stephen, A. T. (2007). “Influnce of compactive efforts on bagasse ash treated black cotton soil.” *Nigerian Journal of Soil and Environmental Research,* Vol. 7, pp. 92 – 101.

Osinubi, K. J. and Stephen, T .A. (2006b). ‘Effect of curing period on bagasse ash stabilized black cotton soil.’ *Proceedings of Bi-monthly Meetings/Workshops organized by the Zaria Chapter of Materials Society of Nigeria*, pp. 1 - 9.

Osinubi, K. J**.** and Stephen, T. A. (2005). ‘Economic utilization of an agro-industrial waste – bagasse ash.’ *Proceedings of the 4th Nigerian Materials Congress “NIMACON 2005”*, Zaria, Nigeria, 17 –19 November, pp.36-40.

Osinubi, K. J. and Stephen, T. A. (2006a). ‘Effect of bagasse ash content on particle size distribution and plasticity characteristics of black cotton soil.’ *Proceedings of the 5th Nigerian Materials Congress “NIMACON 2006”*, Abuja, Nigeria, 17-19 November. pp. 214 - 220.

Osinubi, K. J. and Toro, A. (1996). “Evaluation of superphosphate fertilizer processing residue (SPFR) and Portland cement admixture on black cotton soil.” *Programme and Abstract Volume of Kaduna Polytechnic Annual National Conference – Recent Findings In Engineering Practice, 11 – 12* December, p. 12.

Osinubi, K. J. and Toro, A. (1997). 'Evaluation of admixture stabilization of Black Cotton soil.' *Proceedings 4th Regional Conference on Geotechnical Engineering, GEOTROPIKA '97,* Johor Bahru, 11 - 12 November, Malaysia, pp. 273 – 289.

Osinubi, K. J. and Umar, S.Y (2003). Effect of Blast Furnace Slag on the Index Properties of Black Cotton Soil OfBorno State, Nigeria.’.*Nigerian Society of Engineers Technical Transactions,* Vol. 38, No. 3, pp. 56-64.

Osinubi, K. J., Bafyau, V. and Eberemu, A. O. (2009). ‘Bagasse ash stabilization of lateritic soil.’ Contribution to Chapter 5 in *Appropriate Technologies for Environmental Protection in the Developing World* edited by E. K. Yanful. Springer, Netherlands, pp. 281 - 290

Osinubi, K. J., Eberemu, A. O. and Aliu, O. S. (2007a)..‘Stabilization of laterite with cement and bagasse ash admixture.’ *Proceedings. of the First International. Conference on Environmental Resources, Technology and Policy “ERTEP 2007”*under the auspices of International Society of Environmental Geotechnology , Accra, Ghana, 16 - 19 July, Category B: Mining and Environment, pp. 1 - 14.

Osinubi, K. J., Eberemu, A. O. and Simon, K. L. (2007b). ‘Influence of Bagasse ash content and curing period on the permeability of lateritic soil compacted at reduced Proctor effort.’ *Proceedings of Bi-monthly Meetings/Workshops organized by the Zaria Chapter of Materials Society of Nigeria*, pp.17 -25. .

Osinubi, K.J., Ijimdiya, T. S. and Nmadu, I. (2008a). Effect of compactive effort on lime treated black cotton soil using bagasse ash as admixture. *Book of Abstracts of the 2nd International Conference on Engineering Research & Development: Innovations (ICER&D 2008)*, Benin City, Nigeria, 15-17 April. Technical Session 9B – Construction and Structures, Paper ICERD08056, p. 216 - 217.

Osinubi, K.J., Ijimdiya, T. S. and Nmadu, I. (2008b). Lime stabilization of black cotton soil using bagasse ash as admixture. *Book of Abstracts of the 2nd International Conference on Engineering Research & Development: Innovations (ICER&D* 2008), Benin City, Nigeria, 15-17 April. Technical Session 9B – Construction and Structures, Paper ICERD08058, p. 217.

Osinubi, K. J., Soni, E. J. and Ijimdiya, T. S. (2010). Lime and slag admixture improvement of tropical black clay road foundation.*Transportation Research Board (TRB) 89th Annual Meeting CD-ROM, January 10-14, Washington.D.C* U.S.A Subjected: Recycled Material in Transportation Infrastructure,Session 243:AFP40- physico-chemical and biological processes in Soil Committee, Paper.10-0585, pp1-8.

Osman Sivrikaya, Koray R K and ZekiKaraca (2013), "Recycling waste from natural stone processing plants to stabilize clayey soil", *Environmental Earth Sciences*, Springer Pub., October.

Osula, D. O. A. (1991) "Lime Modification of Problem Laterite". Eng. g Geol. 30, pp 141 – 149.

Ovuarume, U. B., (2011). The effect of locust bean waste ash on lime modified black cotton soil. Unpublished M.Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Oyelakin M.A.(2011). "Effect of Locust Bean Waste Ash on Cement Stabilized Black Cotton Soil." Unpublished M.Sc Thesis, Ahmadu Bello University, Zaria, Nigeria.

Pebble Project (2005). Tailings and Tailings Managements, Northern Dynasty Mines Inc., 1-4.

Phanikumar B R and Sharma R S (2004), "Effect of flyash on engg properties of expansive soil", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 7, pp. 464-767.

Plait, R. M. (1953). "Determination of Swelling Pressure of Black Cotton Soil–A method." *Proceedings of the Third International Conference on Soil Mechanics and Foundation Engineering.* Zurich, Switzerland, 16th – 27th August, Vol. 1, pp. 170 - 172.

Production Division Office of Geotechnical Engineering, (2008). "*Design Procedure for Soil Modification or Stabilization".* Indiana 46219.

Pusch, R, Schomburg, J (1999) Impact of Microstructure on the Hydraulic Conductivity of Undisturbed and Artificially Prepared Smectite Clay.*Journal of Engineering Geology* vol 54,pp167–172

Qian Guoping, Huang Tuo and Bai Shiyao (2011), “Use of cement-stabilized granite mill tailings as pavement subbase”, *Journal of Materials in Civil Engineering*, pp. 1575-1578.

Qiu, Y. and Sego, D.C. (2001), Laboratory properties of mine tailings, Can. Geotech. J., 38: 183-190.

Ramadas, T.L., Darga K.N. and Yesuratnam, G. (2011). “*Geotechnical Characteristics Of Three Expansive Soils Treated With Lime And Flyash*” IJESE. Vol. 04. No 06. Pp.46-49.

Ramana Sastry, M.V.B., Srinivasulu Reddy, M and Gangaraju, Ch.P. (1986). “*Comparative Study of Effect of Addition of Rice-Husk-Ash and Cinder-Ash to Soil-Lime Mixtures*”, Indian highways, Vol. 14, No. 8, pp 5-14.

Ramesh H.N, Krishnaiah A.J and Supriya M.D (2012). “Effect of Lime on the Compaction and Strength Behaviour of Red Earth Treated with Mine Tailings.” International Organization of Scientific Research *Journal of Mechanical and Civil Engineering*.Vol. 2, Issue 4, pp. 01-06.

Ramesh,H.N, Krishnaiah, A.J and Supriya,M.D (2013) “Role of Moulding Water Content on the Strength Properties of Red Earth treated with Mine tailings” .*International Journal of Scientific & Engineering Research* Vol4, Issue 5,pp 47-50.

Reyes, L.R.G., Remoro, E.T.G., Cabral, A.P. and Rodriguez R.C. (2007). “*Characterization of Chromium in contaminated soil studied by SEM, EDS, XRD and Mossbauer spectroscopy*”. JMMCE, Vol. 7, No. 1, pp. 59-70.

Rezende and Carvalho J C (2003), “The use of quarry waste in pavement construction. Resources”, *Conservation & recycling*, Vol. 39, pp. 91-105.

Robert, L. S. (1993) “Fly ash for use in the stabilization of industrial wastes.” In: *Fly Ash for Soil Improvement,* K. D. Sharp (ed.) Geotechnical Engineering Division of the ASCE, Geotechnical Special Publication, No 36, K. D. Sharp(ed) Geotechnical Engineering Division of ASCE, pp. 30-35.

Rogers, C.D.F. and Glendinning, S. (1996). Modification of clay soils using lime. In C. a. Rogers (Ed.), *Proceeding of the Seminar held at Loughborough University on Lime Stabilization* (pp. 99-114). London: Thomas Telford.

Romero, E. and Simms, P.H (2008) Investigation in Unsaturated Soils: A Review with Special Attention to Contribution of Mercury Intrusion Porosimetry and Environmental Scanning Electron Microscopy. *Journal of Geotechnical and Geological Engineering* Vol 8, pp1-23.

Roy, S., Adhikari, G.R. and Gupta, R. N. (2007). Use of gold mill tailings in making bricks: a feasibility study. Waste management and Research, 25, 475-482

Sahel, N. A (1993). “Treatment of calcareous expansive clays.” In: *Fly Ash for Soil Improvement. Geotechnical Special Publications* No. 36, K D. Sharp (ed) Geotechnical Engineering. Division of the ASCE, pp 100-115.

Salahedin, M. (2013) Effects of CEC on Atterberg limits and plastic Index in Different Soil Textures . *International Journal of Agronomy and Plant Production*. Vol., 4 (9), pp 2111-2118.

Samadou, J. (2014) *Stabilization Of Black Cotton Soil With Iron Ore Tailing*. Unpublished M.Sc. Thesis, Civil Engineering Department, Ahmadu Bello University, Zaria.

Sambhandharaska, S. and Moh, Z. C. (1971). “Effect of salt content on thixiotropic behaviour of a compacted clay.*” Proceedings of the 1st Australia New Zealand Conference on Geomechanics*, Malbourne, Vol. 1.

Sani, J.E. (2012). “Locust bean waste ash stabilization of black cotton soil using cement kiln dust as an activator”. Unpublished M.Sc Thesis, Ahmadu Bello University, Zaria, Nigeria.

Searle, P. L. 1984, The single-extraction silver thiourea method for measuring the cationexchange capacity of soil: Some preliminary comments. *New Zealand Soil News*, 32:4, 133-136.

Shackelford, C.D., and Daniel, D.E., (1991) “Diffusion of saturated soils I: Background.” Journal of Geotechnical Engineering, ASCE, 117(3), 467-484.

Shackelford, C.D. (1993) “Contaminant transport.” In D.E. Daniel (1993) Chapter 3, Geotechnical practice for waste Disposal. Chapman and Hall Publishers, Boundary Row,London. Pp.33- 65

Sherwood, P. (1993). *Soil stabilization with cement and lime. State of the Art Review.* London: Transport Research Laboratory, HMSO.

