CEMENT STABILIZATION OF LATERITIC SOIL USING IRON ORE TAILING AS ADMIXTURE

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By

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Declaration

I declare that the work in this dissertation entitled **"**CEMENT STABILIZATION OF LATERITIC SOIL USING IRON ORE TAILING AS ADMIXTURE**"** has been performed by me in the Department of Civil Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

_____	_____	_____
Name of Student	Signature	Date

Certification

This dissertation entitled **"**CEMENT STABILIZATION OF LATERITIC SOIL USING IRON ORE TAILING AS ADMIXTURE**"** by MORIS, IANNA KANYI, meets the regulation governing the award of the degree of Master of Science (Civil Engineering) of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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Dedication

This work is dedicated to my lovely daughter, Ivim Irene Kanyi.

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Abstract

The study was aimed at the evaluation of the effect of iron ore tailings as an admixture in cement stabilization of lateritic soil. Air-dried soil was treated with ordinary Portland cement (OPC) – iron ore tailing (IOT) blend in stepped concentration of 0, 2, 4, 6 and 8 % by dry weight of soil for OPC and 0, 2, 4, 6, 8 and 10 % by dry weight of soil for IOT. The index properties tests carried out on the natural soil showed that the soil belongs to A-7-6(14) in the AASHTO classification system and CL according to the Unified Soil Classification System (USCS). Compaction characteristics of the natural and treated soil samples were determined using three energy levels, namely, British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH). The effect of pozzolanic and particle inter-surface activities on the properties of specimens as well as the leaching potential of IOT were investigated through cation exchange capacity, microanalysis and batch equilibrium tests. Test results showed a decrease in cation exchange capacity with increase in IOT content. The liquid limit decreased from 44.7 % for the untreated soil to 38.5, 34.7 and 31.8 % at 4 % OPC/ 6 % IOT, 6 % OPC/ 6 % IOT and 8% OPC/ 8 % IOT treatments respectively, while the plastic limit increased from the 22.5 to 25.1 % at 6% OPC/ 6% IOT treatment. Unconfined compressive strength (UCS) values of 263.98, 565.37 and 875.46 kN/m^2 obtained for the natural soil after 7 days of curing, increased to 2590.38, 3304.94 and 3504.6 kN/m^2 at 4% OPC/ 6 % IOT treatment and 3783.64, 3860.97 and 3993.14 kN/m^2 at 6 % OPC/6 % IOT treatment for specimens compacted using BSL, WAS and BSH energies, respectively. The treated specimens met the 1720 kN/m^2 requirement for adequate cement stabilization. The California bearing ratio (CBR) results showed significant improvement of the natural soil with peak values of 100 %, 100 % and 100 % (Unsoaked) and 80 %, 80 % and 90 % (Soaked) at 6 % OPC/6 % IOT treatment for BSL, WAS and BSH compaction, respectively.

Durability assessment showed that for BSL compaction specimens treated with 4 % OPC/6 % IOT and 6 % OPC/6 % IOT blend recorded 85 and 87 % resistance to loss in strength respectively, which was greater than the 80 % recommended for 7 days curing and 4 days soaking, although specimens were subjected to harsher condition of 7 days curing and 7 days soaking. Statistical analysis of the results using the two-way analysis of variance (ANOVA) show that OPC/IOT significantly improved the soil properties. Batch equilibrium test results show that the desorbed values of iron and pH of the optimal 6 % OPC / 6 % IOT blend fall within the permissible value recommended by the World Health Organisation (WHO) and Nigeria Industrial Standard (NIS). It is recommended that lateritic soil treated with 4 % OPC/ 6 % IOT blend can be used as a sub-base material in construction of medium trafficked road when compacted with a minimum BSL energy.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AAS	Atomic Absorption Spectrophotometry
ANOVA	Analysis of Variance
AFM	Atomic Force Microscopy
ASTM	American Society for Testing and Materials
BS	British Standard
BSH	British Standard heavy
BSL	British Standard light
CBR	California bearing ratio
CEC	Cation Exchange Capacity
Fcal	F -calculated
Fcrit	F –critical
IOT	Iron ore tailings
LL	Liquid Limit
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPC	Ordinary Portland cement
PI	Plasticity Index
PL	Plastic Limit
SEM	Scanning electron microscopy
TRRL	Transport and Road Research Laboratory
TEM	Transmission electron microscopy

USCS	Unified Soil Classification System
WAS	West African Standard

CHAPTER ONE

INTRODUCTION

1.1 Preamble

The advancement in technology and the desire for safer environment has stimulated the sense of economic reuse and proper management of materials earlier discarded as waste. According to Oriola and Moses (2010), industrial activities often lead to depletion of natural resources, a process that may result in the accumulation of by-products and/or waste materials. Safe disposal of these waste require proper management due the environmental and other health hazards they caused.

Adequate information about the engineering properties of soil and the sub-soil condition is particularly important in the construction of a foundation in most engineering structures. This is necessary for the fact that engineering planning, design and construction of such foundations are anchored on sound geotechnical parameters. Such geotechnical parameters include strength, maximum dry density (MDD), quantity of fines (clay and silts) as well as compaction performance of the proposed highway construction materials (Habeeb *et al.,* 2012)

In Nigeria, the non-availability of generalized relevant geotechnical data, particularly for initial preliminary engineering planning and designs, has been the cause of failure of most of our highway construction projects, such that, failure occurs almost immediately after the project is commissioned. The construction material which is used for engineering highway projects is therefore as important, as other engineering design factors. Thus in road pavement design, the soil (sub-base and base course) materials used in the pavement construction transmit the axle-load to the sub-soil or sub-grade. Hence, the durability of a highway

pavement is a function of the ease and rigidity of the pavement soil to transmit the stress induced on it to the sub-soil such that unnecessary deformation is avoided (Habeeb *et al.*, 2012).

In the tropical part of the world, laterite and lateritic soils are used as a road making material and they form the sub-grade of most tropical road. They are used as sub base and bases for low cost roads and these carry low to medium traffic. Furthermore, in rural areas of Nigeria they are used as building material for moulding of blocks and plastering (Habeeb *et al.*, 2012). Osinubi and Bajeh (1994) reported that a lot of laterite gravels and pisoliths, which are good for gravel roads, occur in tropical countries of the world, including Nigeria. However, there are instances where a laterite may contain a substantial amount of clay minerals that its strength and stability cannot be guaranteed under load especially in the presence of moisture. These types of laterites are also common in many tropical regions of the world; where in most cases sourcing for alternative soil may prove economically unwise but rather to improve the available soil to meet the desired objective (Mustapha, 2006).

The use of soil stabilization products for the improvement of problematic soils is quite widespread across the globe. Over the times, cement and lime have been the two main materials used for stabilizing soils. These materials have rapidly increased in price due to the sharp increase in the cost of energy since the 1970s (Neville, 2000). Although the traditional methods of stabilization include the use of cement, lime and coal fly ash, however, as technology and the understanding of the soil stabilization mechanisms improve; additional stabilization products have been developed (Scholen, 1992).

According to Scholen (1992) new stabilization products, typically called non-traditional stabilizers, are compiled into five groups namely, electrolytes, enzymes, mineral pitches, clay fillers and acrylic polymers. Different methods can be used to improve and treat the geotechnical properties of the problematic soils (such as strength and the stiffness) by

treating it *in situ*. These methods include densifying treatments (such as compaction or preloading), pore-water pressure reduction technique (such as dewatering or electro-osmosis), the bonding of soil particles (by ground freezing, grouting, and chemical stabilization), and use of reinforcing elements (such as geotextiles and stone columns) (Powrie, 1997).

In geotechnical engineering, soil improvement could be achieved by stabilization or modification or both. Soil modification is the addition of a modifier (cement, lime, fly ash, bitumen etc) to a soil to change its index properties, while soil stabilization is the treatment of soils to enable their strength and durability to be improved such that they become totally suitable for construction beyond their original classification. Soil modification and stabilization increases the strength, bearing capacity and durability of the soil (Gidigasu, 1976).

Various types of soil stabilizers (e.g. bitumen, cement and lime) and locally available wastes materials such as bagasse ash (Alhassan, 2006; Moses, 2006;), (Mallikarjuna *et. al*, 2008; Amadi, 2010a,b; Neeraj *et. a.l*, 2012), rice husk ash (Eberemu and Sada, 2013), iron ore tailings (Yisa, 2013; Ishola, 2014; Osinubi *et. al.*, 2015), etc are used as admixtures in stabilization of soil. However, the selection of a particular type of modifier depends upon the type of sub-grade soil and availability of modifier (Laxmikant *et al.*, 2011).

The over-dependence on the utilization of industrially manufactured soil improving additives (cement, lime etc); have kept the cost of construction of stabilized road financially high. This hitherto has continued to deter the underdeveloped and poor nations of the world from providing accessible roads to their rural dwellers who constitute the higher percentage of their population and are mostly, agriculturally dependent. Thus, the use of industrial waste (such as iron ore tailings, IOT) will considerably reduce the cost of construction as well as the environmental hazards they cause. Also, it has been shown by Sear (2005) that Portland cement, by the nature of its chemistry, produces large quantities of CO_2 for every tonne of its

final product. Therefore, replacing proportions of Portland cement in soil stabilization with a secondary pozzolanic material like IOT will reduce the overall environmental impact of the latter.

1.2 Statement of the Problem

Wastes are unwanted materials or substance which are discarded after primary use. Their type, amount and composition vary with the type of activity which may be domestic, agricultural or industrial in nature (Oluremi *et al.,* 2012). The waste that comes from agricultural, industrial, commercial as well as construction activities are composed of a very wide variety of materials such as food wastes, construction waste, paper, plastic and other discarded residual items. The volume of wastes generated worldwide has also increased over the years due to increase in population, socio-economic activities and social development. In other to minimize the effects of these wastes, one of the most attractive options is to look into the possibility of waste minimization and recovery. The exploitation of mineral resources promotes the development of economy and society, but it also generates massive overburden, mill tailings, silt, etc. that may pollute the environment. Therefore, comprehensive utilization of waste/tailings is important in saving resources, improving surroundings and for sustainable development (Mangalpady, 2012).

Adedeji and Sale (1984) reported that iron ore tailings (IOT) are mining and mineral waste from the iron ore mining industry. In Nigeria, the Itakpe and Agbaja iron ore deposits contain large amount of impurities. The Itakpe iron ore is haematite rich, this mineral being inter-grown with magnetite and silica as its major impurity. It has an iron ore deposit of about 200 million tonnes with an average ore content of 36 % (Adepoju and Olaleye, 2001).

Results of research conducted by Soframine (1987) on Itakpe iron ore show that 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 haematite. The deposit has

been developed to supply iron ore concentrates to Ajaokuta steel plant and the Delta steel plant, Aladja, in Nigeria. Information obtained from the processing plant and results of compositional analysis carried out on samples of the tailing material showed that it produces tailing product having between 20 and 22 % iron minerals which are generally fine-grained. The Itakpe iron ore tailings posses pozzolanic properties and is classified as class F in the classification of pozzolanas as given by ASTM C618- 12a, (Ishola, 2014).

The high cost of lime and Portland cement used for improving road bases has led to investigation of the effect of waste resources on the engineering and allied properties of deficient soils. Utilization of industrial/agricultural waste as admixtures in soil modification is considered as one of the suitable methods (Osinubi and Umar, 2003; Yohanna, 2015).

Large amounts of toxic contaminants are being released to the environment around the globe from rapid urbanization and industrialization. Among such contaminants are industrial wastes and ore tailings that result from worldwide mining activities. The overburden material (also known as "waste"), generated during surface mining of minerals, causes serious environmental hazards if surrounding flora and fauna are not properly protected (Qingzhong, 2000; Monalisa *et al.*, 2010).

Effective management of these wastes is a global problem and of growing significance considering the cost of storing and transporting waste, along with the loss of revenue from not reclaiming waste materials, and also the possible associated risk of environmental hazards. It is commonly accepted today in soil improvement work to examine the effects of local materials considered to be waste which actually do not connote worthless substances as they may be economically viable for construction purposes (Osinubi, 2000; Ghose and Sen, 2001).

In recent decades, intensive research and development efforts have been directed towards finding cost-effective and eco-compatible solutions for minimizing and/or utilizing

the waste produced in iron-ore mining operations (Johnson et al., 1992; Bandopadhyay *et al.*, 2002). Research efforts by several researchers (Ferguson, 1993; Osinubi, 2000; Medjo and Riskowski, 2004; Stephen, 2006; Amadi, 2010a; Moses *et al.*, 2012; Moses and Saminu, 2012) to obtain cheaper additives that can be used to substitute the expensive industrially manufactured soil improving additives (e.g., cement, lime, and bitumen) had been reported.

Interest in the use of IOT is principally for its disposal as well as a source of cheap pozzolana thereby achieving a dual purpose of lateritic soil improvement and safe disposal of waste. The major part of Nigeria is underlain by basement complex rocks, the weathering of which had produced lateritic materials spread over most of the area. It is virtually impossible to execute any construction work in Nigeria without the use of lateritic soils (Osinubi, 1998a). Therefore, there is need to investigate the effect of this waste material on the properties of lateritic soil when used as a road construction material.

1.3 Justification for the Study

According to Saranjeet *et al.* (2011), the use of industrial and agricultural wastes (iron ore tailing, fly ash, bagasse ash, locust bean waste ash, etc) for soil improvement is significantly beneficial to the environment. The bulk utilization of iron ore tailing is possible by using it in soil improvement for construction of structures such as embankments, pavements, and earth retaining structures where soil is used as a construction material. Previous investigations (Roy *et al.*, 2007; Mallikarjuna, 2008; Ramesh *et al*, 2012; Yisa, 2013; Ishola 2014; Osinubi *et al.*, 2015), have shown that mining tailings could be used to improve the geotechnical properties of marginal soils. Results of stabilization of lateritic soil with IOT conducted by Yisa, (2013) showed that although IOT improved the geotechnical properties of the soil, it could not be used as a stand-alone additive to achieve minimum

strength requirement for lightly trafficked pavement. This therefore, forms the basis for this study.

The conventional improvement of the soil with lime and ordinary Portland cement has been confirmed in its requirement for construction works (Balogun 1991; Matawal and Tomarin, 1996) but the cost of blending cement with the soil is usually very expensive (Osinubi and Oyelakin, 2012). The use of agricultural and industrial waste in soil stabilization would therefore provide cheaper additives to substitute the conventional but expensive industrially manufactured additives such as cement, lime and bitumen.

1.4 Aim and Objectives

The aim of the research was to evaluate the effect of iron ore tailings as an admixture, in cement stabilization of lateritic soil when used for the construction of road pavements.

The specific objectives of the study include:

1. Determination of the physical properties of the natural and stabilized lateritic soil.
2. Determination of the cation exchange capacity (CEC) of the stabilized soil.
3. Determination of the moisture-density relationship of the natural and stabilized soil using three compactive efforts (British Standard light, West African Standard or Intermediate' and British Standard heavy).
4. Determination of the effectiveness of ordinary Portland cement and iron ore tailings blend for the improvement of the lateritic soil sample collected using strength (unconfined compressive strength, UCS and California bearing ratio, CBR) and durability tests.

5. Statistical evaluation of test results using two-way analysis of variance (ANOVA) and multiple linear regression.
6. Determination of the optimum quantity of cement and IOT blend required for adequate stabilization of lateritic soil.
7. Microanalysis of the optimal mixture using scanning electron microscope (SEM).
8. Determination of the leaching potential of the optimally treated lateritic soil through batch equilibrium study

1.5 Scope of the Study

The research was focused on the determination of the suitability of iron ore tailings as an admixture in cement stabilization of lateritic soil in road construction. Tests were carried out to determine the optimum quantities of additives required to provide the desired strength when lateritic soil is stabilized with 0, 2, 4, 6 and 8 % cement and 0, 2, 4, 6, 8 and 10 % IOT blend by dry weight of soil. Tests involving compaction were carried out using the energies of British Standard light (BSL), West African Standard (WAS) or 'Intermediate' and British Standard heavy (BSH). Tests were carried out in accordance with BS 1377 (1990) and BS 1924 (1990) for the natural soil and treated soil, respectively.

1.6 Significance of Study

The study was carried out to establish that iron ore tailings can be successfully employed as an admixture in cement stabilization of lateritic soil for road construction. Moreover, the environmental problems associated with disposal of iron ore tailings would be greatly minimized.

CHAPTER TWO

LITERATURE REVIEW

2.1 Laterite

The term *Laterite* was used by Buchanan (1807) to describe a soil material vesicular in nature having porous properties and an unstratified structure with contents of ferruginous matter having yellow ochre as a result of the high iron content and occurring naturally in Malabar, India. The term *Laterite* was used to describe this soil because it was widely used as a material in making mud bricks. Formed as a result of long-lasting weathering of parent rocks, laterites and lateritic soils are soils reddish-brown or rusty-red in colour having high content of iron and aluminium and other oxides of metallic elements or oxides and hydroxides of sesquioxides formed and found in tropical and subtropical regions. Since its discovery by Buchanan (1807), laterite has been defined and described by a number of researchers in several different ways.

Laterite and lateritic soils form a group comprising a wide variety of red, brown, and yellow, fine-grained residual soils of light texture as well as nodular gravels and cemented soils (Lambe and Whitman, 1979). They are characterized by the presence of iron and aluminium oxides or hydroxides, particularly those of iron, which give the colours to the soils (Amu *et al.,* 2011). The term laterite may be correctly applied to clays, sands, and gravels in various combinations while “lateritic soil” refers to materials with lower concentrations of oxides. Bridges (1970) reported that the correct usage of the term laterite is for “a massive vesicular or concretionary ironstone formation nearly always associated with uplifted peneplains originally associated with areas of low relief and high groundwater”. Fookes (1997) named laterites based on hardening, such as "ferric" for iron-rich cemented crusts, "alcrete" or bauxite for aluminium-rich cemented crusts, "calcrete" for calcium carbonate-rich

crusts, and "silcrete" for silica rich cemented crusts . Other definitions have been based on the ratios of silica (SiO_2) to sesquioxides (Fe_2O_3 + Al_2O_3) Amu *et al.* (2011).

Kandiah and Joachin (1941) classified laterite on the basis of silica- sesquioxide ratio (SiO_2 / Al_2O_3 +Fe_2O_3) adopting the same limiting values as those proposed by Martin and Doyne, (1927, 1930) using silica-alumina ratio (SiO_2 / Al_2O_3). Ratio less than 1.33 was considered indicative of true laterite, those between 1.33 and 2.00 of lateritic soil and those greater that 2.00 of non-lateritic tropically weathered soils. Bell (1993) also used a similar classification.

These controversies surround the definition of laterites further proves the complexity of its genesis, occurrence, texture and nature of the laterite which are primarily due to the properties of the parent rock and the weathering process. Alexander and Cady (1962) settled on a broader and concise definition of laterite soils. They defined laterite as a highly weathered material rich in secondary oxides of iron, aluminium or both, nearly void of bases and primary silicates but may contain large amounts of quartz and kaolinites; hard or capable of hardening on exposure to wetting and drying.

Ola (1975) used local terminology in defining laterite as all products of tropical weathering with reddish, brown colour with or without nodules or concretion and but not exclusively found below hardened ferruginous crust of hardpan. On the other hand, Osula (1984) defined laterite, (which is a modification of that given by Alexander and Cady (1962)), as a highly weathered tropical soil rich in secondary oxides of any or a combination of iron, aluminium and manganese.

Gidigasu (1976) reviewed all the available definitions of laterite and finally summarized the term laterite soils as “all the residual and non-residual tropically weathered soils which genetically form a chain of materials ranging from decomposed rocks through

clays to the sesquioxide rich concretionary rocks". This definition formed the basis most of where all laterite soils today are defined, described and identified.

Agbede (1992) reported that the geotechnical characteristics and engineering behavior of red soils depend mainly on the genesis and degree of weathering (i.e. decomposition, laterisation, desiccation and hardening). Morphological characteristics as well as the type and content of secondary minerals are other genetic characteristic.

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, the degree to which the soils have been compacted as well as the traffic and environmental conditions (Gidigasu, 1976).

The geotechnical characteristics and field performance of laterite are considerably influenced by the mode of formation (genesis), morphological characteristics, degree of weathering and the chemical and mineralogical composition, all of which can in turn be related to the weathering system determined by the joint effects of the pedogenic factors (parent materials, climate, vegetation, etc) (Dumbleton *et al.*, 1966; Gidigasu, 1976). These factors also influence and are influenced by topography and drainage conditions so that soils having similar mineralogical and geotechnical characteristics can often be associated with particular topographical areas (Dumbleton and Newill, 1962).

2.1.1 Genesis and formation of laterites

The weathering processes which lead to the formation of laterite involve chemical and physical decomposition of the primary rock material into the laterite constituents. The laterite formation process involves the following three stages (Gidigasu, 1976);

1. The first stage is the weathering or decomposition stage. This decomposition involves the physical and chemical weathering of the parent rock by agents. The physical

weathering occurs via agents of thermal destruction- caused by seasonal temperature changes, erosion forces- caused by abrasive action of rock pieces carried by water and wind, and organic agents via mechanical action of plant roots in search of nourishment and those of burrowing animals. The chemical process of the rock weathering through one or more hydrolysis, hydration, oxidation and reduction, carbonation and ionic exchange between the rock minerals and water or gases. The intensity of rock weathering depends upon the action of the agents and the resistance of the rock via its constituent elements.

2. The second stage of the laterite soil forming process involves leaching under drainage conditions of the combined silicate and bases formed during the decomposition stage and further accumulation from outside sources of oxides and hydroxides of sesquioxides e.g. Al_2O_3 and Fe_2O_3. The leaching process of the dissolved primary materials is an important process of the laterite soil formation process because laterite soils would not form if these primary chemical constituents are not leached out (Sherman, 1952; Mohr and Van Baren, 1954). The mechanism of leaching involves the acid dissolution of the host material's lattice, followed by hydrolysis and precipitation of insoluble oxides and sulphates of iron, aluminium and silica under high temperature conditions (Whittington and Muir, 2000).
3. The third stage of the laterization process is the partial and complete dehydration of the sesquioxide rich minerals and secondary minerals. This last stage depends on the extent of physico-chemical weathering, the primary rock forming mineral and the nature of the weathering system determined by the soil forming process (Gidigasu, 1976). The physico-chemical implication of the process has been noted to affect the properties of the laterite soil thus formed. The parent rock material, vegetation and climatic condition, drainage and time of decomposition affect the properties such as

density, specific gravity and decrease in plasticity and loss on ignition (Sherman *et al.,* 1953; Mohr and Van Baren, 1954).

2.1.2 Morphology of laterites

Gidigasu (1976) identified by genesis that there are two major categories of laterite soils namely; Bauxitic (or aluminous) laterites and Ferrugenous laterites. These two are however not easily distinguishable under field conditions and the differences are rather qualitative which is of no much significance. The geotechnical and physical properties of the soils are what is important and are generally determined in the laboratory. The process of laterite soil formation affects much of its morphological properties. The degree of parent rock decomposition, the type and composition of parent rock, degree of leaching and dehydration all have marked effects on the texture, colour and structure of the laterite soil formed. Laterites are known to have reddish brown colours or reddish shades (Gidigasu, 1976) because of the various degrees of hydration of iron, manganese and titanium. Maignien (1966) further reported that the red shades reflect the degree of maturation stating that ferruginous laterite materials seem to change from red to brown with age while aluminous become brighter in colour.