Slate, F. O. and Johnson, A. W. (1953). “Stabilization of Soil with Calcium Chloride.” *Highway Research Board*, Bulletin 24, pp. 96.

Sloane R.L. (1965): Early reaction determination in two hydroxide-kaolinite systems by electron microscopy and diffraction. *Proceedings, 13 th National Conference on Clays and Clay Minerals*, New York, Pergamon press, pp. 331-339.

Soframine (1987). Evaluation of the National Iron Ore Mining Project, Itakpe. National Steel Development Agency (NSDA) - Personal communication.

Stephen, A. T. (2006). Stabilization Potential of Bagasse Ash on Black cotton Soil. Unpublished M.Sc. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria.

Surendra Ray, Govinda R. Adhikari and Rama N Gupta, Use of gold mill tailings in making bricks: a feasibility study. Wast management and Research, 25, 2007, 475-482

Tomlinson, M.J (1999), *Foundation Design and Construction*. 6th Edition, Longman Harlow, Essex.

Tovey, N. K., and Hounslow, M. W. (1995). Quantitative microporosity and orientation analysis in soils and sediments, *Journal of the Geological Society of London*, Vol. 152, pp. 119–129.

Tribble, J. S., Mackenzie, E. T. and. Urmos. J (1991). Physical Property Changes Accompanying Deep Burial of Clay-rich Sediments. Pp. 93-108 in R. H. Bennett, W. R. Bryant, M. H. Hulbert (eds.), *Microstrucutre of Fine-grained Sediments from Mud to Shale*. New York: Springer-Verlag

TRRL (1977). "A guide to the structural design of bitumen surfaced roads in tropical and sub-tropical countries." *Transport and Road Research Laboratory, Road Note 31*, H. M. S. O., London.

Umar, S. Y. and Osinubi, K. J.. (2003). "The effect of blast furnace slag (BFS) on the index properties of black cotton soil of Borno State, Nigeria." *Nigerian Society of Engineers Technical Transactions*, Vol. 38, No 3, pp. 56-64.

Umar, S.Y. and Elinwa, A. U. (2005). "The effect of iron ore tailings (IOT) and lime on engineering properties of problem laterite." *Journal of Raw Materials Research.* Vol. 2, pp. 215-232.

Warren, K. W. and Kirby, T. M. (2004). "Expansive clay soil: A widespread and costly geohazard." *Geostrata*, Geo-Institute of the American Society Civil Engineers, Jan pp. 24-28.

Warrick, A.W (2002).Soil physics companion (ed). CRC Press LLC. Boca Raton, London, New York Washington, D.C. P: 19.

Wei, W. (2010). "*Analysis of soil microstructure parameters based on image mosaic technology*". Xiao-Yuan He Confrence publication, Vol.1, pp 286-289.

World Health Organization (2006) *Guideline for Drinking Water Quality*, World Health Organization: Geneva; 2006.

Yoder, E. J. and Witczak, M. W. (1975). *Principles of Pavement Design*. John Wiley and Sons. Inc. New York, 300-321.

Yohanna, P. (2014). The Use of Iron Ore Tailing as Admixture In Cement Modification of Black Cotton Soil. Unpublished M.Sc. Thesis, Civil Engineering Department, Ahmadu Bello University, Zaria.

Yorimichi, K and Kazuhiko N. (1999), "Experimental studies on cement stabilization of soft clay utilizing waste rock powder as a supplement material", *Proc. Jpn. Soc. Civil Engg*., pp. 1-12, in Japanese.

Zhang, G., Germaine, J. T., Whittle, A. J. (2005) "Drying induced alteration to the microstructure of a tropical soil. Proceedings of International Symposium on advanced experimental unsaturated soil mechanics, Trento, Italy. In: Tarantino A, Romero E, Cui YJ (eds) Advanced experimental unsaturated soil mechanics. Taylor & Francis Group, London, pp 443-449, 27-29 June 2005

APPENDIX

A4.1a: Test Results of Natural Moisture Content for Black Cotton Soil

Natural Moisture Content for Black Cotton Soil			
Container No	RI	R2	R3
Mass of Container M1	13.6	12.7	13.2
Mass of Container + Wet Soil M2	45	50.2	45.1
Mass of Container + Dry Soil M3	39.8	44.2	39.9
Mass of Dry Soil (M3-M1)=Ws	26.2	31.5	26.7
Mass of Wet Soil (M2- M1)	31.4	37.5	31.9
Ww = (M2-M1)-(M3-M1)	5.2	6	5.2
Moisture Content = W = Ww/Ws	19.85	19.05	19.48
Average W	19.46		

Table A4.1b: Test Results of Specific Gravity of Lime

Flask No	Y1	Y2	Y3
Mass of Bottle M1	47	40.1	46.7
Mass of Bottle + Soil M2	53.3	47.9	53.2
Mass of Bottle + Soil + Water M3	100.2	94.1	100.2
Mass of Bottle + Water M4	96.9	90	96.8
M4 - M1	49.9	49.9	50.1
M3 – M2	46.9	46.2	47.0
M2 – M1	6.3	7.8	6.5
(M4 - M1) - (M3 - M2)	3.0	3.7	3.1
Gs = (M2-M1) / ((M4-M1)-(M3-M2))	2.10	2.11	2.10
Average Specific Gravity Gs	2.10		

Table A4.1c: Test Results of Specific Gravity of Iron Ore Tailing

Flask No	Y1	Y2	Y3
Mass of Bottle M1	37.4	43.9	26.5
Mass of Bottle + Soil M2	57.6	59.9	50
Mass of Bottle + Soil + Water M3	101	105.5	92.6
Mass of Bottle + Water M4	86.8	94.3	76.1
M4 - M1	49.4	50.4	49.6
M3 – M2	43.4	45.6	42.6
M2 – M1	20.2	16	23.5
(M4 - M1) - (M3 - M2)	6.0	4.8	7.0
Gs = (M2-M1) / ((M4-M1)-(M3-M2))	3.37	3.33	3.36
Average Specific Gravity Gs	3.35		

Table A4.2: Test Results of Specific Gravity for Soil-Lime-IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	2.48	2.47	2.45	2.43	2.42
2	2.50	2.48	2.47	2.45	2.44
4	2.52	2.49	2.49	2.48	2.46
6	2.56	2.54	2.53	2.50	2.48
8	2.57	2.56	2.54	2.52	2.51
10	2.59	2.57	2.56	2.55	2.53

Table A4.3: Test Results of Free Swell values for Soil- Lime-IOT Mixtures

IOT CONTENT (%)	LIME CONTENT (%)				
	0	2	4	6	8
0	52.5	48.3	42.8	44.5	42.3
2	50	47.5	41	40.5	34
4	49.3	45.5	40.3	37	34.5
6	47.8	43.5	38.4	35.5	30
8	48	39.3	37.8	34.8	30.4
10	48.4	43	37	37	31.3

Table A4.4a: Test Results of Cation Exchange Capacity Tests Result for Soil-Lime-IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	52.2	45.5	50	49	49.1
2	52	41.4	49.1	44.8	47.1
4	48.6	42.2	47	46.9	47.1
6	37.4	36.7	41.8	39	35
8	36.2	34.6	36.3	31.7	33.7
10	33.9	31.1	29.2	26.4	28.2

Table A4.4 (b): Test Results of pH for Soil-Lime IOT Mixtures

IOT CONTENT (%)	LIME CONTENT (%)				
	0	2	4	6	8
0	6.42	7.16	8.08	9.10	10.50
2	6.61	7.23	8.70	9.30	9.80
4	6.8	7.28	8.66	9.35	9.65
6	6.92	7.33	8.91	9.85	9.40
8	7.12	7.56	8.60	9.75	9.28
10	7.03	7.47	8.93	9.75	9.30

Table A4.4(c): Test Results of Desorption Isotherm for Iron Fe^{2+} for Soil-Lime IOT Mixtures

IOT CONTENT (%)	LIME CONTENT(%)				
	0	2	4	6	8
0	0.004	0.016	0.016	0.100	0.063
2	0.024	0.032	0.032	0.192	0.081
4	0.124	0.052	0.044	0.144	0.216
6	0.076	0.088	0.088	0.161	0.126
8	0.031	0.132	0.152	0.224	0.272
10	0.204	0.181	0.116	0.292	0.242

Table A4.5 (a): Wet Sieve Analysis value for Soil- Lime -IOT mixes

0 % LIME											
BS SIEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	99.1	4.76	97.8	4.76	98.8	4.76	99.5	4.76	96.3	4.76	99.05
2.36	98.4	2.36	97	2.36	98.3	2.36	98.65	2.36	95.6	2.36	97.9
2	98	2	96.7	2	97.9	2	98.25	2	95.25	2	97.9
0.6	95.8	0.6	94.9	0.6	96.2	0.6	96.55	0.6	93.65	0.6	95.95
0.425	88.7	0.425	88.3	0.425	90.1	0.425	90.9	0.425	88.5	0.425	89.9
0.3	86.8	0.3	86.5	0.3	88.3	0.3	89.2	0.3	86.9	0.3	88.1
0.212	85	0.212	84.8	0.212	86.5	0.212	87.55	0.212	85.35	0.212	86.35
0.15	83.2	0.15	82.8	0.15	84.3	0.15	85.55	0.15	83.05	0.15	83.8
0.075	80.7	0.075	79.5	0.075	80.6	0.075	81.55	0.075	78.25	0.075	78.6
0.0106	42.7	0.01	44.2	0.011	42.3	0.0097	47.59	0.011	40.92	0.0106	39.91
0.0092	22.6	0.009	23.3	0.009	23.2	0.0088	23.79	0.009	22.1	0.0089	21.18
0.0077	19.3	0.008	20	0.008	19.1	0.0076	18.05	0.007	18.82	0.0076	17.92
0.0058	15.9	0.006	16.7	0.006	15.8	0.0056	14.77	0.006	16.37	0.0056	15.47
0.0042	9.22	0.004	9.58	0.004	9.95	0.0042	7.38	0.004	11.46	0.0041	9.77