Texturally, laterites range from earthy to rocky materials forming chains of materials starting with fresh rocks and ending with concretionary sesquioxide rich rocks (Gidigasu, 1976). Macro-structurally on the other hand, laterite soils have structures similar to those of the parent rocks. Fine-grained soils may have variable structure unassociated in nature to the parent rock, genesis and the degree of weathering of the rock and the sesquioxide enrichment (Alexander and Cady, 1962; Maignien, 1966). Maignien (1966) further classified the macro-structural patterns of laterite rocks into three:

1. The indurated elements form a continuous coherent skeleton.
2. The indurated elements are free concretions or nodules in earth matrix.

3. The indurated elements cement pre-existing materials.

In essence, the morphological properties of the laterite soils are all related directly (or indirectly) to the laterization process. The parent rock for instance depends on the degree of decomposition and or dehydration while the origin and state at excavation of the laterite soil on the other hand depend on the degree of sesquioxide enrichment and on the dehydration.

2.1.3 Geotechnical properties of laterite soils

Laterite soil is a product of tropical weathering with red, brown or dark brown colour, with or without nodules or concretions and generally (but not exclusively) found below hardened ferruginous crusts or hardpan (Ola, 1983). Laterite soils are known to be expansive depending on the quantity of halloysite and montmorillonite they contain. This property is also a factor of the composition of the parent rocks and on the laterization process.

The engineering properties of laterite soils are those properties relevant to the engineer and are only determined in the laboratory from the soil samples obtained on the field either by methods of disturbed or undisturbed sampling. They are used for the classification of the soils and subsequently for use (or otherwise) in engineering applications e.g. in foundation and highway construction. Gidigasu (1976) identified that the geotechnical properties of laterite soil are influenced by their genesis, degree of weathering, morphology, chemical and mineralogical composition and also on the environmental factors. These factors are responsible for their variability and inhomogeneity. The engineering properties of laterite soils are only determined in the laboratory (Gidigasu, 1976; Ola, 1983) and they are; particle size analysis and grading carried out via sieve analysis, Atterberg limits tests to determine the plasticity of clay soils, moisture-density relationship done via compaction, permeability tests to determine the ease or otherwise of water movements, the strength tests in service done via unconfined compression and triaxial for plastic soils, direct shear tests for

cohesionless soils, consolidation properties to determine its response to modelled foundation load, the California bearing ration, (CBR) tests and so on.

The geotechnical properties of laterites soils were determined from different soil samples by many researchers. Their results further confirmed the variations in properties of the soils being dependent on many factors including the climatic and environmental conditions. Ola 1983; Osinubi, 1998b; Osinubi *et al.,* 2007a,b; Ijimdiya, 2007; Amadi, 2010a,b; Eberemu *et al.,* 2013, have all done in-depth research using laterite soils collected from borrow pits in Shika, Zaria. The liquid limits of these soils were all around 40 %; plastic limits were a little in excess of 20 % having MDD above 1.7 Mg/m^3 corresponding to OMC of about 17.5 %, specific gravity between 2.55 and 2.8 and are generally predominantly clays with above 50 % passing through sieve No.200.

Okunlola *et al.* (2014) worked on laterite soils collected from borrow pits along Ogbomosho-Ibadan road in south-western Nigeria. Their results showed that the soils had average specific gravity of 2.72. Atterberg limits tests conducted showed the liquid limit and plastic limits were averagely 49 % and 27 %, respectively. The soil had a maximum dry density (MDD) of between 1.57 g/cm^3 and 1.87 g/cm^3 corresponding to moisture content of 11 - 16.5 % with CBR values of 17-60 % soaked and 42-74 % unsoaked. Habeeb *et al.* (2012) also collected laterite from Oyo state and investigated the geotechnical properties of the soil for use as subgrade and base materials. 35 % of the soils passed BS No. 200 sieve. The liquid limit was found to be 48% and plastic limit 25 %. MDD was 1.9 Mg/m^3 and OMC 14.3 %. Specific gravity of the laterite was 2.65, CBR unsoaked was 78 %.

In the Niger Delta region of Nigeria, the geotechnical properties of laterite soil were investigated by Ugbe (2011). The soil was predominantly A-2 with fines ranging from 14 to 50 % having very low gravel contents (0 – 6 %) and thus not suitable as base course material.

CBR value was reported to be between 3 and 43 % (soaked condition), MDD 1.7 to 2.14 Mg/m^3, OMC 7.7 % to 18 % and mean specific gravity of 2.62.

2.2 Iron Ore Tailings

Iron ore is being beneficiated around the world to meet the raw material requirements of the iron and steel industries. Iron ore has its own peculiar mineralogical characteristics and for optimum product extraction at any site requires tailoring of the metallurgical treatment and specific beneficiation process selection for use. The choice of beneficiation technique depends on the nature of the gangue and its association with the ore structure. The prime function of beneficiation of iron ore is to improve the content of the finished iron. Beneficiation proceeds mainly from washing, sizing by classification, jigging and then magnetic separation (Mohanty *et al.,* 2010). After beneficiation, the rejected portion of the iron ore may include coarse and fine particulates in the wash water, and these particulates may form slurry known as wet tailings. Ponds are utilized for disposal of tailings.

Iron ore tailings are the remnant of rock mineral debris after the useful metals such as iron are removed from the raw iron ore which goes through the beneficiation process of crushing, screening, grinding, grading, and then re-election, flotation or cyanide while mining (Chen *et al.,* 2012). Tailings contain all other constituents of the ore but the extracted metal, among them heavy metals and other toxic substances that are either added to the tailings in the milling process or available with the ore before that (ICOLD, 2003; Mahmood and Mulligan, 2007). They are usually stacked in the tailings pond of a mine. But piling up tailings not only takes up a lot of arable land, but also consumes the human, financial and material resources to establish and maintain the tailings pond. What's worse, it poses security risks. The tailings storage mismanagement will damage the ecological environment and lead to pollution of soil, sediment, surface and groundwater too. Up till now, the most common methods of utilizing iron ore tailings as resource are recycling element, making it the backfill

material for backfilling mining or the raw material for cement production, producing floor or building bricks, being the filler in road construction and so on (Huang, 2013).

However, due to the high cost of land and also bearing in mind that the deforestation of the areas normally found around iron ore mines for the construction of tailings ponds are protected by statute, it is worthwhile examining the feasibility of minimizing the pondage volumes (Ghose, 1997). Tailings embankments are susceptible to rapid erosion, cutting down and complete breaching (Toland, 1977). The creation of artificial tailings ponds creates environmental problems of air and water pollution, deforestation and has impact on agriculture and forestry (Ghose and Sen, 1999). With the development of economies, more minerals are in demand and mining scales becomes large. If the tailings are not disposed of, the land will be seized, the environment will be polluted, and the useful resources cannot be fully used. Tailings are mainly used in the production of cement, land reclamation, filling, production of architectural glass and building ceramics, production of paving materials and walling materials (Amaratunga and Yaschyshyn, 1997, Yongguang and Xiaolei, 2010). Understanding of the tailings begins with the knowledge of the process, which produced the tailings.

Laboratory characterization of iron-ore tailings or slimes has indicated that they are largely made up of extremely fine materials. More than 60 % of the particulates in such slimes have diameters that are < 20 μm (Das *et al.,* 1992, 1993). Moreover, the silica and alumina content of the tailings is quite high, which requires both beneficiation and agglomeration treatment prior to their use in steel making. The iron ore tailings are also contaminated with parts per million levels of heavy metal ions such as Cu, Pb, Zn, Cr, Sn, Mo and U, as well as lower levels of macronutrients. Many of these potentially toxic elements leach and become pollutants of water (Das *et al.,* 1993).

Itakpe iron ore deposit in Kogi state, Nigeria 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 tonnes 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).

According to Soframine (1987), the Itakpe iron ore deposit in Nigeria has a total estimated reserve of about 182.5 million metric tonnes and consists of mainly 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. Itakpe iron ore processing plant produces a waste material of about 64 % of its capacity (Ajaka, 2009).

Large amounts of toxic contaminants are released to the environment around the globe due to rapid urbanization and industrialization. Among such contaminants are industrial waste and ore tailings that result from worldwide mining activities. The ore is beneficiated by crushing, screening, grinding, washing, classifying jigging, cycloning, processing in magnetic separator (Sen and Ghose, 1997). The rejected portion of the ore after the beneficiation process may include coarse and fine particulate in the wash water and form slurries known as wet tailings. The physical and chemical nature of the tailing slime from beneficiation plant depends on the type of ore, the milling operations used to beneficiate the ore, and the water content in the effluent (Ghose, 1997). In mining operations, during the processing of low-grade ores, significant quantities of wastes or tailings are produced. It has been roughly estimated that for every ton of metal extracted from ores, roughly 2-12 tonnes of overburden (waste) materials are removed.

2.3 Soil Stabilization

The increasing population and development of construction industry requires that geotechnical engineer possess sufficient knowledge and information about the methods of improving surface soils for use in various construction projects. Soil stabilization is the process of improving the physical and engineering properties of a soil to obtain some predetermined targets (Eisazadeh, 2010). This technique is done in order to render the material suitable and satisfactory for use as foundation or subgrade, subbase and base material. The chief aim of stabilizing a soil is to improve the soil strength, bearing capacity and durability under adverse stress conditions i.e. 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; Amu et al., 2011; Portelinha *et al.,* 2012). Soft, compressible soils also termed problem soils because of their ability to reduce in volume with applied pressure cannot carry loads satisfactorily and thus, need to be stabilized so that they can satisfy the purpose intended. McNally (1998) reported that the improvements in engineering properties caused by stabilization can include the following: increases in soil strength (shearing resistance), stiffness (resistance to deformation) and durability (wear resistance), reductions in swelling potential or dispersivity (tendency to deflocculate) of wet clay soils and other desirable characteristics, such as dust proofing and water proofing unsealed roads. Its objectives are: improvement of the strength of the soil and bearing capacity, decreasing permeability and water absorption, and increasing the durability under varying moisture content.

Soil modification essentially involves the improvement of the soil frictional characteristics and the reduction of its plasticity characteristics. This is distinct from soil stabilization, which is the improvement of the strength of the soil (Ovuarume, 2011). As with modification, many kinds of agents are used in stabilization. Soil modification/stabilization

can also be defined as the improvement of the original soil properties to meet specific engineering requirements.

The industrially manufactured additives for modifying soils are lime, cement and bitumen. In view of increasing demand for safe and cost-effective engineering in modern technology, construction materials in their natural forms may not satisfy all technology engineering requirements, hence the necessity for modification of construction materials to enhance their purposes. This explains why effort is being directed to material conversion of industrial wastes and "bio-wastes" to engineering products and materials (Collins and Ciesiellski, 1993). One of the ways of achieving such optimum engineering is to use lime, cement, bitumen, and agricultural and industrial waste such as iron ore tailings; rice husk ash to stabilize soils such as lateritic soils which otherwise will be unworkable and unstable for engineering purposes in their natural form.

Research into new and innovative use of waste material is continually being advanced, particularly concerning the feasibility, environmental suitability and performance of the beneficial reuse of most waste materials. In order to make soil useful and meet foundation engineering design requirements, since the cost of procuring materials that meet specification requirement is increasingly becoming uneconomical, researches have been intensified with the aim of using admixtures/additives to reduce the cost of procuring cement and other modifying agents (Moses *et al.,* 2012; Salahudeen *et al.*, 2014).

Soil stabilization aims at improving soil strength and increasing resistance to softening by water through bonding the soil particles together waterproofing the particles or both (Sherwood, 1993). The easiest and simplest means of stabilizing a soil is by compaction (to bring the particles together into a denser and compact whole via mechanical means) or by drainage (Makusa, 2012). Other methods involve adding binders to the soil in order to improve its strength, durability, particle grading and even workability.

2.3.1 Benefits of soil stabilization

Substantial savings: By choosing to stabilize the existing sub-grade, the costs associated with excavating the existing soil, removing it from the site, and replacing it with suitable materials are eliminated. This can result in substantial savings to the owner (Mukesh and Patel, 2012).

Reduces weather related delays: In areas where climate and weather conditions prevent site work during certain time of the year, soil stabilization may be utilized to treat unstable soils in order to continue site work. This can impact construction schedules in a positive way and translate into cost savings for an owner who does not have to wait for good weather to continue work on the project

Eliminates supply problems: In areas where suitable materials to replace existing materials is in short supply or if the site is in a remote area where aggregate supply is cost-prohibitive to import, soil stabilization becomes a cost effective alternative.

Additional material reduction: In roadway sections or parking areas, the sections of base materials and asphalt paving may be reduced if the existing sub-grade is stabilized in order to create sufficient strengths. This reduction in the sections of base material and asphalt paving can also create cost savings to the owner.

2.3.2 Mechanical stabilization

The most basic form of mechanical stabilisation is compaction, which increases the performance of a natural material. Mechanical method of soil improvement by compaction is the densification of the soil by the application of mechanical energy (Sani, 2012). Mechanical stabilisation of a material is usually achieved by adding a different material in order to improve the grading or decrease the plasticity of the original material. The physical properties of the original material will be changed, but no chemical reaction is involved. For example, a

material rich in fines could be added to a material deficient in fines in order to produce a material nearer to an ideal particle size distribution curve. This will allow the level of density achieved by compaction to be increased and hence improve the stability of the material under traffic. The proportion of material added is usually from 10 to 50 per cent.

Provided suitable materials are found in the vicinity, mechanical stabilisation is usually the most cost-effective process for improving poorly-graded materials. This process is usually used to increase the strength of a poorly-graded granular material up to that of a well-graded granular material. The stiffness and strength will generally be lower than that achieved by chemical stabilisation and would often be insufficient for heavily trafficked pavements. It may also be necessary to add a stabilising agent to improve the final properties of the mixed material.

In the field, hand–operated vibrating plates and motorized vibratory rollers of various sizes are very efficient in compacting sand and gravely soils. Large falling weights have been used to dynamically compact loose granular fills (Markwick, 1944). Fine-grained cohesive soils are compacted in the field by using common compaction equipments like; sheepsfoot rollers, rubber-tyred rollers, etc. The objective of mechanical compaction is the improvement of the engineering properties of the soil mass which include a reduction in settlement due to reduced void ratio, Increase in soil strength and a Reduction in shrinkage (O'Flaherty, 1988).

2.3.3 Chemical stabilization

Chemical stabilization includes the use of admixtures (chemicals and emulsions) as cementing agents, modifiers, water proofing, and water retaining and miscellaneous chemicals to improve the engineering properties of undesirable soils. The behaviour of each of these admixtures differs vastly from the others; each has its particular use and conversely each has its own limitations (Gidigasu, 1976).

The strength gain is achieved via the use of cementitious stabilizers, primarily cement and lime which are the conventional stabilizers, and sometimes waterproofing materials (bitumen) to coat the soil aggregate grains and retard water absorption (Yoder, 1959, Sherwood 1993, Al-Tabbaa and Evans, 2005)

2.3.3.1 Cement stabilization

Any cement can be used for stabilisation, but Ordinary Portland cement is the most widely used throughout the world. The addition of cement to a material, in the presence of moisture, produces hydrated calcium aluminate and silicate gels, which crystallise and bond the material particles together. Most of the strength of a cement-stabilised material comes from the physical strength of the matrix of hydrated cement. A chemical reaction also takes place between the material and lime, which is released as the cement hydrates, leading to a further increase in strength. 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)

Granular materials can be improved by the addition of a small proportion of Portland cement, generally less that 10 per cent. The addition of more than 15 per cent cement usually results in conventional concrete. In general, the strength of the material will steadily increase with a rise in the cement content. This strength increase is approximately 500 to 1000 kPa (UCS strength) for each 1 per cent of cement added (Lay, 1986). The elastic modulus of an unbound natural gravel or crushed rock will be in the range 200-400 MPa. When stabilised, this will increase to a range of approximately 2,000 to 20,000 MPa.

Cement stabilised materials can be mixed in-situ or mixed at a plant and transported to site. To achieve stronger cement bound materials, i.e. greater than about 10 MPa cube strength at 7 days, the materials should generally be plant mixed (DETR, 1998).

One of the main problems with stabilising a material is in mixing of the cement. The particle size of ordinary Portland cement is quite well defined with a range of 0.5-100 microns and a mean of 20 microns (Ingles and Metcalf, 1972). The larger particles of cement never completely hydrate, and it has been found that the same amount of a more finely ground cement will produce higher strengths. Finely ground cements are, however, expensive to produce and it has been suggested (Ingles and Metcalf, 1972) that the larger particles of cement could be replaced with smaller particles of inert filler.

The greater bulk would aid the distribution process so that the same amount of active cement would be available throughout the material. Thus producing an equally effective binder, this could be cheaper than ordinary cement.

The use of cement as a stabiliser is more widespread than lime. This is due to many reasons, but the main factors are likely to be the cost and the higher strengths that are attainable using cement. Other factors include availability, past experience and the more hazardous nature of lime. The price of cement is often similar to that of quicklime or hydrated lime; however cement can be used on a wider range of materials and the strengthening effect of cement is much more than that of an equal amount of lime. Hence either higher strength is possible using an equal amount of cement instead of lime or the same specified strength can be achieved using a lower quantity of cement than lime (Sherwood, 1993).

2.3.3.2 *Mechanism of cement stabilization*

Cement stabilization mechanism is mainly controlled by hydrolysis and hydration. 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 result 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 ordinary Portland Cement (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 aluminium 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).

2.3.4 Admixture stabilization

Results reported by researchers (Ola 1983; Balogun, 1991; Matawal and Tomarin, 1996) show that the conventional modification of expansive soils with lime or cement or both is effective; however the cost of these modifiers is high thereby making the process uneconomical. In various attempts to achieve an economically effective modification of deficient soil, many chemical/agricultural or industrial additives have been mixed with lime or cement or both (Osinubi, *et al*, 2009a, b, 2011; Osinubi and Gadzama, 2009; Osinubi and Muazu, 2010; Moses and Osinubi, 2013; Ochepo and Osinubi, 2013; Yamusa *et al.*, 2013).

2.3.5 Industrial /Agricultural wastes admixtures stabilization

It is worthy to note that most industrial or agricultural wastes possess pozzolanic property that is, having cementitious tendencies on exposure to moisture (O'Flaherty, 1988). Pozzolanas are siliceous and aluminuous 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 cementitious properties (Robert, 1993). A pozzolan is broadly defined as an amorphous or glassy silicon or alumino-silicate material that reacts with calcium hydroxide formed during the hydration of Portland cement in concrete to create additional cementitious material in the form of calcium silicate and calcium silico-aluminate hydrates (Amu *et al.*, 2011). There are mainly two types of pozzolanas namely, the natural pozzolan and the artificial pozzolan. Natural pozzolans are present on the earth surface as diatomaceous earth, volcanic ash, opaline shale, pumicite, and tuff. Natural pozzolans have been used in dam controls and alkali-silica reaction. Artificial pozzolans include coal fly ash (pulverized fuel ash, PFA), ground granulated blast furnace slag, silica fume, and metakaolin (calcined clay). The common feature of all these pozzolans is that they are silicates or alumino silicates that have been converted to amorphous or glass phases in a high temperature furnace or combustion chamber, followed by rapid cooling or quenching under various conditions.

Development has shown the potentials of utilizing agricultural wastes for producing cementitious compounds in conjunction with lime. Many plants, during growing process pick up silica from the ground, into the structure of their leaves, stalks and other parts. Therefore, when such agricultural products are burnt, organic materials which are the largest proportion are broken down and disappear as carbon dioxide, and water vapour. The resulting ash consists mainly of organic residue, mostly silica. When silica is in its reactive form, it can combine with lime to form insoluble cementitious compounds (Smith, 1992).

Several reseachers (Fakiyesi and Osinubi, 1995; 1996; Osinubi, 1997; Sridevi *et al.,* 2005; Mu'azu, 2007; Oyelakin, 2011; Laxmikant *et al.,* 2011; Azige, 2012; Yisa, 2013; Ishola, 2014; Yohanna, 2015) have shown that industrial and agricultural wastes could be used for the stabilization/modification of problematic soils. The materials have been used as admixtures in lime or cement treatment for the improvement of the engineering properties of expansive soils as reported by Osinubi and Toro (1996; 1997) as well as Osinubi and Medubi (1997a, b).

Recent studies have also focused on the use of industrial and agricultural waste as possible admixtures for improving marginal soils (Ferguson, 1993; Osinubi, 2001; Osinubi and Mustapha, 2005; Osinubi and Stephen, 2005, 2006a, b; Osinubi and Eberemu, 2006; Osinubi and Stephen, 2007; Osinubi *et al.,* 2007a, b; Osinubi and Mustapha, 2008; Osinubi *et al.,* 2008a, b; Srirama and Rama, 2008; Osinubi and Ijimdiya, 2008; 2009; Osinubi and Mustapha, 2009; Osinubi *et al.,* 2009a, b; 2010; Amadi, 2010a, b; Osinubi *et al.,* 2011; Osinubi and Oyelakin, 2012).

Roy *et al.* (2007) examined the effects of gold mine tailings at different proportion of gold mine tailing- cement mixtures on problem soils 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. Yisa (2013) investigated the effect of IOT in the stabilization of lateritic soil, while Ishola (2014) studied the potential of IOT as a modifier for lateritic soil. Both results suggest the potential of IOT if admixed with a potent additive (cement or lime) will significantly improve engineering properties of lateritic soil. Also, Osinubi *et al.* (2015) carried out a study on the cement modification of tropical black clay using iron ore tailing as admixture while Etim (2015) studied the potential of lime admixed with IOT in the

stabilization of black cotton soil. Their findings showed significant improvement of the index properties of the black cotton soil.

2.4 Microanalysis of Soil

Scanning electron microscopy (SEM), invented in 1931 by Max Knoll and Ernst Ruska, provides a greater image of specimen using electrons (Hawkes, 1998). In this technique, a beam of electrons is focused vertically on the specimen. When the beam interacts with the specimen in vacuum, electrons and X-rays are emitted from the specimen. The detectors then collect X-rays, primary electrons, and electrons caused by the interaction of primary electrons with the specimen; these are subsequently converted into signals and then transferred to the screen to prepare the final image (Hawkes, 1998). SEM has been widely used to study the nanostructure of soil particles (Lin *et al.,* 2007).

The microscopic structure of fine soils can be used as an index in identifying the type of environmental processes and in estimating their resistance. In observing soil structure on a small scale, some novel methods of investigations in the nanometer range and for particulate analysis have been suggested by Yalamanchili *et al.* (1998). Transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM) are direct methods for particulate imaging at the nanoscale level that provide information such as the dimension, shape, and morphology of particles (Kollensperger *et al.,* 1999).

Transmission electron microscopy (TEM) uses electron emission toward the specimen, similar to SEM; however, in TEM, the emitted electrons pass through the specimen and reach a phosphorous detector to provide a pattern of the specimen's structure (Williams and Carter, 2009). This device has also been employed for imaging soil nanostructure (Citeau *et al.,* 2006). In a study carried out by Shephard *et al.* (1980) on marine clay sediments in North America, nanometer images of this region's soil were prepared by TEM for the evaluation of soil porosity. In addition, they showed that higher-ordered

orientation of soil particles in the nanostructure leads to higher shear strength in comparison with clay sediments with random orientation.

In recent years, atomic force microscopy (AFM) has been used in determining surface topography and studying surface forces. In AFM, a sharp tip connected to a cantilever scans the specimen's surface (Sarid, 1997). In geotechnics, AFM images are frequently used to study the surface morphology of soil nanoparticles, measure the adhesive force between soil particles, and to measure the friction angle between particulate soil particles (Michael, 2002).