2 % LIME											
BS SIEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	99.7	4.76	100	4.76	99.7	4.76	98.9	4.76	99.15	4.76	99.75
2.36	98.8	2.36	99	2.36	99.1	2.36	98	2.36	98.1	2.36	99.2
2	98.4	2	98.5	2	98.6	2	97.6	2	97.7	2	98.85
0.6	96.8	0.6	96.6	0.6	96.5	0.6	95.4	0.6	95.85	0.6	96.75
0.425	89.6	0.425	90.2	0.425	90.3	0.425	88.2	0.425	89.2	0.425	90.65
0.3	87.2	0.3	88.4	0.3	88.8	0.3	86.3	0.3	87.25	0.3	88.9
0.212	85	0.212	86.6	0.212	87.2	0.212	84.5	0.212	85.3	0.212	87.05
0.15	82.6	0.15	84.6	0.15	85.3	0.15	82.15	0.15	82.95	0.15	84.8
0.075	80	0.075	81.7	0.075	82.2	0.075	78.4	0.075	79.3	0.075	80.8
0.0129	29.4	0.012	33.5	0.015	40.9	0.014	48.66	0.0143	47.59	0.012	31.92
0.0095	20.2	0.009	24.3	0.012	29.2	0.0125	28.86	0.0121	32	0.009	23.74
0.008	15.1	0.008	19.7	0.009	20.9	0.0093	19.79	0.009	24.615	0.0075	19.64
0.0059	14.3	0.006	16.8	0.008	17.6	0.0077	15.67	0.0074	22.154	0.0055	18.01
0.0042	12.6	0.004	13.4	0.006	17.1	0.0057	14.02	0.0054	19.692	0.0041	14.73
				0.004	16.7	0.0041	11.55	0.004	16.41		

4 % LIME											
BS SIEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	100	4.76	98.6	4.76	99.7	4.76	99.4	4.76	98.3	4.76	96
2.36	99.1	2.36	98	2.36	98.5	2.36	98.6	2.36	97.05	2.36	95.35
2	98.7	2	97.7	2	98.1	2	98.2	2	96.85	2	94.95
0.6	96.9	0.6	95.9	0.6	96.2	0.6	96.25	0.6	95.1	0.6	93.3
0.425	91.3	0.425	89.9	0.425	89.9	0.425	90.45	0.425	89.4	0.425	87.8
0.3	88.1	0.3	88.2	0.3	88.2	0.3	88.75	0.3	87.85	0.3	86.15
0.212	86.6	0.212	86.7	0.212	86.5	0.212	87	0.212	86.15	0.212	84.55
0.15	84.7	0.15	84.8	0.15	84.5	0.15	84.75	0.15	84	0.15	82.1
0.075	82.1	0.075	81.8	0.075	81.3	0.075	80.95	0.075	79.9	0.075	77.1
0.0109	46	0.008	39.5	0.01	49.3	0.0082	36.38	0.0152	43.708	0.0204	47.59
0.0084	36.8	0.007	32.8	0.008	35.9	0.0069	31.42	0.0117	35.461	0.0164	37.74
0.0073	30	0.005	30.2	0.007	28.8	0.005	29.76	0.0086	29.276	0.0124	30.36
0.0053	28.7	0.004	26.9	0.005	28.4	0.0038	26.46	0.0072	25.565	0.0092	22.97
0.0042	16.1			0.004	27.6			0.0052	23.916	0.0075	20.1
								0.0039	20.617	0.0055	18.87
										0.004	18.05

6 % LIME											
BS SIEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	99.7	4.76	99.4	4.76	99.3	4.76	99.6	4.76	98.2	4.76	98.75
2.36	98.8	2.36	98.3	2.36	98.4	2.36	98.45	2.36	97.25	2.36	98.1
2	98.4	2	97.9	2	98	2	98.15	2	96.8	2	97.7
0.6	96.1	0.6	95.7	0.6	96	0.6	96.35	0.6	95.1	0.6	96.2
0.425	88.7	0.425	88.4	0.425	89.1	0.425	90.2	0.425	88.75	0.425	90.95
0.3	86.4	0.3	86.4	0.3	87.2	0.3	88.4	0.3	86.75	0.3	89.5
0.212	84.3	0.212	84.6	0.212	85.3	0.212	86.65	0.212	84.7	0.212	87.95
0.15	81.9	0.15	82.2	0.15	83.2	0.15	84.5	0.15	81.85	0.15	85.65
0.075	78.8	0.075	78.9	0.075	79.2	0.075	80.25	0.075	75.95	0.075	79.95
0.0081	39.9	0.008	37.2	0.016	42.3	0.0162	39.17	0.0221	41.447	0.0198	48.53
0.007	34	0.007	31.3	0.012	33.5	0.0123	32.5	0.0173	32.329	0.0155	41.13
0.0052	30.6	0.005	28.7	0.009	24.3	0.009	25	0.0127	25.697	0.0119	32.9
0.0039	25.5	0.004	24.5	0.008	21	0.0075	20.83	0.0095	18.237	0.0088	25.5
				0.006	19.3	0.0056	19.17	0.0078	15.75	0.0075	20.98
				0.004	16.8	0.0041	17.5	0.0058	15.336	0.0055	18.92
								0.0042	13.263	0.004	17.27

8 % LIME											
BS SIEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	97.95	4.76	99.45	4.76	100	4.76	93.85	4.76	98.35	4.76	99
2.36	97.4	2.36	98.4	2.36	99.2	2.36	93.1	2.36	97.45	2.36	98
2	97	2	97.9	2	98.9	2	92.85	2	97.1	2	97.65
0.6	95.25	0.6	96.25	0.6	97.35	0.6	91.3	0.6	95.25	0.6	95.9
0.425	89.45	0.425	90.8	0.425	92.25	0.425	86.85	0.425	89.75	0.425	90.05
0.3	87.7	0.3	89.3	0.3	90.7	0.3	85.6	0.3	88.1	0.3	88.3
0.212	86.05	0.212	87.85	0.212	89.2	0.212	84.4	0.212	86.35	0.212	86.6
0.15	84.05	0.15	85.95	0.15	87.25	0.15	82.4	0.15	83.8	0.15	83.75
0.075	80.9	0.075	82.5	0.075	83.75	0.075	78.2	0.075	78.05	0.075	77.6
0.0082	40.05	0.0078	44.06	0.0079	41.28	0.0077	41.89	0.0079	39.479	0.0104	44.65
0.0072	31.53	0.0069	33.89	0.007	32.86	0.0068	32.68	0.007	29.505	0.0085	30.59
0.0052	31.1	0.0051	32.19	0.0051	32.01	0.005	31.84	0.0051	29.089	0.0072	24.8
0.0038	28.97	0.0038	30.5	0.0037	31.17	0.0037	30.16	0.0038	28.674	0.0053	23.98
										0.0039	23.15

Table A4.5 (b): Dry Sieve value for Soil – Lime - IOT mixes (BSL Compaction)

	0% LIME					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	72.35	74.65	75.7	76.45	73.95	75.95
2.36	42.1	44.6	46.75	43.5	42	41.4
2	35.05	36.35	38.3	34.95	33.95	32.65
0.6	18.95	19.4	19.8	17	17.25	16.65
0.425	4.15	3.7	3.3	2.9	3.15	2.9
0.3	2.8	2.45	1.95	1.8	2	1.85
0.212	2.05	1.8	1.25	1.15	1.4	1.35
0.15	1.6	1.4	0.85	0.8	1	1
0.075	1.15	0.95	0.4	0.35	0.25	0.3

	2% LIME					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	94.5	96.35	95.85	97.2	96.4	96.8
2.36	72.5	72.75	74.1	74.55	69.25	74.85
2	63.9	64	65.35	66.45	59.35	65.85
0.6	42.4	44.55	44.2	45.55	37.65	44.65
0.425	10.4	12.05	12.3	13	11.05	14.4
0.3	5.3	6.8	6.7	7.05	6.7	8.7
0.212	2.4	3.6	3.55	3.65	3.85	5.3
0.15	0.8	1.55	1.65	1.6	2.05	3.2
0.075	0.1	0.15	0.1	0.1	0.4	0.95

	4% LIME					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	95.75	97.3	96.8	97.2	96.55	95.4
2.36	77.2	81.7	81.95	83.05	81.35	80.25
2	64.9	75.8	75.45	77.15	75	74.65
0.6	51.8	57.95	58.5	58.6	57.8	55.4
0.425	20.5	23.65	24.15	23.45	24.7	22.45
0.3	11.9	15.8	15.75	15.55	17.9	15.6
0.212	6.05	10.1	9.7	10	12.85	11.05
0.15	2.9	5.65	5.1	6.2	8.6	8.25
0.075	0.95	1.85	1.8	2.65	4.05	4.35

BS SIEVE SIZE	6% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	97.5	98.4	99.15	98.25	98.55	99.7
2.36	71.1	76.3	82.75	87.05	86.95	90.65
2	62.05	67.05	75.8	82.05	81.45	86.2
0.6	41	46.3	58.5	66.9	66.25	71
0.425	12.7	14.3	25.55	31.15	30.8	35.2
0.3	7.35	8.5	17.3	22.65	22.45	26.5
0.212	3.95	4.2	10.7	15.65	15.55	18.95
0.15	1.8	1.65	5	9.2	10	12.9
0.075	0.25	0.2	0.85	3	2.95	4.55

BS SIEVE SIZE	8% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	96.05	96.85	98.2	98.6	100	100
2.36	80.9	81.25	84.75	85	91	92.55
2	68.9	69.65	74.55	75.4	82.3	84.75
0.6	55	56.55	61.8	63.55	70.95	73.9
0.425	23.5	24.9	28.95	33.25	38.55	42
0.3	14.7	16.1	19.45	23.4	27.75	32.15
0.212	8.05	9.45	11.75	15.3	19.2	23.05
0.15	4.4	5.15	6.8	8.3	11.05	13.75
0.075	2.2	2.5	3.35	4	5.1	6.1

Table A4.5(c): Dry Sieve value for Soil – Lime - IOT mixes (WAS Compaction)

BS SIEVE SIZE	0% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	78.55	78.2	82	84.6	83.9	86.9
2.36	45.1	50	47.8	51.25	50.15	56.6
2	31.65	35.95	32.3	35.1	35.1	40.6
0.6	20.45	22.6	18.85	22.6	22.75	27.2
0.425	4.3	4.2	3.4	4.15	3.85	6.15
0.3	2.65	2.55	2.05	2.1	1.95	3.8
0.212	1.55	1.75	1.5	1.15	1.15	2.6
0.15	0.9	1.3	1	1.15	0.65	1.75
0.075	0.4	0.8	0.45	0.65	0.05	0.9

BS SIEVE SIZE	2% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	94.2	94.75	96.45	95.7	96.15	96.15
2.36	73.1	77.1	80.95	81.35	80.75	81.2
2	58.75	63.75	68.95	70.1	69.2	70.1
0.6	45.65	50.95	56.85	57.45	56.6	59.55
0.425	15.4	18.85	23.6	24.2	24.3	27.4
0.3	8.7	11.6	15.4	16.55	17.05	20.4
0.212	4.45	6.45	8.75	10.35	11.45	14.6
0.15	2.05	3.1	4.8	6.25	7.25	10.9
0.075	0.7	1.15	2	2.25	2.7	6

BS SIEVE SIZE	4% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	95.95	97.15	97.5	97.25	97.6	97.6
2.36	77.15	75.35	81.75	76.05	81.3	79.35
2	64.85	61.55	71	63.25	69.45	66.55
0.6	51.75	48.15	59.1	50.3	57.35	54.45
0.425	20.45	19.7	27.35	19.45	27.95	25.45
0.3	11.85	13.3	19.5	11.45	20.2	19.2
0.212	6	7.95	12.7	6.15	13.8	13.25
0.15	2.85	4.2	7.4	3.15	8.5	8.35
0.075	0.9	0.75	2.2	1.4	2.95	2.85

BS SIEVE SIZE	6% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	98	97.2	97.75	98.15	97.85	99
2.36	83	84.6	80.2	83.75	77.4	87.6
2	71.25	66.2	67.5	73.65	64.2	79.4
0.6	58.3	53.35	54.1	61.55	51.85	67.8
0.425	26.85	23.7	23.35	29.65	25.5	37.5
0.3	18.3	16.7	16.1	21.55	19.6	29.55
0.212	11.4	11.4	10.7	15.4	16.1	21.8
0.15	6	6.55	6.4	10.25	11.5	15.75
0.075	2.6	3.15	2.15	4.5	5.65	7

BS SIEVE SIZE	8% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	98.05	98.25	98.45	100	100	100
2.36	84.2	81.5	83.35	87.55	86.7	88.7
2	72.45	70.7	74.2	77.15	74.25	77.15
0.6	60.5	57.95	63.15	64.9	61.8	65.85
0.425	28.35	27.9	31.85	33.3	31.4	35.75
0.3	18.7	19.15	23.05	24.2	23.55	28.25
0.212	11.55	11.85	16.55	17.25	16.85	21.5
0.15	5.85	6.4	9.45	11.35	9.55	14.6
0.075	2.4	2.8	4.55	5.35	3.9	6.95

Table A4.5 (d): Dry Sieve value for Soil – Lime - IOT mixes (BSH Compaction)

BS SIEVE SIZE	0% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	78.5	82	85.75	86	85.5	90.45
2.36	44.4	48.9	51.85	55.5	55.15	61.75
2	34.95	39.8	43.2	46.85	46.3	53.55
0.6	17.5	21.45	23.85	26.15	27.35	33
0.425	3.35	4	4.65	4.45	5.55	7.35
0.3	2	2.3	2.65	2.45	3.25	4.5
0.212	1.25	1.2	1.55	1.45	2.15	3
0.15	0.75	0.65	0.9	0.9	1.5	2.2
0.075	0.3	0.05	0.25	0.1	0.5	0.45

BS SIEVE SIZE	2% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	98.15	97.8	96.7	98.1	98.9	99.05
2.36	78.6	79.45	73.85	81.75	83.75	84.45
2	70.45	71.8	65.85	74.95	76.95	77.8
0.6	49.95	52.6	45.85	55.1	58.3	58.55
0.425	15.45	18.6	15.35	21	24.05	24.25
0.3	9.4	11.45	9.75	14.05	16.55	17.1
0.212	5.2	6.6	6.25	9.1	10.9	12
0.15	1.95	3.1	3.45	5.05	7.15	7.9
0.075	0.05	0.45	0.75	1.2	1.7	1.9

BS SIEVE SIZE	4% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	98.5	98.5	98.45	98.6	99.4	99.5
2.36	77.35	75.85	76.6	75.35	81.25	79.25
2	69.25	68.5	68.1	66.8	73.75	71.35
0.6	47.95	48.3	48.05	45.1	54.4	54.75
0.425	16.65	17.15	16.95	15.8	23.55	24.65
0.3	10.6	11.35	11.35	10.8	17.75	18.45
0.212	6.05	6.85	7.05	6.85	12.8	14
0.15	2.7	3.4	3.7	4.3	8.7	9.8
0.075	0.1	0.25	0.1	0.05	2.05	2.5

BS SIEVE SIZE	6% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	97.45	97.8	97.05	98.7	99.25	99.4
2.36	82.4	82.3	80.25	81.15	80.7	86
2	75.7	75.95	71.45	74.75	73	80.35
0.6	58	58.75	50.65	55.65	54.25	63.15
0.425	22.35	25.6	20	24.75	23.6	30.9
0.3	14.35	17.7	14.4	18.5	17.95	24.15
0.212	8.2	11.5	9.6	13.15	13.4	18.35
0.15	3.4	6.05	4.9	8.5	9.6	13.4
0.075	1.4	0.65	0.15	2.05	3	4.2

BS SIEVE SIZE	8% LIME					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	97.65	98.3	98.5	98.55	99.15	99.25
2.36	81.05	83.85	83.2	84.8	80.9	85.65
2	73.95	76.9	75.5	79.5	73	79.5
0.6	55.8	57.25	56.05	61.55	55.4	62.15
0.425	24.65	24.85	24.6	27.75	24.3	28.9
0.3	17.45	18	17.8	20.6	18.15	22.35
0.212	11.05	11.7	12.9	14.7	13.6	17.55
0.15	5.35	6.4	8.45	9.8	9.4	13.7
0.075	0.15	0.15	2.15	2.55	2.05	5.85

Table A4.6: Test Results of Liquid Limit for Soil - Lime – IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	56.8	54.4	51.3	52.7	47.5
2	54	53.5	49.8	51.4	45.4
4	53.5	51.8	48.9	50.3	44.5
6	53.1	51.2	47.3	48.5	43.8
8	52.7	49.9	46.7	45.2	44.1
10	50.8	50	48.5	45.5	44.9

Table A4.7: Test Results of Plastic Limit for Soil - Lime – IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	29.2	28.2	26.63	26	24
2	26.3	26.9	25	24	20.2
4	25.64	25.11	23.72	22.83	19.65
6	24.51	24.21	21.8	20.6	18.95
8	23.8	23.41	21	18	18
10	23	22.81	22	19.7	18.1

Table A4.8: Test Results of Plasticity Index for Soil - Lime – IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	27.6	26.2	24.67	26.7	23.5
2	27.7	26.6	24.8	27.4	25.2
4	27.86	26.69	25.18	27.47	24.85
6	28.59	26.99	25.5	27.9	24.85
8	28.9	26.49	25.7	27.2	26.1
10	27.8	27.19	26.5	25.8	26.8

Table A4.9: Test Results of Linear Shrinkage for Soil - Lime – IOT Mixtures

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	18.11	17.01	14.17	11.02	9.06
2	16.54	15.98	13.39	10.00	5.91
4	16.14	15.43	12.20	7.48	5.67
6	15.75	15.35	11.97	7.09	5.51
8	14.96	13.94	11.81	5.91	4.88
10	14.17	12.05	8.82	4.72	4.33

Table A4.10 (a): Test Results of Maximum Dry Density for Soil–Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	1.550	1.535	1.520	1.510	1.495
2	1.565	1.540	1.550	1.535	1.505
4	1.595	1.560	1.580	1.570	1.550
6	1.610	1.570	1.599	1.620	1.585
8	1.630	1.615	1.635	1.645	1.625
10	1.600	1.600	1.610	1.620	1.590

Table A4.10 (b): Test Results of Maximum Dry Density for Soil–Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	1.600	1.580	1.550	1.530	1.560
2	1.620	1.635	1.600	1.550	1.580
4	1.630	1.650	1.610	1.600	1.620
6	1.660	1.680	1.640	1.645	1.680
8	1.670	1.690	1.680	1.700	1.720
10	1.690	1.670	1.660	1.645	1.630

Table A4.10 (c): Test Results of Maximum Dry Density for Soil–Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	1.700	1.685	1.610	1.640	1.660
2	1.750	1.713	1.650	1.677	1.675
4	1.760	1.735	1.670	1.710	1.727
6	1.770	1.754	1.725	1.715	1.745
8	1.760	1.795	1.810	1.775	1.820
10	1.740	1.770	1.740	1.760	1.790

Table A4.11 (a): Test Results of Optimum Moisture Content for Soil–Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	24	24.5	24	24.9	25.5
2	20.7	22.5	23.5	24.2	24.5
4	20.5	21	22.7	23.1	24.1
6	19	21.5	20.5	21	22
8	18.5	20.9	20.2	19.7	21.3
10	19	20	20.9	20	20.4

Table A4.11 (b): Test Results of Optimum Moisture Content for Soil–Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	19.8	21.3	22.5	23.4	23
2	19.5	19.75	20.6	21.4	22.4
4	18.5	19	20.2	21.3	21.8
6	17.2	18	19.8	18.5	19
8	15	17.3	16	16.7	18.3
10	16.5	16.4	18	16	19

Table A4.11 (c): Test Results of Optimum Moisture Content for Soil–Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	19.5	20.6	21.5	21.3	22.4
2	17	18.4	20.7	19.5	21.5
4	16	17.5	18	19.3	19.5
6	15.5	16.8	17.4	18.7	18
8	14	14.4	15.4	16	15
10	14.9	14.3	14.6	15.5	15.5

Table A4.12 (a): Test Results of Unconfined Compressive Strength (7 days curing) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	107.24	208.22	294.47	611.23	672.56
2	137.67	347.52	473.54	742.71	854.38
4	197.31	404.66	540.31	782.44	953.46
6	227.66	518.48	648.39	977.17	1058.18
8	288.48	574.46	843	992.56	1074.54
10	238.41	379.51	486.42	762.91	849.95

Table A4.12 (b): Test Results of Unconfined Compressive Strength (7 days curing) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	326.25	583.31	995.87	1088.7	1292.8
2	394.35	612.82	1093.49	1129.51	1330.94
4	428.13	701.79	1114.61	1279.37	1376.74
6	483.5	767.92	1276.01	1452.3	1492.59
8	589.14	818.06	1392.53	1476.92	1569.02
10	609.46	862.64	1053.94	1255.68	1332.04

Table A4.12 (c): Test Results of Unconfined Compressive Strength (7 days curing) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	408.35	821.28	1164.66	1258.33	1327.27
2	434.8	973.89	1236.39	1347.6	1475.54
4	444.73	990.69	1363.04	1391.43	1556.51
6	667.55	1062.54	1373.19	1518.18	1646.05
8	725.92	1229.53	1503.47	1646.17	1688.76
10	542.79	1032.24	1243.83	1457.56	1526.71

Table A4.13 (a): Test Results of Unconfined Compressive Strength (14 days curing) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	258.72	564.24	1019.97	1246.62	1358.77
2	299.85	767.48	1020.64	1501.73	1418.72
4	349.67	885.61	1243.7	1511.46	1628.83
6	451.63	1189.49	1289.86	1564.69	1747.77
8	483.7	1237.63	1494.27	1624.39	1893.59
10	344.16	927.72	1245.78	1527.56	1552.88