2.4.1 Determination of clay fabric by scanning electron microscope

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 provides 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 pore structures changes with stress state, transfer of water and air, temperature, flocculation, long term gravimetric actions and weathering (Li and Zhang, 2009).

Several studies have been undertaken on soil micro porosity structure. Barden and Sides (1970) as well as Sridharan *et al.* (1971) studied inter-aggregate pores and intra-aggregate pores in compacted clays. This type of micro porosity structure was called a "dual-structure" or ''double-structure" by subsequent researchers (e.g., Alonso *et al.,* 1987). Research studies showed that the inter-aggregate pores easily change during soil compaction (Coulon and Bruand, 1989; Penumadu and Dean, 2000; Sivakumar and Wheeler, 2000), consolidation (Delage and Lefebvre, 1984; Griffiths and Joshi, 1989) and drying (Simms and Yanful, 2001; Cuisinier and Laoui, 2004).

2.4.2 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 further 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 the study 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 yielded direct information on the fabric. Photomicrographs were presented indicating various fabric features such as parallel clay orientation. The fabrics formed in the undisturbed and remoulded clays are explained in terms of inter-particle forces and history of the material subsequent to deposition or remoulding. 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.

2.5 Statistical Analysis

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures (such as "variation" among and between groups), developed by R.A. Fisher (Viv *et al.*, 2004). It is a technique for analyzing the way in which the mean of a variable is affected by different types and

combinations of factors and can be used to compare any number of groups or treatments. Analysis of variance (ANOVA) is a particular form of statistical hypothesis testing heavily used in the analysis of experimental data. A statistical hypothesis test is a method of making decisions using data. A test result (calculated from the null hypothesis and the sample) is called statistically significant if it is deemed unlikely to have occurred by chance, assuming the truth of the null hypothesis. A statistically significant result, when a probability (p-value) is less than a threshold (significance level), justifies the rejection of the null hypothesis, but only if priori probability of the null hypothesis is not high.

In the typical application of ANOVA, the null hypothesis is that all groups are simply random samples of the same population. Rejecting the null hypothesis would imply that different treatment results in altered effects. Additionally, it can be used in cases of two sample analysis of variance (ANOVA) and results will be the same as the t-test. Thus, analysis of variance (ANOVA) technique is the best technique when the independent variable has more than two groups. The analysis of variance (ANOVA) considers some basic assumptions on which this test is performed:

2.5.1 Assumptions

Independence of case: Independence of case assumption means that the case of the dependent variable should be independent or the sample should be selected randomly. There should not be any pattern in the selection of the sample.

Normality: Distribution of each group should be normal. The Kolmogorov-Smirnov or the Shapiro-Wilk test may be used to confirm normality of the group.

Homogeneity: Homogeneity means variance between the groups should be the same. Levene's test is used to test the homogeneity between groups. If particular data follows the above

assumptions, then the analysis of variance (ANOVA) is the best technique to compare the means of two populations, or more than two populations.

2.5.2 Types of analysis of variance (ANOVA)

One-way analysis of variance (ANOVA): When we are comparing more than three groups based on one factor variable, then it said to be one way analysis of variance (ANOVA). For example, if we want to compare whether or not the mean output of three workers is the same based on the working hours of the three workers, then it said to be one way analysis of variance (ANOVA).

Two- way analysis of variance (ANOVA): When factor variables are more than two, then it is said to be two-way analysis of variance (ANOVA). For example, based on working condition and working hours, we can compare whether or not the mean output of three workers is the same. In this case, it is said to be two-way analysis of variance (ANOVA).

K-way analysis of variance (ANOVA): When factor variables are k, then it is said to be the k-way of analysis of variance (ANOVA).

2.5.3 Key terms and concepts

Sum of square between groups: The sum of the square between groups is determined by calculating the individual means of the group, then the deviation from the individual mean for each group is taken. Finally, sum all groups after the square of the individual group.

Sum of squares within group: Sum of squares within a group is determined by calculating the grand mean for all groups and then deviation from the individual group. The sum of all groups is done after the square of the deviation is determined.

F –ratio: To calculate the F-ratio, the sum of the squares between groups is divided by the sum of the square within a group.

Degree of freedom: To calculate the degree of freedom between the sums of the squares group, subtract one from the number of groups. The sum of the square within the group's degree of freedom is calculated by subtracting the number of groups from the total observation. BSS df = (g-1) for BSS is between the sum of squares, where g is the group, and df is the degree of freedom. WSS df = (N-g) for WSS within the sum of Squares, where N is the total sample size.

Level of Significance: At a predetermine level of significance (usually at 5%), compare and calculate the value with the critical table value. However, computers can automatically calculate the probability value for F-ratio. If p-value is lesser than the predetermined significance level, then group means will be different. Or, if the p-value is greater than the predetermined significance level, it means that there is no difference between the groups' mean.

2.6 Summary

This chapter attempt to establishing how various additives has been used to improve the geotechnical properties of deficient soils. It is well documented in literature the adequacy of industrially manufactured additives such as cement, lime and bitumen in the stabilization or modification of problematic soils. However, the high cost of these products has induced intensive researched into the use of industrial, Agricultural and domestic waste of their potential use in improving marginal soils.

Various studies showed that the use of these wastes has the propensity of improving the poor soils especially when used as an admixture in the stabilization or modification process. Although, industrial and agricultural waste showed potential of improving problem soils, the manner of application or blending the additives with the poor soils should be closely monitored so as to optimally achieve the set goals.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Lateritic soil

The lateritic soil sample used for this study was collected by method of disturbed sampling from a lateritic soil formation in Shika, Zaria (Longitude 7 °N 45′ E Latitude 11° 15′ N). The soil samples was collected at depths between 1.5 and 2.0 m corresponding to the B - horizon usually characterized by accumulation of material leached from the overlying A – horizon.

The samples was collected in large bags while a sizeable amount was collected and sealed airtight in a polythene bag in order to obtain the natural moisture content immediately upon returning to the laboratory. The soil was transported down to the Soil Mechanics Research Laboratory of the Department of Civil Engineering, Ahmadu Bello University, Zaria, thereafter, the soil samples were air–dried, pulverized and then sieved through several standard sieves for different types of tests with the largest sieve been BS No. 4 sieve (4.76 mm aperture).

3.1.2 Iron ore tailings

The iron ore tailings (IOT) used for this study was collected from National Mining Ore Company in Itakpe, Ajaokuta Local Government Area of Kogi State, geographically located in North Central Nigeria. The company supplies the steel works of Ajaokuta and Aladja with iron ore. The IOT was then passed through British Standard No 200 (0.075 mm aperture) sieve and kept to be mixed with the laterite in the appropriate percentages.

3.1.3 Cement

The ordinary Portland cement (OPC) used for the study was purchased from the open market in Samaru, Zaria.

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 weighing containers were cleaned and weighed to the nearest 0.001 g as M_1 using an electronic weighing balance of 0.001 g accuracy. 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 0.001 g 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 0.001 g 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 Equation 3.1

$$w\ (\%) = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \qquad (3.1)$$

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)

3.2.2 Specific gravity

The determination of specific gravity was carried out according to BS 1377 (1990) test (B) for fine–grained soils. The density bottle and the stopper were weighed to the nearest 0.001 g as 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 is 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 as M_4. The specific gravity was calculated using Equation 3.2

$$G_s = \frac{(M_2 - M_1)}{(M_4 - M_1) - (M_3 - M_2)} \tag{3.2}$$

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.

3.2.3 Cation exchange capacity

The cation exchange capacity (CEC) 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 (0.1N 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 $AgNO^3$) till the leachate became negligible, the soil was tested to drain thoroughly, 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 distillate was collected. The NH_4-borate was titrated with a standard acid 0.1N HCl. The cation exchange capacity (CEC) was calculated using Equation 3.3

$$\text{CEC} = \frac{(\text{Titre} - \text{B}) \times \text{NA}}{\text{Weight of Soil}} \times 100 \qquad (3.3)$$

where:

B = Blank

NA = Normality of acid

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

3.2.4 Batch equilibrium absorption

The procedures adopted for Batch Equilibrium Adsorption Test (BEAT) was in accordance with that described by Shackelford and Daniel (1991). Batch equilibrium tests were performed with lateritic soil - cement / IOT 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-IOT/cement mixtures (30 g dry weight) in 1:4 mixing ratio. The soil-cement / 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 Equation 3.4

$$C_s = \frac{(C_i - C_f) \times V}{M_s} \quad (3.4)$$

where:

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

C_i = Initial concentration of distil water (mg/l)

C_f = Equilibrium concentration of solute (mg/l)

V = Volume of distil water used (cm^3)

M_s = Mass of dry soil (g)

3.2.5 Particle size distribution

Particle size analysis tests were conducted for the natural and treated soil sample viz; wet sieving and dry sieving.

3.2.5.1 Wet sieving

The particle size analysis was carried out in accordance with BS 1377(1990) Part 2. 200 g of the soil sample was weighed, wet sieved to remove clay and silt particles using BS No. 200 (0.075 mm) sieve under tap water. Washing was done carefully to avoid damage to the sieves. After washing, the sample was dried in an oven set to 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 and then shaken 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 of percentage passing against sieve sizes.

3.2.5.2 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. 40 (425 μm aperture). The dry sample was then mixed 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.

3.2.6 Atterberg limits

The Atterberg limit tests (after Albert Atterberg) include the determination of the liquid limits, plastic limits and the plasticity index for the natural soil. They were also conducted in accordance with Test 1(A) BS 1377 (1990) Part 2.

3.2.6.1 Liquid limit

The soil sample for liquid limit (LL) was air dried and 200 g of the material sieved through BS No. 40 sieve (425 μm apertures) was obtained and thoroughly mixed with water to form a homogeneous paste on a flat glass plate. A portion of the soil/water mixture was then placed in the cup of the Casagrande apparatus, levelled 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 came 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. 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.

3.2.6.2 Plastic limit

A portion of the soil used for the liquid limit test was retained for the determination of plastic limit (PL). The ball of the soil 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.

3.2.6.3 Plasticity index

The plasticity index (PI) of the soil is the difference between the liquid limit (LL) of the soil and the corresponding plastic limit (PL). The plasticity index was calculated as:

$$PI = LL - PL \tag{3.5}$$

where:

PI =Plasticity Index (%)

LL =Liquid Limit (%)

PL = Plastic Limit (%)

3.2.6.4 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 levelled 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 Equation 3.6

$$\text{linear shrinkage}(\%) = \frac{(\text{change in length})}{(\text{original length})} \times 100 \qquad (3.6)$$

3.2.7 Compaction characteristics

3.2.7.1 Maximum dry density

The compaction tests were carried out for the natural soil and the stabilized soils (in different percentages of admixtures); all according to BS 1377 (1990) Part 4, using the British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) energies. 3000 g of dry soil sample was weighed and mixed thoroughly with the varying percentage of additives. Using varying percentages of water content at an increment of 8 % equivalent added for every compaction.

In the British Standard light (BSL), soil samples were compacted in three (3) layers, with each layer rammed 27 blows using a 2.5 kg rammer dropping from a height of 304.8 mm above the soil. The blows were distributed uniformly over the surface of each layer. The

collar was then removed and the soils were levelled to the brim of the mould with a straight edge. The mould and the compacted soil were weighed. Two representative samples (one from the top and the other from the bottom) were then taken from the compacted soil for the determination of moisture content. The whole soil sample was removed from the mould and placed on a large mixing tray; another 8 % water equivalent was added to the sample and mixed properly. The compaction was repeated using the same number of blows and layers as described above. Successive increments of 8 % water equivalents were added until when reduction in weight of the mould and the soil sample was noticed. At least two more compactions were carried out after the peak weight of the mould and the compacted soil sample was obtained.

In the West African Standard (WAS) compaction test the same procedure was adopted but a 4.5 kg rammer was used on 5 layers with each layer receiving 10 blows from a rammer dropping from a height of 450.20 mm. On the other hand, the British Standard heavy (BSH) compaction involved the same procedure adopted for WAS compaction except that each of the 5 layers received 27 blows. After determining the moisture content for every water increment, the results were plotted. Smooth curves were drawn through the resulting points and the positions of optimum moisture content and the maximum dry density were determined on the graphs. The bulk density was given by Equation 3.7

$$\rho_b = \frac{M_S}{V_s} \tag{3.7}$$

where:

ρ_b = Bulk density (Mg/m³)

M_s = Mass of compacted soil (Mg)

V_s = Volume of Mould (m³)

The dry unit weight was determined using the expression

$$\rho_d = \frac{\rho_b}{1-w} \quad (3.8)$$

where:

ρ_d = Dry unit weight (Mg/m³)

ρ_b = Bulk density (Mg/m³)

w = Optimum moisture content (%).

3.2.7.2 Optimum moisture content

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

3.2.8 Strength characteristics

3.2.8.1 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 and 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, 14 days and then 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 using Equation 3.9

$$\delta = \frac{[R \times C_r \times (100 - E\,\%) \times 1000 kN/m^2]}{100 \times A_0} \quad (3.9)$$

where:

$$E\ (\%) = \frac{v}{L_0} \quad (3.10)$$

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

3.2.8.2 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 OPC/IOT stabilized 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.

5000 g of the soil sample/soil-stabilizer sample were mixed at their respective optimum moisture contents in 2360 cm^3 BS mould, for each of BSL, WAS and BSH compaction energy levels. For BSL, the compaction was in three layers each receiving 62 blows from the 2500 g rammer; for the WAS, the samples were compacted in five layers with

25 blows from the 4500 g rammer and the BSH, the sample received 62 blows in five layers from the 4500 g 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 and 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 Equation 3.11

$$CBR = \frac{Measure\ Load}{Standard\ Load} \times 100 \qquad (3.11)$$

where: standard load = 13.24 kN of 2.5mm penetration

= 19.96 kN of 5.0mm penetration

3.2.9 Deformation properties

3.2.9.1 Elastic modulus

The term ‘elastic modulus’ is defined as the ratio of stress to strain and is a measure of the material’s stiffness properties. In a pavement engineering context, one of the most fundamental engineering properties of any material is the elastic modulus. In addition to the

modulus of a material, it is also important to know its strength because a material may be very stiff, but not very strong and could crack or break under heavy traffic (DFID, 2000). The modulus of elasticity of a cemented material can be measured by several different methods including: *dynamically* (E_d) using electrodynamic excitation of long beams of 150 mm section or *statically* (E_s) by loading 150mm diameter cylinders fitted with extensiometers. Croney and Croney (1998) reports that comparative studies have consistently shown the dynamic modulus to be higher than the static value.

Materials cemented with pozzolanic stabilisers such as lime and cement, perform in a more elastic, semi-brittle manner under traffic than unbound materials. Ideally, knowledge of a material's stiffness modulus and shear strength are required to determine an appropriate thickness for the overlying pavement layers (DFID, 2000). The number of factors involved in knowing these variables is high, for example the shear strength will depend on factors including the effective stress which is dependent on the stress history, etc. To simplify matters, index tests are often used. Historically, the CBR has been used but it is now often thought to be useful only for modified materials where the strength of the materials measured in the CBR test would not exceed 100 per cent. The Unconfined Compressive Strength test is considered a more useful guide to the elastic modulus and many correlations exist, for example TRH13 (CSRA, 1986) and (Austroads, 1992).

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 wax-cured for 7 days and de-waxed top and bottom before being soaked for another 7 days to the UCS of the specimen cured for 14 days using Equation 3.12.

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

3.2.11 Microanalysis

The procedures adopted for micro analysis was in accordance with that described by Kozłowski *et al.* (2011). The scanning electron microscope (SEM) observations were carried out on air-dried samples of 8 - 10 mm in diameter. Such a sample preparation in the case of soils in which contacts between structural units are stable lead to practically no microstructural changes during drying .The samples were broken and covered by a layer of gold of approximately 40 nm to prevent electrisation. The observation of the surface of the fracture was made by scanning electron microscope by applying voltage of 15 kV. As a rule, only surfaces parallel to stratification were examined. The photographs were taken at two magnifications: x4800 and x5300. The lesser magnification images was used to determine the quantitative pore space parameters, while the x5300 magnification images made it possible to characterize the microstructure qualitatively, among other things to determine the types of contacts. The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens.

3.2.11.1 Sample preparation and launching

Soil sample sieved through BS No 4 and compacted at optimum moisture content using British standard light (BSL) compaction, cured for seven (7) and twenty eight (28) days respectively. The sample was sliced prior to testing. Specimens were mounted and secured onto the stage which is controlled by a goniometer. The SEM generated a 2-dimensional image which displays spatial variations in their properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnifications ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm).

Essential components of all SEM include the following: Electron Source (‘‘Gun’’); Electron Lenses; Sample Stage; Detectors for all signals of interest.

3.2.11.2 Electron column

The electron column is where the electron beam was generated under vacuum, focused to a small diameter, and scanned across the surface of a specimen by electromagnetic deflection coils. The lower portion of the column is called the specimen chamber (Cheney, 2009). The secondary electron detector is located above the sample stage inside the specimen chamber. The manual stage controls are found on the front side of the specimen chamber and allow for x-y-z movement, 360 rotation and 90 tilt however only the tilt cannot be controlled through the computer system thus manual controls was used to manipulate the orientation of the sample inside the sample chamber. Components of electron Column are as follows; Electron gun, Condenser Lenses, Apertures, Scanning System and Specimen Chamber.

3.2.11.3 Vacuum system

A vacuum system was used to provide a controlled electron beam required for the electronic column under vacuum at a pressure of at least 5×10^{-5} Torr. A high vacuum pressure was required for a variety of reasons. First, the current that passes through the filament causes the filament to reach temperatures around 2700K (Lyman *et al*, 1990). A hot tungsten filament oxidize and burn out in the presence of air at atmospheric pressure. Secondly, the ability of the column optics to operate properly requires a fairly clean, dust-free environment. Third, air particles and dust inside the column can interfere and block the electrons before the ever reach the specimen in the sample chamber (Postek *et al*., 1980). In order to provide adequate vacuum pressure inside the column, a vacuum system consisting of two or more pumps is typically present. Separate pumps were used because one pump isn’t really capable of doing all the work but, in conjunction they provided a good vacuum

pressure relatively quickly and efficiently. A majority of the initial pumping was done by the action of a mechanical pump often called a roughing pump. The roughing pump operates first during the pump down process and has excellent efficiency above 10^{-2} Torr.

3.2.11.4 Electron beam specimen interactions

Scanning electron microscope (SEM) visual inspection of the surface of a material utilizes signals of two types, secondary and backscattered electrons. Secondary and backscattered electrons are constantly being produced from the surface of the specimen while under the electron beam however they are a result of two separate types of interaction. Secondary electrons which resulted from the inelastic collision and scattering of incident electrons with specimen electrons. They are generally characterized by possessing energies of less than 50 eV (Postek *et al.,* 1980). They are used to reveal the surface structure of a material with a resolution of ~10 nm or better. Backscattered electrons are a result of an elastic collision and scattering event between incident electrons and specimen nuclei or electrons. Backscattered electrons was generated further from the surface of the material to resolve topographical contrast and atomic number contrast with a resolution of >1 micron. While there are several types of signals that are generated from a specimen under an electron beam the X-ray signal is typically the only signal that is used for scanning electron microscopy. The X-ray signal is a result of recombination interactions between free electrons and positive electron holes that are generated within the material. The X-ray signal can originate from further down into the surface of the specimen surface and allows for determination of elemental composition through energy dispersive X-ray spectroscopy (EDS) analysis of characteristic X-ray signals.

3.2.11.5 Scanning electron microscopy images

Scanning electron microscope images of three-dimensional objects were interpreted by electron lense. The purpose of the electron lenses was to create a small, focused electron probe on the specimen. SEM generate an electron beam at the specimen surface with spot size less than 10 nm in diameter while still carrying sufficient current to form acceptable image. Typically the electron beam is defined by probe diameter (d) in the range of 1 nm to 1 μm, probe current (i) – pA to μA; and probe convergence (α) – 10^{-4} to 10^{-2} radians. Images in the electron beam were focused into a fine probe, which was scanned across the surface of the specimen with the help of scanning coils. Each point on the specimen that was struck by the accelerated electrons emits signal in the form of electromagnetic radiation. Selected portions of this radiation, usually secondary (SE) and/or backscattered electrons (BSE), were collected by a detector and the resulting signal was amplified and displayed on a TV screen or computer monitor.

*3.2.11.6 Lenses in the s*canning electron microscope

The purpose of the electron lenses was to produce a convergent electron beam with desired crossover diameter. The lenses are metal cylinders with cylindrical hole, which operate in vacuum. Inside the lenses magnetic field was generated, which in turn was varied to focus or defocus the electron beam passing through the hole of the lens. SEM employs one to three condenser lenses to de-magnify the electron-beam crossover diameter in the electron gun to a smaller size. The first and second condenser lenses control the amount of demagnification. Usually in the microscopes there is a single control labelled, “spot size”, “condenser”, or “resolution”. The design of the lenses often incorporates space for the scanning coils, the stigmator, and the beam limiting aperture.

3.2.15.7 Interaction volume

The concept of interaction volume of the primary beam electrons and the sampling volume of the emitted secondary radiation are important both in interpretation of SEM images and in the proper application of quantitative X-ray microanalysis. The image details and resolution in the SEM were determined not by the size of the electron probe by itself but rather by the size and characteristics of the interaction volume. When the accelerated beam electrons strike a specimen they penetrate inside it to depths of about 1 μm and interact both elastically and inelastically with the solid, forming a limiting interaction volume from which various types of radiation emerge, characteristic and brehmsstrahlung X-rays, and cathode luminescence in some materials. The combined effect of elastic and inelastic scattering controls the penetration of the electron beam into the solid. The resulting region over which the incident electrons interact with the sample is known as interaction volume. The interaction volume has several important characteristics, which determine the nature of imaging in the SEM. The energy deposition rate varies rapidly throughout the interaction volume, being greatest near the beam impact point. The interaction volume has a distinct shape.

3.2.11.8 Image formation

The SEM image is a 2D intensity map in the analogue or digital domain. Each image pixel on the display corresponds to a point on the sample, which is proportional to the signal intensity captured by the detector at each specific point. The image was generated and displayed electronically. The images in the SEM are formed by electronic synthesis, no optical transformation takes place, and no real of virtual optical images are produced in the SEM. In an analog scanning system, the beam is moved continuously; with a rapid scan along the X-axis (line scan) supplemented by a stepwise slow scan along the Y-axis at predefined number of lines. The time for scanning a single line multiplied by the number of lines in a

frame gives the frame time. In digital scanning systems, only discrete beam locations are allowed. The beam was positioned in a particular location remains there for a fixed time, called dwell time, and then it was then moved to the next point. When the beam is focused on the specimen an analog signal intensity was measured by the detector. The voltage signal produced by the detector's amplifier is digitized and stored as discrete numerical value in the corresponding computer registry. The digital image is viewed by converting the numerical values stored in the computer memory into an analogue signal for display on a monitor.

3.2.11.9 *Magnification in s*canning electron microscope

Magnification was achieved by scanning an area on the specimen, which is smaller than the display. Increase or decrease in magnification was achieved by respectively reducing or increasing the length of the scan on the specimen. For accurate magnification measurements a calibration was necessary. Magnification in the SEM depends only on the excitation of the scan coils and not on the excitation of the objective lens, which determines the focus.