Table A4.13 (b): Test Results of Unconfined Compressive Strength (14 days curing) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	452	903.72	1259.22	1426.28	1628.59
2	790.73	1153.91	1308.13	1527.85	1873.58
4	897.02	1174.84	1519.12	1730.8	1953.17
6	967.21	1370.36	1722.32	1939.19	1966.42
8	1204.26	1434.72	1873.58	2228.04	2092.03
10	763.59	1220.87	1388.97	1679.8	1766.83

Table A4.13 (c): Test Results of Unconfined Compressive Strength (14 days curing) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	902.44	1221.74	1466.14	1339.07	1894.83
2	982.19	1253.78	1645.96	1568.6	1971.99
4	1104.59	1501.12	1731.41	1947.82	2214.41
6	1276.01	1570.5	2104.11	2502.88	2350.16
8	1385.14	1782.8	2174.92	2658.46	2558.73
10	1304.95	1577.89	1860.17	2109.89	2231.38

Table A4.14 (a): Test Results of Unconfined Compressive Strength (28 days curing) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	528.37	985.88	1192.06	1343.16	1680.23
2	667.55	1122.46	1417.85	1654.15	1841.1
4	707.22	1229.17	1552.88	1781.71	1961.7
6	755.84	1301.19	1586.57	1898.9	2014.86
8	890.06	1443.90	1637.59	1936.11	2042.37
10	468.29	1076.25	1397.25	1595.05	1793.33

Table A4.14 (b): Test Results of Unconfined Compressive Strength (28 days curing) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	995.87	1456.55	1747.77	1835.78	1907.34
2	1102.96	1544.15	1807.16	1848.26	2044.72
4	1219.66	1603.4	1925.94	1927.58	2248.35
6	1374.46	1722.88	2027.76	2200.51	2332.1
8	1398.77	1679.9	2180.47	2319.92	2456.32
10	1268.94	1552.3	1825.23	1722.88	2046.99

Table A4.14 (c): Test Results of Unconfined Compressive Strength (28 days curing) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	1124.9	1648.14	1791.94	2143.47	2290.26
2	1154.43	1799.64	1867.88	2275.33	2330.47
4	1382.95	1884.93	2098.16	2340.67	2469.28
6	1506.92	1936.11	2120.19	2563.59	2585.6
8	1480.4	2053.21	2212.06	2542.51	2732.12
10	1491.86	1731.93	1950.64	2215	2370.13

Table A4.15 (a): Test Results of Unconfined Compressive Strength (7 days curing, 7days soaking) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	27.41	81.72	120.27	313.43	293.33
2	35.45	117.48	297.35	361.59	281.28
4	46.32	201.28	321.46	385.01	448.48
6	60.95	246.47	377.16	490.23	482.19
8	85.63	305	423.11	546.49	711.26
10	67.37	173.85	310.72	451.86	498.27

Table A4.15 (b): Test Results of Unconfined Compressive Strength (7 days curing, 7days soaking) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	32.41	170.26	250.58	318.58	312.29
2	53.98	211.28	317.44	295.38	422.19
4	66.63	318.48	451.86	420.49	545.66
6	121.72	365.56	507.88	475.12	610.3
8	172.09	382.03	519.08	521.79	654.79
10	120.43	314.3	329.5	411.49	456.79

Table A4.15 (c): Test Results of Unconfined Compressive Strength (7 days curing, 7days soaking) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	89.7	317.23	496.37	576.93	537.13
2	134.9	545.86	711.63	728.78	792.92
4	177.23	550.44	831.67	818.79	835.52
6	248.11	627.84	912.61	973.91	1320.79
8	220.09	608.75	990.58	1370.37	1206.87
10	196.97	460.57	537.27	860.83	745.93

Table A4.16 (a): Test Results of California Bearing Ratio (Unsoaked) for Soil-Lime-IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	4.62	11.45	29.66	31.78	41.52
2	5.5	13.45	31.35	34.79	44.89
4	9.8	16.3	33.67	40.12	47.88
6	12.2	22.78	35.07	43.64	51.27
8	13.98	23.2	44.07	44.89	52.12
10	11.86	20	35.07	39.83	46.29

Table A4.16 (b): Test Results of California Bearing Ratio (Unsoaked) for Soil-Lime-IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	7.87	16.58	36.44	55.08	54.53
2	10.12	21.61	39.41	60.15	65.25
4	12.71	27.97	46.94	74.2	79.66
6	16.58	33.9	50.03	77.54	80.66
8	18.64	38.22	51.27	79.23	83.19
10	14.05	32.32	55.08	62.4	76.27

Table A4.16 (c): Test Results of California Bearing Ratio (Unsoaked) for Soil-Lime-IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	13.47	24.53	42.72	60.04	79.94
2	14.87	27.92	48.54	65.37	81.63
4	18.61	42.3	58.36	77.4	82.05
6	19.46	50.76	70.7	81.21	84.59
8	20.73	44.83	76.56	84.17	88.4
10	13.96	36.19	61.33	71.48	71.9

Table A4.17 (a): Test Results of California Bearing Ratio (Soaked) for Soil-Lime-IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	3.37	8.46	20.3	25.25	32.57
2	3.81	9.26	24.53	29.46	33.39
4	7.29	11.78	25.25	31.7	35.35
6	8.98	14.59	27.49	32.99	37.22
8	11.42	20.2	30.58	35.53	41.03
10	7.19	12.27	20.73	24.1	39.28

Table A4.17 (b): Test Results of California Bearing Ratio (Soaked) for Soil-Lime-IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	4.24	12.37	24.73	36.54	44.97
2	5.62	11.44	30.64	41.04	52.84
4	8.43	13.98	34.85	46.19	53.81
6	9.75	16.95	42.37	50	56.21
8	12.37	19.96	38.79	44.97	61.44
10	8.71	14.33	34.74	44.91	50.31

Table A4.17 (c): Test Results of California Bearing Ratio (Soaked) for Soil-Lime-IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	8.04	12.27	33.11	36.47	57.52
2	10.1	12.69	42.08	48.22	58.79
4	11.22	16.92	46.01	49.38	63.13
6	12.27	17.76	51.18	61.75	63.97
8	15.23	19.03	56.11	53.29	68.94
10	10.15	22.42	51.34	48.26	54.15

Table A4.18 (a): Test Results of Resistance to Loss in Strength for Soil-Lime-IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	10.59	14.48	11.79	25.14	21.59
2	11.82	15.31	29.13	24.08	19.83
4	13.25	22.73	25.85	25.47	27.53
6	13.50	20.72	29.24	31.33	27.59
8	17.70	24.68	28.32	33.64	37.56
10	19.58	18.74	24.94	29.58	32.09

Table A4.18 (b): Test Results of Resistance to Loss in Strength for Soil-Lime-IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	7.17	18.84	19.90	22.34	19.18
2	6.83	18.31	24.27	19.33	22.53
4	7.43	27.11	29.74	24.29	27.94
6	12.58	26.68	29.49	24.50	31.04
8	14.29	26.63	27.71	23.42	31.30
10	15.77	25.74	23.72	24.50	25.85

Table A4.18 (c): Test Results of Resistance to Loss in Strength for Soil-Lime-IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	19.85	35.10	39.42	40.45	32.98
2	17.06	47.31	54.40	47.70	42.32
4	19.76	46.85	54.75	47.31	42.78
6	25.65	45.82	52.99	50.22	67.17
8	18.28	42.43	52.87	61.51	57.69
10	25.80	37.72	38.68	51.25	42.22

Table A4.19: Analysis of Variance for Specific Gravity of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	12.25	2.45	0.00065	0% Lime	6	15.22	2.536667	0.001867
2% IOT	5	12.34	2.468	0.00057	2% Lime	6	15.11	2.518333	0.001897
4% IOT	5	12.44	2.488	0.00047	4% Lime	6	15.04	2.506667	0.001867
6% IOT	5	12.61	2.522	0.00102	6% Lime	6	14.93	2.488333	0.001977
8% IOT	5	12.7	2.54	0.00065	8% Lime	6	14.84	2.473333	0.001747
10% IOT	5	12.8	2.56	0.0005					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.046107	5	0.009221	279.4343	8.72E-18	2.71089
Lime	0.01478	4	0.003695	111.9697	2.15E-13	2.866081
Error	0.00066	20	3.3E-05			
Total	0.061547	29				

Table A4.20: Analysis of Variance for Free swells of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	230.4	46.08	18.422	0% Lime	6	296	49.33333	3.094667
2% IOT	5	213	42.6	39.925	2% Lime	6	267.1	44.51667	10.94567
4% IOT	5	206.6	41.32	36.842	4% Lime	6	237.3	39.55	4.823
6% IOT	5	195.2	39.04	47.823	6% Lime	6	229.3	38.21667	13.34167
8% IOT	5	190.3	38.06	42.428	8% Lime	6	202.5	33.75	21.003
10% IOT	5	196.7	39.34	42.768					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	218.3867	5	43.67733	18.33128	7.39E-07	2.71089
Lime	865.1787	4	216.2947	90.7784	1.58E-12	2.866081
Error	47.65333	20	2.382667			
Total	1131.219	29				

Table A4.21: Analysis of Variance for Cation Exchange Capacity of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	245.8	49.16	5.843	0% Lime	6	260.3	43.38333	71.30567
2% IOT	5	234.4	46.88	16.387	2% Lime	6	231.5	38.58333	28.85367
4% IOT	5	231.8	46.36	5.893	4% Lime	6	253.4	42.23333	67.09067
6% IOT	5	189.9	37.98	6.622	6% Lime	6	237.8	39.63333	81.13867
8% IOT	5	172.5	34.5	3.655	8% Lime	6	240.2	40.03333	77.51067
10% IOT	5	148.8	29.76	8.243					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.046107	5	0.009221	279.4343	8.72E-18	2.71089
Lime	0.01478	4	0.003695	111.9697	2.15E-13	2.866081
Error	0.00066	20	3.3E-05			
Total	0.061547	29				

Table A4.22: Analysis of Variance for Liquid Limit of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	262.7	52.54	12.143	0% Lime	6	320.9	53.48333	3.845667
2% IOT	5	254.1	50.82	12.012	2% Lime	6	310.8	51.8	3.372
4% IOT	5	249	49.8	11.71	4% Lime	6	292.5	48.75	2.799
6% IOT	5	243.9	48.78	12.897	6% Lime	6	293.6	48.93333	9.610667
8% IOT	5	238.6	47.72	12.512	8% Lime	6	270.2	45.03333	1.782667
10% IOT	5	239.7	47.94	6.983					

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
IOT	85.672	5	17.1344	16.02994	2.12E-06	2.71089
Lime	251.65	4	62.9125	58.85724	8.85E-11	2.866081
Error	21.378	20	1.0689			
Total	358.7	29				

Table A4.23: Analysis of Variance for Plastic Limit of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	134.03	26.806	4.05718	0% Lime	6	152.45	25.40833	4.883857
2% IOT	5	122.4	24.48	6.997	2% Lime	6	150.64	25.10667	4.348427
4% IOT	5	116.95	23.39	5.60775	4% Lime	6	140.15	23.35833	4.672977
6% IOT	5	110.07	22.014	5.62143	6% Lime	6	131.13	21.855	8.76255
8% IOT	5	104.21	20.842	7.88082	8% Lime	6	118.9	19.81667	4.934667
10% IOT	5	105.61	21.122	4.57542					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	129.5645	5	25.91289	61.34744	1.92E-11	2.71089
Lime	130.5105	4	32.62762	77.24421	7.17E-12	2.866081
Error	8.447913	20	0.422396			
Total	268.5229	29				

Table A4.24: Analysis of Variance for Plasticity Index of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	128.67	25.734	2.68878	0% Lime	6	168.45	28.075	0.28679
2% IOT	5	131.7	26.34	1.678	2% Lime	6	160.16	26.69333	0.125627
4% IOT	5	132.05	26.41	1.81275	4% Lime	6	152.35	25.39167	0.450177
6% IOT	5	133.83	26.766	2.48423	6% Lime	6	162.47	27.07833	0.544817
8% IOT	5	134.39	26.878	1.58392	8% Lime	6	151.3	25.21667	1.300667
10% IOT	5	134.09	26.818	0.56012					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4.67367	5	0.934734	2.108411	0.106581	2.71089
Lime	34.36449	4	8.591122	19.37837	1.18E-06	2.866081
Error	8.866713	20	0.443336			
Total	47.90487	29				

Table A4.25: Analysis of Variance for Linear Shrinkage of Soil-Lime-IOT Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	69.37134	13.87427	14.79408	0% Lime	6	95.66929	15.94488	1.844504
2% IOT	5	61.81102	12.3622	19.71294	2% Lime	6	89.76646	14.96108	3.025554
4% IOT	5	56.92606	11.38521	21.89409	4% Lime	6	72.3622	12.06037	3.36392
6% IOT	5	55.66929	11.13386	21.9468	6% Lime	6	46.21685	7.702808	5.762237
8% IOT	5	51.49906	10.29981	21.48043	8% Lime	6	35.35921	5.893202	2.737699
10% IOT	5	44.09724	8.819449	19.00439					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	74.71288	5	14.94258	33.36633	4.81E-09	2.71089
Lime	466.3742	4	116.5936	260.3499	6.1E-17	2.866081
Error	8.956681	20	0.447834			
Total	550.0438	29				

Table A4.26 (a): Analysis of Variance for Maximum Dry Density of Soil-Lime-IOT Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	7.61	1.522	0.000457	0% Lime	6	9.55	1.591667	0.000867
2% IOT	5	7.695	1.539	0.000493	2% Lime	6	9.42	1.57	0.00103
4% IOT	5	7.855	1.571	0.000305	4% Lime	6	9.494	1.582333	0.001751
6% IOT	5	7.984	1.5968	0.000394	6% Lime	6	9.5	1.583333	0.002877
8% IOT	5	8.15	1.63	0.000125	8% Lime	6	9.35	1.558333	0.002617
10% IOT	5	8.02	1.604	0.00013					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.042175	5	0.008435	47.80805	1.91E-10	2.71089
Lime	0.004086	4	0.001022	5.789911	0.002907	2.866081
Error	0.003529	20	0.000176			
Total	0.049789	29				

Table A4.26 (b): Analysis of Variance for Maximum Dry Density of Soil-Lime-IOT Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	7.82	1.564	0.00073	0% Lime	6	9.87	1.645	0.00115
2% IOT	5	7.985	1.597	0.00112	2% Lime	6	9.905	1.650833	0.001604
4% IOT	5	8.11	1.622	0.00037	4% Lime	6	9.74	1.623333	0.002187
6% IOT	5	8.305	1.661	0.000355	6% Lime	6	9.67	1.611667	0.004127
8% IOT	5	8.46	1.692	0.00037	8% Lime	6	9.79	1.631667	0.003617
10% IOT	5	8.295	1.659	0.00053					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.055587	5	0.011118	28.38511	1.96E-08	2.71089
Lime	0.006067	4	0.001517	3.87234	0.017332	2.866081
Error	0.007833	20	0.000392			
Total	0.069487	29				

Table A4.26 (c): Analysis of Variance for Maximum Dry Density of Soil-Lime-IOT Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8.295	1.659	0.00128	0% Lime	6	10.48	1.746667	0.000627
2% IOT	5	8.465	1.693	0.00152	2% Lime	6	10.452	1.742	0.001575
4% IOT	5	8.602	1.7204	0.001118	4% Lime	6	10.205	1.700833	0.005164
6% IOT	5	8.709	1.7418	0.000489	6% Lime	6	10.277	1.712833	0.002538
8% IOT	5	8.96	1.792	0.000608	8% Lime	6	10.417	1.736167	0.003926
10% IOT	5	8.8	1.76	0.00045					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.056768	5	0.011354	18.33671	7.37E-07	2.71089
Lime	0.009472	4	0.002368	3.824622	0.018188	2.866081
Error	0.012384	20	0.000619			
Total	0.078624	29				

Table A4.27 (a): Analysis of Variance for Optimum Moisture Content of Soil-Lime-IOT Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	122.9	24.58	0.407	0% Lime	6	121.7	20.28333	4.101667
2% IOT	5	115.4	23.08	2.362	2% Lime	6	130.4	21.73333	2.506667
4% IOT	5	111.4	22.28	2.242	4% Lime	6	131.8	21.96667	2.686667
6% IOT	5	104	20.8	1.325	6% Lime	6	132.9	22.15	4.923
8% IOT	5	100.6	20.12	1.202	8% Lime	6	137.8	22.96667	4.070667
10% IOT	5	100.3	20.06	0.488					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	82.224	5	16.4448	35.6746	2.66E-09	2.71089
Lime	22.88467	4	5.721167	12.41124	3.1E-05	2.866081
Error	9.219333	20	0.460967			
Total	114.328	29				

Table A4.27 (b): Analysis of Variance for Optimum Moisture Content of Soil-Lime-IOT Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	110	22	2.135	0% Lime	6	106.5	17.75	3.451
2% IOT	5	103.65	20.73	1.432	2% Lime	6	111.75	18.625	3.13175
4% IOT	5	100.8	20.16	2.023	4% Lime	6	117.1	19.51667	5.057667
6% IOT	5	92.5	18.5	0.97	6% Lime	6	117.3	19.55	8.627
8% IOT	5	83.3	16.66	1.573	8% Lime	6	123.5	20.58333	4.169667
10% IOT	5	85.9	17.18	1.612					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	110.6218	5	22.12435	38.26528	1.43E-09	2.71089
Lime	27.41633	4	6.854083	11.85452	4.24E-05	2.866081
Error	11.56367	20	0.578183			
Total	149.6018	29				

Table A4.27 (c): Analysis of Variance for Optimum Moisture Content of Soil-Lime-IOT Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	105.3	21.06	1.173	0% Lime	6	96.9	16.15	3.715
2% IOT	5	97.1	19.42	3.217	2% Lime	6	102	17	5.852
4% IOT	5	90.3	18.06	2.043	4% Lime	6	107.6	17.93333	7.638667
6% IOT	5	86.4	17.28	1.487	6% Lime	6	110.3	18.38333	4.937667
8% IOT	5	74.8	14.96	0.628	8% Lime	6	111.9	18.65	9.315
10% IOT	5	74.8	14.96	0.288					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	147.6697	5	29.53393	61.38835	1.91E-11	2.71089
Lime	25.722	4	6.4305	13.36624	1.85E-05	2.866081
Error	9.622	20	0.4811			
Total	183.0137	29				

Table A4.28 (a): Analysis of Variance for Unconfined Compressive Strength (7 days curing) of Soil-Lime-IOT Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	1893.72	378.744	62568.14	0% Lime	6	1196.77	199.4617	4512.812
2% IOT	5	2555.82	511.164	84775.87	2% Lime	6	2432.85	405.475	16853.84
4% IOT	5	2878.18	575.636	89782.54	4% Lime	6	3286.13	547.6883	34155.11
6% IOT	5	3429.88	685.976	115712.7	6% Lime	6	4869.02	811.5033	21654.98
8% IOT	5	3773.04	754.608	104129.8	8% Lime	6	5463.07	910.5117	22799.05
10% IOT	5	2717.2	543.44	66320.77					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	440812.8	5	88162.57	29.85214	1.27E-08	2.71089
Lime	2034093	4	508523.4	172.1877	3.43E-15	2.866081
Error	59066.15	20	2953.308			
Total	2533972	29				

Table A4.28 (b): Analysis of Variance for Unconfined Compressive Strength (7 days curing) of Soil-Lime-IOT Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	4286.927	857.3855	154872.9	0% Lime	6	2830.83	471.805	12389.24
2% IOT	5	4561.11	912.222	153307.5	2% Lime	6	4346.54	724.4233	12528.84
4% IOT	5	4900.64	980.128	161776.5	4% Lime	6	6926.447	1154.408	22402.59
6% IOT	5	5472.32	1094.464	199854.5	6% Lime	6	7682.48	1280.413	25659.71
8% IOT	5	5845.67	1169.134	191048.2	8% Lime	6	8394.13	1399.022	11711.13
10% IOT	5	5113.76	1022.752	86833.34					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	331345.8	5	66269.15	14.38886	4.84E-06	2.71089
Lime	3698660	4	924665	200.7703	7.72E-16	2.866081
Error	92111.73	20	4605.587			
Total	4122118	29				

Table A4.28 (c): Analysis of Variance for Unconfined Compressive Strength (7 days curing) of Soil-Lime-IOT Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	4979.89	995.978	145715.7	0% Lime	6	3224.14	537.3567	17655.25
2% IOT	5	5468.22	1093.644	169782.8	2% Lime	6	6110.17	1018.362	17664.21
4% IOT	5	5746.4	1149.28	197926.9	4% Lime	6	7884.58	1314.097	15011.36
6% IOT	5	6267.51	1253.502	154570	6% Lime	6	8619.27	1436.545	18551.14
8% IOT	5	6793.85	1358.77	157408.1	8% Lime	6	9220.84	1536.807	16634.66
10% IOT	5	5803.13	1160.626	156828.6					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	396132.9	5	79226.58	50.38226	1.19E-10	2.71089
Lime	3897478	4	974369.5	619.6271	1.18E-20	2.866081
Error	31450.19	20	1572.509			
Total	4325061	29				