3.3 Statistical Analysis

The methods of analysis used in this research are:

1. Graphical method using Microsoft excel software package.
2. Two-way analysis of variance (ANOVA) without replication using the Microsoft excel software package.
3 Regression analysis using Microsoft Excel software package

3.3.1 Graphical method using microsoft Excel Software Package

In the Graphical method using Microsoft Excel software package, graphs were used to show the relationship between two quantities. An independent variable usually plotted on

the X-axis and a dependant variable on the Y- axis. The graphs were plotted using the Microsoft excel package.

3.3.2 Two - way analysis of variance (ANOVA) without replication using the Microsoft Excel software package

In this method, the Microsoft Excel software package was used to analyze the results of the test carried out on the soil-cement-IOT mixtures based on the two - way analysis of variance (ANOVA) without replication. The aim of the analysis was to find out if there was any significant effect of the additives on the various lateritic soil – cement – iron ore tailings mixtures.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Properties of Materials Used in the Study

4.1.1 Index properties of the natural soil

The preliminary index properties tests conducted on the natural lateritic soil in accordance with BS1377 (1990) showed that the soil is fine-grained, with a natural moisture content of 19.4 %. A study of the geological map of Nigeria after Akintola (1982) and the soil map of Nigeria after Areola (1982) reveals that the soil sample belongs to the group of ferruginous tropical soils derived from acid igneous and metamorphic rocks. X-ray diffraction test after Osinubi (1998b) revealed the soils within the study area were previously found to have kaolinite as the predominant clay minerals.

The summary of these properties are shown in Table 4.1. The particle size distribution curve is shown in Figure 4.1. The soil is reddish brown in colour with liquid limit of 44.7 %, plastic limit of 22.5 % and plasticity index of 22.2 %. The soil is classified as CL soil in the Unified Soil Classification System, USCS (ASTM, 1992) or A-7-6(14) according to AASHTO soil classification system (AASHTO, 1986). The natural soil also has linear shrinkage of 8.1 % and specific gravity of 2.52.

The soaked California bearing ratio (CBR) values of the natural soil for the British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) compactive efforts are 5 %, 6 % and 8 %, respectively, and unconfined compressive strength (UCS) for BSL, WAS and BSH energy levels are 264 kN/m^2, 565.4 kN/m^2 and 875.5 kN/m^2, respectively.

Based on the above findings, the soil falls below the standard recommendation for most geotechnical construction works especially for sub-base and base courses in highway construction (Butcher and Sailie, 1984; Osinubi and Medubi, 1997a, b). Detailed test results are shown in Tables A1– A48 in the Appendix A.

Table 4.1: Properties of the natural soil

Property	Quantity
Percentage passing No. 200 sieve	67.9
Natural moisture content (%)	19.4
Liquid limit (%)	44.7
Plastic limit (%)	22.5
Plasticity index (%)	22.2
Linear shrinkage (%)	8.1
Specific gravity	2.52
AASHTO classification	A-7-6(14)
USCS	CL
Maximum Dry Density (Mg/m^3)	
British Standard light	1.61
West African Standard	1.67
British Standard heavy	1.77
Optimum moisture content (%)	
British Standard light	22.5
West African Standard	21.0
British Standard heavy	15.3
Unconfined Compressive Strength (kN/m^2)	
British Standard light	264.0
West African Standard	565.4
British Standard heavy	875.5
California Bearing Ratio (Unsoaked) (%)	
British Standard light	10
West African Standard	14
British Standard heavy	17
California Bearing Ratio (24 hours soaking) (%)	
British Standard light	5
West African Standard	6
British Standard heavy	8
Colour	Reddish Brown

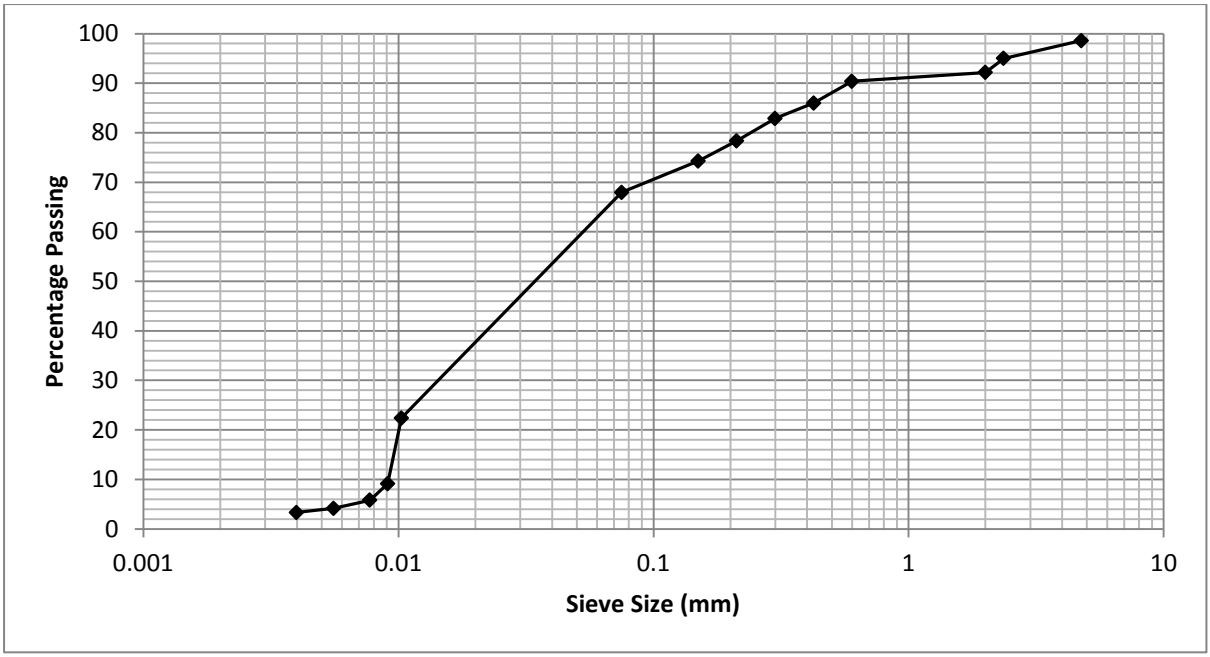


Figure 4. 1: Particle size distribution curve for the natural soil

4.1.2 Oxides composition of materials used for the study

The oxide composition of ordinary Portland cement (OPC) after Czernin (1962), and that of the Itakpe iron ore tailings determined using method of X-Ray Fluorescence (Nuclear Energy Test) after Ishola (2014) is shown in Table 4.2. The little amount of CaO in IOT (0.607%) to be used for the stabilization process was supplemented by the calcium oxide present in OPC (63%). The higher silicon oxide content in IOT also aided those in OPC to provide the required oxides needed for stabilization. Cement and IOT would therefore act together to modify and stabilize the natural soil.

Table 4.2 .Chemical compositions of ordinary Portland cement and iron ore tailings.

Oxide	Composition by weight (%)	
	*Ordinary Portland Cement	**Iron ore tailings
Lime (CaO)	63.0	0.607
Silica (SiO_2)	20.0	45.64
Alumina (Al_2O_3)	6.0	3.36
Alkali (Na_2O)	1.0	0.405
Alkali (K_2O)	-	0.607
Sulphur oxide ($S0_3$)	2.0	-
Tin oxide(TiO_2)	-	0.24
Manganese oxide(MnO)	-	0.067
Iron oxide (Fe_2O_3)	3.0	47.7
MgO	-	0.393
Loss on Ignition	2.0	3.0

*Czernin (1962)
**Ishola (2014)

According to Yohanna (2015), iron ore tailings is classified as Class F pozzolana in accordance with the properties given in Table 4.3

Table 4.3: 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

Source: ASTM (2013)

4.2 Effect of Iron Ore Tailings on Ordinary Portland Cement Stabilization of Lateritic Soil

4.2.1 Specific gravity

The effect of iron ore tailings on specific gravity of soil-cement mixtures is shown in Figure 4.2. The results obtained show an increase in the specific gravity values with increasing percentage of the additives (cement and iron ore tailings). The specific gravity of IOT obtained was within the range reported by other researchers (Mittal and Morgenstern, 1975; Crowder *et al.*, 2000; Garand *et al.*, 2000; Haile *et al.*, 2000; Qiu and Sego, 2001; Demers and Haile, 2003). The value of specific gravity of the soil increased from 2.52 for the natural soil to 2.72 at 0% cement /10 % IOT and 2.81 at 8 % cement / 10 % IOT blend. Similar trend of increase was observed for the various percentages of additives in the lateritic soil – cement – IOT mixtures considered. The increase in the specific gravity of the soil – cement mixture

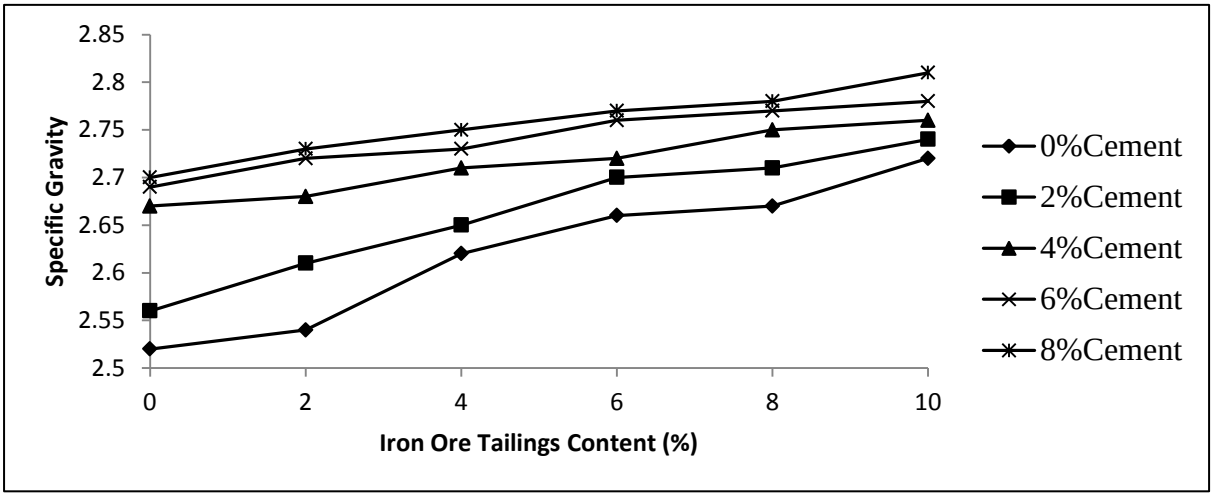


Figure 4.2: Variation of specific gravity of soil – cement mixtures with iron ore tailings content.

with iron ore tailings content could be as a result of the high specific gravity of the additives (cement 3.11 and IOT 3.31) replacing the soil with low specific gravity of 2.52. A similar

trend was reported by Etim (2015) and Yohanna (2015). Detailed test results are shown in Tables A2 – A4 in the Appendix A.

The two – way analysis of variance (ANOVA) test on specific gravity results summarized in Table 4.4 shows that the effects of cement and IOT were statistically significant, with cement having a more pronounced effect. Detailed test results are shown in Table A49 in the Appendix A.

Table 4.4: Two-way analysis of variance result for specific gravity of lateritic soil- cement-iron ore tailings mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Specific Gravity	Cement	4	40.316	2.647E-08	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	26.940	3.068E-09	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.2 Cation exchange capacity

The variation of cation exchange capacity (CEC) of lateritic soil – cement mixture with iron ore tailings content is shown in Figure 4.3. The CEC values for cement and IOT are 6.5 and 18.9 Cmol/kg, respectively. Generally, the CEC of soil – cement mixtures decreased with higher IOT content. The value decreased from 39.6 Cmol/kg for the natural soil to a value of 27.5 Cmol/kg at 0 % Cement / 10 % IOT treatment. The recorded decrease in CEC could be as a result of the increase in pH of the lateritic soil by cement that had a higher calcium hydroxide content which supplied free Ca^{2+} required for the cation exchange between the clay mineral particles (Akinmade, 2008). The decrease in CEC may also be due to the decrease in the clay size fraction of the soil (Warrick, 2002; Salahedin, 2013; Osinubi *et al.,* 2015). Detailed test results are shown Table A5 in the Appendix A.