Table A4.28 (d): Analysis of Variance for Unconfined Compressive Strength (14 days curing) of Soil-Lime-IOT Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	4448.32	889.664	217112.2	0% Lime	6	2187.73	364.6217	7560.573
2% IOT	5	5008.42	1001.684	242936.7	2% Lime	6	5572.169	928.6948	64825.85
4% IOT	5	5619.27	1123.854	268930.8	4% Lime	6	7314.22	1219.037	32216.32
6% IOT	5	6243.44	1248.688	247360.3	6% Lime	6	8976.45	1496.075	16932.11
8% IOT	5	6733.579	1346.716	288660.7	8% Lime	6	9600.56	1600.093	40427.36
10% IOT	5	5598.1	1119.62	252052.4					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	675057.9	5	135011.6	20.03835	3.61E-07	2.71089
Lime	5933459	4	1483365	220.1602	3.14E-16	2.866081
Error	134753.2	20	6737.66			
Total	6743270	29				

Table A4.28 (e): Analysis of Variance for Unconfined Compressive Strength (14 days curing) of Soil-Lime-IOT Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	5669.81	1133.962	215969.9	0% Lime	6	5074.81	845.8017	62145.42
2% IOT	5	6654.2	1330.84	164229.6	2% Lime	6	7258.42	1209.737	34904.38
4% IOT	5	7274.95	1454.99	179545.4	4% Lime	6	9071.34	1511.89	59124.46
6% IOT	5	7965.5	1593.1	179298.8	6% Lime	6	10531.96	1755.327	84717.36
8% IOT	5	8832.63	1766.526	189161.7	8% Lime	6	11280.62	1880.103	26766.92
10% IOT	5	6820.06	1364.012	160900.9					

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
IOT	1208155	5	241630.9	37.13455	1.87E-09	2.71089
Lime	4226288	4	1056572	162.3771	6.06E-15	2.866081
Error	130138.1	20	6506.904			
Total	5564580	29				

Table A4.28 (f): Analysis of Variance for Unconfined Compressive Strength (14 days curing) of Soil-Lime-IOT Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	6824.22	1364.844	131526.6	0% Lime	6	6955.32	1159.22	37235.4
2% IOT	5	7422.52	1484.504	144083.9	2% Lime	6	8907.83	1484.638	45530.25
4% IOT	5	8499.35	1699.87	180271.3	4% Lime	6	10982.71	1830.452	74199.98
6% IOT	5	9803.66	1960.732	271815.3	6% Lime	6	12126.72	2021.12	264302.9
8% IOT	5	10560.05	2112.01	284710.8	8% Lime	6	13221.5	2203.583	59493.57
10% IOT	5	9084.28	1816.856	144681.9					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	2003257	5	400651.3	20.00486	3.66E-07	2.71089
Lime	4227806	4	1056951	52.77448	2.39E-10	2.866081
Error	400553.9	20	20027.7			
Total	6631616	29				

Table A4.28 (g): Analysis of Variance for Unconfined Compressive Strength (28 days curing) ofSoil-Lime-IOT Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	5729.7	1145.94	183375.1	0% Lime	6	4017.33	669.555	23586.21
2% IOT	5	6703.11	1340.622	213840.7	2% Lime	6	7158.85	1193.142	27493.84
4% IOT	5	7232.68	1446.536	245720.2	4% Lime	6	8784.2	1464.033	26718.66
6% IOT	5	7557.36	1511.472	256084.5	6% Lime	6	10209.08	1701.513	48484.69
8% IOT	5	7950.03	1590.006	209489.2	8% Lime	6	11333.59	1888.932	19936.09
10% IOT	5	6330.17	1266.034	268980.9					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	675333.1	5	135066.6	48.44195	1.7E-10	2.71089
Lime	5454198	4	1363550	489.0401	1.23E-19	2.866081
Error	55764.32	20	2788.216			
Total	6185295	29				

Table A4.28 (h): Analysis of Variance for Unconfined Compressive Strength (28 days curing) of Soil-Lime-IOT Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	7943.31	1588.662	139198.6	0% Lime	6	7360.66	1226.777	24373.78
2% IOT	5	8347.25	1669.45	132093.9	2% Lime	6	9559.18	1593.197	9437.953
4% IOT	5	8924.93	1784.986	151868.6	4% Lime	6	11514.33	1919.055	26172.83
6% IOT	5	9657.71	1931.542	148982.1	6% Lime	6	11854.93	1975.822	54215.78
8% IOT	5	10035.38	2007.076	201709.3	8% Lime	6	13035.82	2172.637	42833.88
10% IOT	5	8416.34	1683.268	85709.08					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	663521.9	5	132704.4	21.81755	1.8E-07	2.71089
Lime	3316597	4	829149.3	136.3181	3.27E-14	2.866081
Error	121649.2	20	6082.461			
Total	4101768	29				

Table A4.28 (i): Analysis of Variance for Unconfined Compressive Strength (28 days curing) of Soil-Lime-IOT Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8998.71	1799.742	209303.2	0% Lime	6	8141.46	1356.91	30293.83
2% IOT	5	9427.75	1885.55	223027.9	2% Lime	6	11053.96	1842.327	21360.03
4% IOT	5	10175.99	2035.198	183428.1	4% Lime	6	12040.87	2006.812	26390.63
6% IOT	5	10712.41	2142.482	205177.7	6% Lime	6	14080.57	2346.762	29832.03
8% IOT	5	11020.3	2204.06	234974.8	8% Lime	6	14777.86	2462.977	28704.78
10% IOT	5	9759.56	1951.912	126040.8					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	593176.1	5	118635.2	26.44257	3.6E-08	2.71089
Lime	4638079	4	1159520	258.4451	6.56E-17	2.866081
Error	89730.47	20	4486.524			
Total	5320986	29				

Table A4.28 (j): Analysis of Variance for Unconfined Compressive Strength (7 days curing, 7 days soaking) of Soil-Lime-IOT Mixtures (BSL compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	836.16	167.232	16585.62	0% Lime	6	323.13	53.855	467.5006
2% IOT	5	1093.15	218.63	18586.41	2% Lime	6	1126.19	187.6983	6768.739
4% IOT	5	1402.55	280.51	25483.36	4% Lime	6	1850.07	308.345	10715.45
6% IOT	5	1657	331.4	32603.72	6% Lime	6	2548.61	424.7683	7560.761
8% IOT	5	2071.88	414.376	56405.6	8% Lime	6	2714.81	452.4683	24920.13
10% IOT	5	1502.07	300.414	33129.26					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	187110.2	5	37422.05	11.50515	2.48E-05	2.71089
Lime	666123.2	4	166530.8	51.19875	3.14E-10	2.866081
Error	65052.68	20	3252.634			
Total	918286.1	29				

Table A4.28 (k): Analysis of Variance for Unconfined Compressive Strength (7 days curing, 7 days soaking) of Soil-Lime-IOT Mixtures (WAS compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	1084.12	216.824	14196.06	0% Lime	6	567.26	94.54333	2741.453
2% IOT	5	1300.27	260.054	18918.64	2% Lime	6	1761.91	293.6517	7206.987
4% IOT	5	1803.12	360.624	33588.71	4% Lime	6	2376.34	396.0567	12505.41
6% IOT	5	2080.58	416.116	34708.61	6% Lime	6	2442.85	407.1417	7659.244
8% IOT	5	2249.78	449.956	33429.67	8% Lime	6	3002.02	500.3367	16273.35
10% IOT	5	1632.51	326.502	16705.37					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	200193.9	5	40038.79	25.23062	5.35E-08	2.71089
Lime	574450	4	143612.5	90.49805	1.62E-12	2.866081
Error	31738.25	20	1586.913			
Total	806382.2	29				

Table A4.28 (l): Analysis of Variance for Unconfined Compressive Strength (7 days curing, 7 days soaking) of Soil-Lime-IOT Mixtures (BSH compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	2017.36	403.472	40618.18	0% Lime	6	1067	177.8333	3340.353
2% IOT	5	2914.09	582.818	71009.18	2% Lime	6	3110.686	518.4477	13146.76
4% IOT	5	3213.65	642.73	82267.78	4% Lime	6	4480.13	746.6883	40395.88
6% IOT	5	4083.26	816.652	161745.8	6% Lime	6	5329.61	888.2683	73540.94
8% IOT	5	4396.656	879.3312	217148.1	8% Lime	6	5439.16	906.5267	88402.77
10% IOT	5	2801.57	560.314	66815.48					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	768578.4	5	153715.7	9.443296	9.62E-05	2.71089
Lime	2232863	4	558215.7	34.29316	1.08E-08	2.866081
Error	325555.1	20	16277.76			
Total	3326996	29				

Table A4.29 (a): Analysis of Variance for California Bearing Ratio (Unsoaked) of Soil-Lime-IOT Mixtures (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	119.03	23.806	233.1033	0% Lime	0% Lime	57.96	9.66	14.53616
2% IOT	5	129.98	25.996	260.1178	2% Lime	2% Lime	107.18	17.86333	24.05427
4% IOT	5	147.77	29.554	257.5783	4% Lime	4% Lime	208.89	34.815	25.13527
6% IOT	5	164.96	32.992	247.0939	6% Lime	6% Lime	235.05	39.175	25.56675
8% IOT	5	178.26	35.652	263.0316	8% Lime	8% Lime	283.97	47.32833	15.9123
10% IOT	5	153.05	30.61	203.7243					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	477.7191	5	95.54382	39.55887	1.06E-09	2.71089
Lime	5810.292	4	1452.573	601.4219	1.59E-20	2.866081
Error	48.30462	20	2.415231			
Total	6336.315	29				

Table A4.29 (b): Analysis of Variance for California Bearing Ratio (Unsoaked) of Soil-Lime-IOT Mixtures (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	170.5	34.1	464.4961	0% Lime	6	79.97	13.32833	15.95542
2% IOT	5	196.54	39.308	568.1363	2% Lime	6	170.6	28.43333	65.60871
4% IOT	5	241.48	48.296	834.0165	4% Lime	6	279.17	46.52833	52.09814
6% IOT	5	258.71	51.742	764.8554	6% Lime	6	408.6	68.1	103.0827
8% IOT	5	270.55	54.11	748.8349	8% Lime	6	439.56	73.26	123.6716
10% IOT	5	240.12	48.024	613.7853					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	1472.372	5	294.4743	17.86257	9.08E-07	2.71089
Lime	15646.79	4	3911.697	237.2803	1.51E-16	2.866081
Error	329.7111	20	16.48556			
Total	17448.87	29				

Table A4.29 (c): Analysis of Variance for California Bearing Ratio (Unsoaked) of Soil-Lime-IOT Mixtures (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	220.7	44.14	715.4169	0% Lime	6	101.1	16.85	9.7322
2% IOT	5	238.33	47.666	733.3077	2% Lime	6	226.53	37.755	102.784
4% IOT	5	278.72	55.744	681.8766	4% Lime	6	358.21	59.70167	164.5156
6% IOT	5	306.72	61.344	722.2149	6% Lime	6	439.67	73.27833	87.91142
8% IOT	5	314.69	62.938	848.5213	8% Lime	6	488.51	81.41833	30.40622
10% IOT	5	254.86	50.972	638.5608					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	1415.666	5	283.1333	10.09242	6.16E-05	2.71089
Lime	16798.51	4	4199.628	149.6978	1.33E-14	2.866081
Error	561.0807	20	28.05404			
Total	18775.26	29				

Table A4.29 (d): Analysis of Variance for California Bearing Ratio (Soaked) of Soil-Lime-IOT Mixtures (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	89.95	17.99	143.7964	0% Lime	6	42.06	7.01	9.38588
2% IOT	5	100.45	20.09	166.682	2% Lime	6	76.56	12.76	18.1286
4% IOT	5	111.37	22.274	150.833	4% Lime	6	148.88	24.81333	15.54675
6% IOT	5	121.27	24.254	145.3986	6% Lime	6	179.03	29.83833	19.98366
8% IOT	5	138.76	27.752	142.1418	8% Lime	6	218.84	36.47333	11.04059
10% IOT	5	103.57	20.714	152.5903					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	297.1542	5	59.43085	16.22173	1.93E-06	2.71089
Lime	3532.495	4	883.1238	241.0499	1.3E-16	2.866081
Error	73.27312	20	3.663656			
Total	3902.922	29				

Table A4.29 (e): Analysis of Variance for California Bearing Ratio (Soaked) of Soil-Lime-IOT Mixtures (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	122.85	24.57	280.4039	0% Lime	6	49.12	8.186667	8.488267
2% IOT	5	141.58	28.316	392.1589	2% Lime	6	89.03	14.83833	9.865417
4% IOT	5	157.26	31.452	390.9796	4% Lime	6	206.12	34.35333	38.14891
6% IOT	5	175.28	35.056	423.1326	6% Lime	6	263.65	43.94167	21.39158
8% IOT	5	177.53	35.506	387.4692	8% Lime	6	319.58	53.26333	30.70407
10% IOT	5	153	30.6	338.5712					

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
IOT	428.1328	5	85.62657	14.90994	3.69E-06	2.71089
Lime	8736.003	4	2184.001	380.2947	1.47E-18	2.866081
Error	114.8583	20	5.742917			
Total	9278.994	29				

Table A4.29 (e): Analysis of Variance for California Bearing Ratio (Soaked) of Soil-Lime-IOT Mixtures (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	147.41	29.482	401.0341	0% Lime	6	67.01	11.16833	5.935657
2% IOT	5	171.88	34.376	476.6645	2% Lime	6	101.09	16.84833	14.97846
4% IOT	5	186.66	37.332	496.1213	4% Lime	6	279.83	46.63833	67.32678
6% IOT	5	206.93	41.386	606.6453	6% Lime	6	297.37	49.56167	67.47502
8% IOT	5	212.6	42.52	573.8054	8% Lime	6	366.5	61.08333	28.05535
10% IOT	5	186.32	37.264	389.924					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	566.3571	5	113.2714	6.426762	0.00103	2.71089
Lime	11424.28	4	2856.07	162.0469	6.18E-15	2.866081
Error	352.4992	20	17.62496			
Total	12343.14	29				

Table A4.30 (a): Analysis of Variance for Resistance to Loss in Strength of Soil-Lime-IOT Mixtures (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	83.59948	16.7199	40.36211	0% Lime	6	86.4377	14.40628	12.19324
2% IOT	5	100.1681	20.03361	47.24321	2% Lime	6	116.6538	19.4423	16.39994
4% IOT	5	114.8283	22.96566	32.49243	4% Lime	6	149.27	24.87833	44.23133
6% IOT	5	122.3763	24.47525	53.5126	6% Lime	6	169.2474	28.20791	15.02146
8% IOT	5	141.8983	28.37965	59.92999	8% Lime	6	166.1853	27.69754	43.17701
10% IOT	5	124.9238	24.98477	34.95723					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	416.3213	5	83.26426	6.973745	0.000643	2.71089
Lime	835.1967	4	208.7992	17.48784	2.59E-06	2.866081
Error	238.7935	20	11.93968			
Total	1490.312	29				

Table A4.30 (b): Analysis of Variance for Resistance to Loss in Strength of Soil-Lime-IOT Mixtures (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	87.42179	17.48436	35.11304	0% Lime	6	64.07119	10.67853	16.06534
2% IOT	5	91.27014	18.25403	46.55567	2% Lime	6	143.3058	23.88431	17.13847
4% IOT	5	116.5128	23.30257	82.61368	4% Lime	6	154.8272	25.80453	14.85501
6% IOT	5	124.286	24.85721	53.41886	6% Lime	6	138.3806	23.06343	4.041259
8% IOT	5	123.3414	24.66827	41.57458	8% Lime	6	157.8355	26.30592	23.04901
10% IOT	5	115.5881	23.11762	17.65376					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	263.1788	5	52.63575	9.351928	0.000103	2.71089
Lime	995.1517	4	248.7879	44.20278	1.17E-09	2.866081
Error	112.5666	20	5.628332			
Total	1370.897	29				

Table A4.30 (c): Analysis of Variance for Resistance to Loss in Strength of Soil-Lime-IOT Mixtures (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	167.7979	33.55959	68.15258	0% Lime	6	126.3863	21.06438	14.08634
2% IOT	5	208.7868	41.75736	209.0523	2% Lime	6	255.2303	42.53839	26.10932
4% IOT	5	211.4415	42.28829	177.2757	4% Lime	6	293.1056	48.85094	58.24357
6% IOT	5	241.8448	48.36897	225.1782	6% Lime	6	298.4308	49.73847	47.46348
8% IOT	5	232.7711	46.55422	301.0252	8% Lime	6	285.1548	47.5258	155.6838
10% IOT	5	195.6657	39.13314	84.08192					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	704.4351	5	140.887	3.506844	0.019431	2.71089
Lime	3455.566	4	863.8916	21.50328	5.2E-07	2.866081
Error	803.4974	20	40.17487			
Total	4963.499	29				

Table A4.31 (a): Test Results of Unconfined Compressive Strength (ratio of 28 days to 7 days curing periods) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	4.93	4.73	4.05	2.20	2.50
2	4.85	3.23	2.99	2.23	2.15
4	3.58	3.04	2.87	2.28	2.06
6	3.32	2.51	2.45	1.94	1.90
8	3.09	2.51	1.94	1.95	1.90
10	1.96	2.84	2.87	2.09	2.11

Table A4.31 (b): Test Results of Unconfined Compressive Strength (ratio of 28 days to 7 days curing periods) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	3.05	2.50	1.76	1.69	1.48
2	2.80	2.52	1.65	1.64	1.54
4	2.85	2.28	1.73	1.51	1.63
6	2.84	2.24	1.59	1.52	1.56
8	2.37	2.05	1.57	1.57	1.57
10	2.08	1.80	1.73	1.37	1.54

Table A4.31 (c): Test Results of Unconfined Compressive Strength (ratio of 28 days to 7 days curing periods) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	2.75	2.01	1.54	1.70	1.73
2	2.66	1.85	1.51	1.69	1.58
4	3.11	1.90	1.54	1.68	1.59
6	2.26	1.82	1.54	1.69	1.57
8	2.04	1.67	1.47	1.54	1.62
10	2.75	1.68	1.57	1.52	1.55

Table A4.32 (a): Test Results of Unconfined Compressive Strength (ratio of 14 days to 7 days curing periods) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	2.41	2.71	3.46	2.04	2.02
2	2.18	2.21	2.16	2.02	1.66
4	1.77	2.19	2.30	1.93	1.71
6	1.98	2.29	1.99	1.60	1.65
8	1.68	2.15	1.77	1.64	1.76
10	1.44	2.44	2.56	2.00	1.83

Table A4.32 (b): Test Results of Unconfined Compressive Strength (ratio of 14 days to 7 days curing periods) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	1.39	1.55	1.26	1.31	1.26
2	2.01	1.88	1.20	1.35	1.41
4	2.10	1.67	1.36	1.35	1.42
6	2.00	1.78	1.35	1.34	1.32
8	2.04	1.75	1.35	1.51	1.33
10	1.25	1.42	1.32	1.34	1.33

Table A4.32 (c): Test Results of Unconfined Compressive Strength (ratio of 14 days to 7 days curing periods) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	2.21	1.49	1.26	1.06	1.43
2	2.26	1.29	1.33	1.16	1.34
4	2.48	1.52	1.27	1.40	1.42
6	1.91	1.48	1.53	1.65	1.43
8	1.91	1.45	1.45	1.61	1.52
10	2.40	1.53	1.50	1.45	1.46

Table A4.33 (a): Test Results of Unconfined Compressive ratio of 14 days curing to (7 days curing + 7 days soaked) for Soil Lime–IOT Mixtures (BSL Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	9.44	6.90	8.48	3.98	4.63
2	8.46	6.53	3.43	4.15	5.04
4	7.55	4.40	3.87	3.93	3.63
6	7.41	4.83	3.42	3.19	3.62
8	5.65	4.06	3.53	2.97	2.66
10	5.11	5.34	4.01	3.38	3.12

Table A4.33 (b): Test Results of Unconfined Compressive ratio of 14 days curing to (7 days curing + 7 days soaked) for Soil Lime–IOT Mixtures (WAS Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	13.95	5.31	5.03	4.48	5.21
2	14.65	5.46	4.12	5.17	4.44
4	13.46	3.69	3.36	4.12	3.58
6	7.95	3.75	3.39	4.08	3.22
8	7.00	3.76	3.61	4.27	3.19
10	6.34	3.88	4.22	4.08	3.87

Table A4.33 (c): Test Results of Unconfined Compressive ratio of 14 days curing to (7 days curing + 7 days soaked) for Soil Lime–IOT Mixtures (BSH Compaction)

IOT CONTENT, %	LIME CONTENT, %				
	0	2	4	6	8
0	10.06	3.85	2.95	2.32	3.53
2	7.28	2.30	2.31	2.15	2.49
4	6.23	2.73	2.08	2.38	2.65
6	5.14	2.50	2.31	2.57	1.78
8	6.29	2.93	2.20	1.94	2.12
10	6.63	3.43	3.46	2.45	2.99