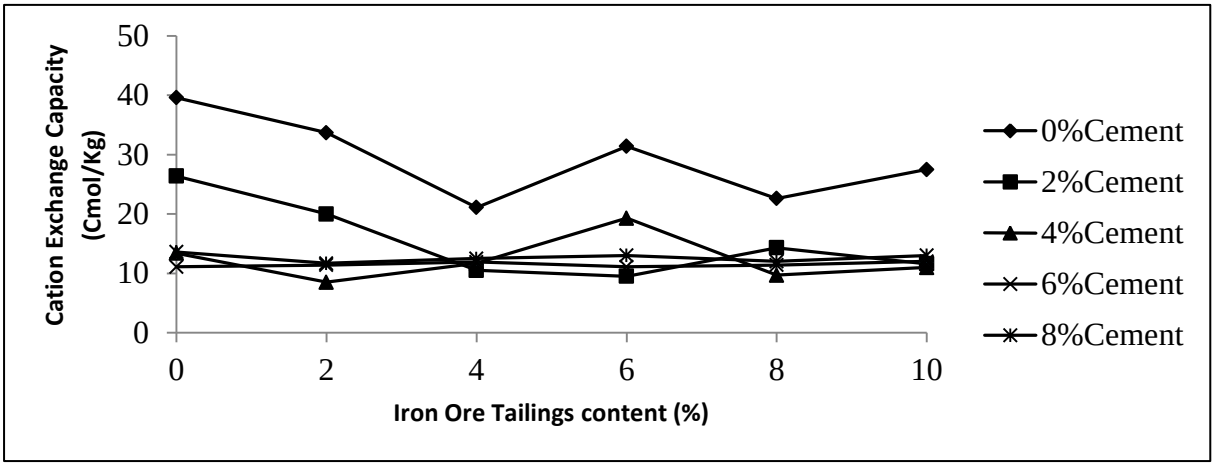


Figure 4.3: Variation of cation exchange capacity of lateritic soil – cement mixtures with iron ore tailings content.

The result of the two – way analysis of variance (ANOVA) performed on the CEC results (see Table 4.5) shows that cement has a significant effect on the cation exchange capacity of the mixture, while the effect of iron ore tailings was not statistically significant. Detailed test results are shown in Tables A50 in the Appendix A.

Table 4.5: Two-way analysis of variance result for cation exchange capacity of lateritic soil-cement-iron ore tailings mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
CEC	Cement	4	18.63	1.60E-06	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	1.994	0.123533	2.711	$F_{CAL}<F_{CRIT}$, No Significant effect

4.2.3 Particle size distribution

4.2.3.1 Wet sieving

The particle size distribution curves obtained from the hydrometer test conducted on the lateritic soil - cement - iron ore tailings mixtures are shown in Figures 4.4 – 4.8. The results show that the percentage of fines reduced with increase in IOT content from a value of 68.0 % for the natural soil to 65.6 % for 0 % cement / 6 % IOT treatment (see Figure 4.4) and

thereafter the percentage of fines increased with higher IOT content. Similar trends were also observed for the various cement contents considered (see Figures 4.5 – 4.8). The initial reduction in fines fraction with increase in IOT content may not be unconnected to the flocculation and agglomeration of the lateritic soil - cement mixtures and this enabled the clay fraction to form larger soil sizes (Hopkins *et al.*, 2002; Akinmade, 2008; Oyelakin, 2011; Jung and Bobet, 2008; Al karagooly, 2012; Portelinha *et al.*, 2012). The aggregation or clusters of clay minerals and clay-sized mineral fragments formed due to ion exchange at the surface of the soil particles resulted in more stable silt-sand-like structures. The lateritic soil-cement mixture became more granular with up to 6 % IOT content. These findings are in agreement with those reported by Winterkorn and Chandrasekharen (1951), Clare and O'Reilly (1960) and Amadi (2010a).

The initial decrease in fine fraction with increase in IOT content (see Figures 4.4- 4.8) could also be due to the formation of products of pozzolanic reaction between the $Ca(OH)_2$ from lime and silicate from both clay fraction and the IOT (Akinmade, 2008; Oyelakin, 2011). The subsequent increase in fines fraction to about 76.6 % at 10% IOT content could be assumed to be due to excess IOT that was not used in the agglomeration process and hence the lateritic soil-IOT mixture became finer. Detailed test results are shown in Tables A6 in the Appendix A.

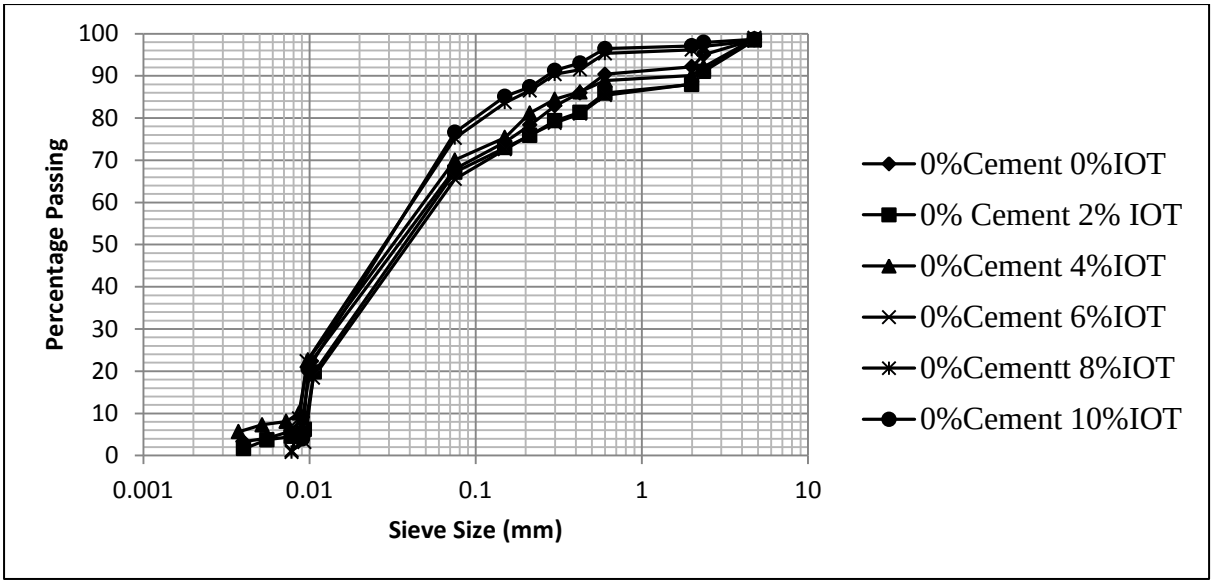


Figure 4.4: Particle size distribution curves for lateritic soil –0 % cement – iron ore tailings mixtures

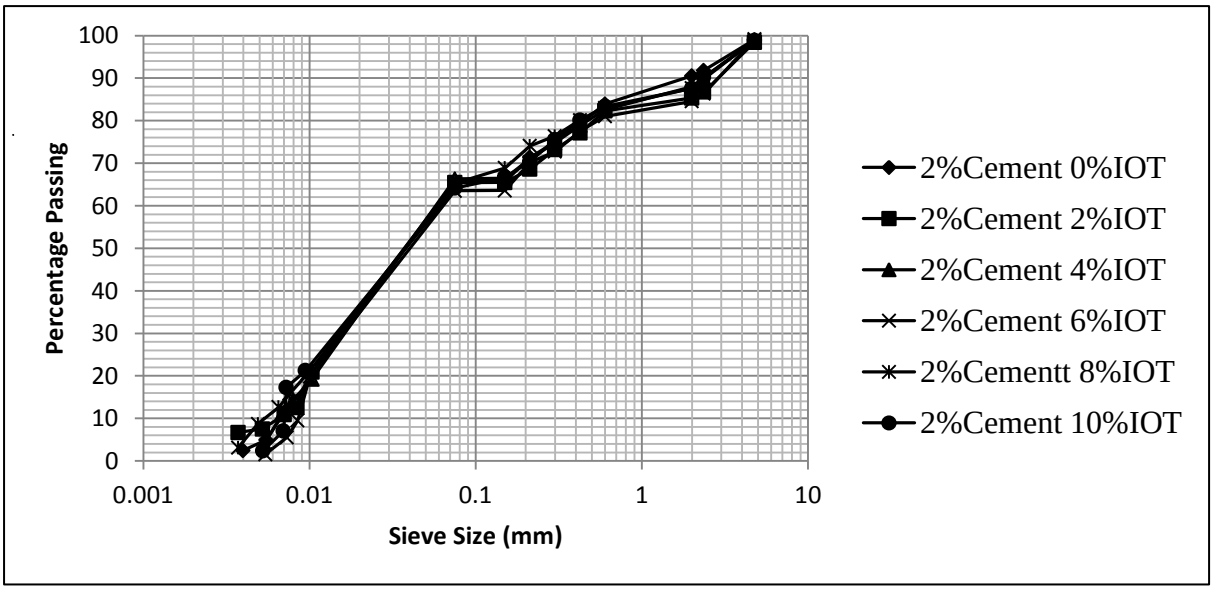


Figure 4.5: Particle size distribution curves for lateritic soil - 2 % cement – iron ore tailings mixtures.

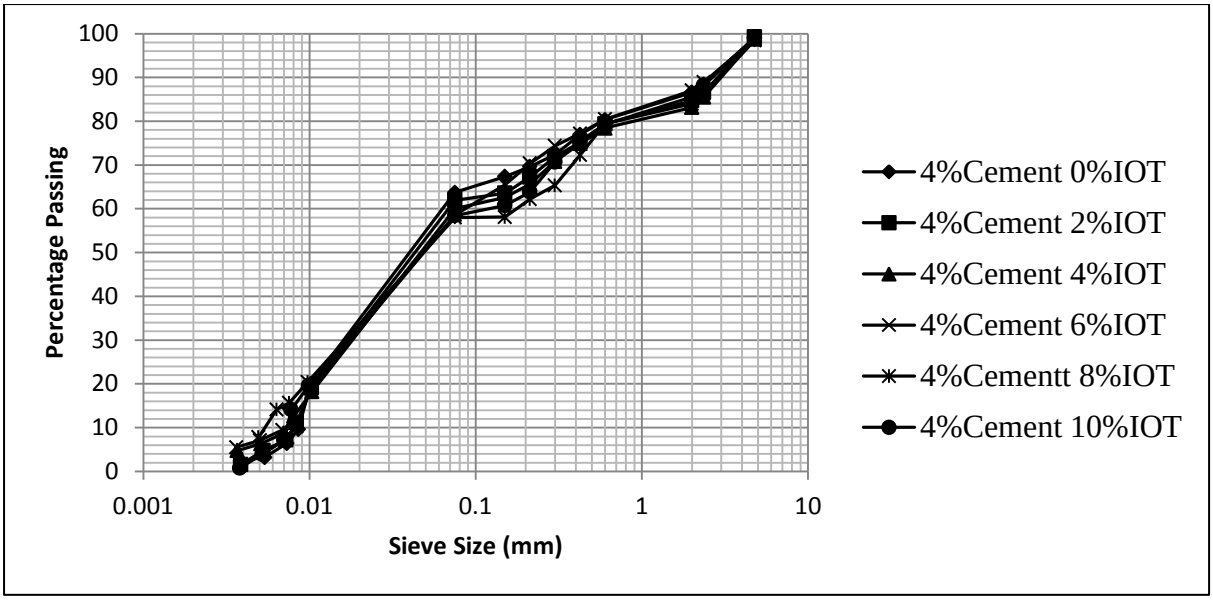


Figure 4.6: Particle size distribution curves lateritic soil - 4 % cement – iron ore tailings mixtures

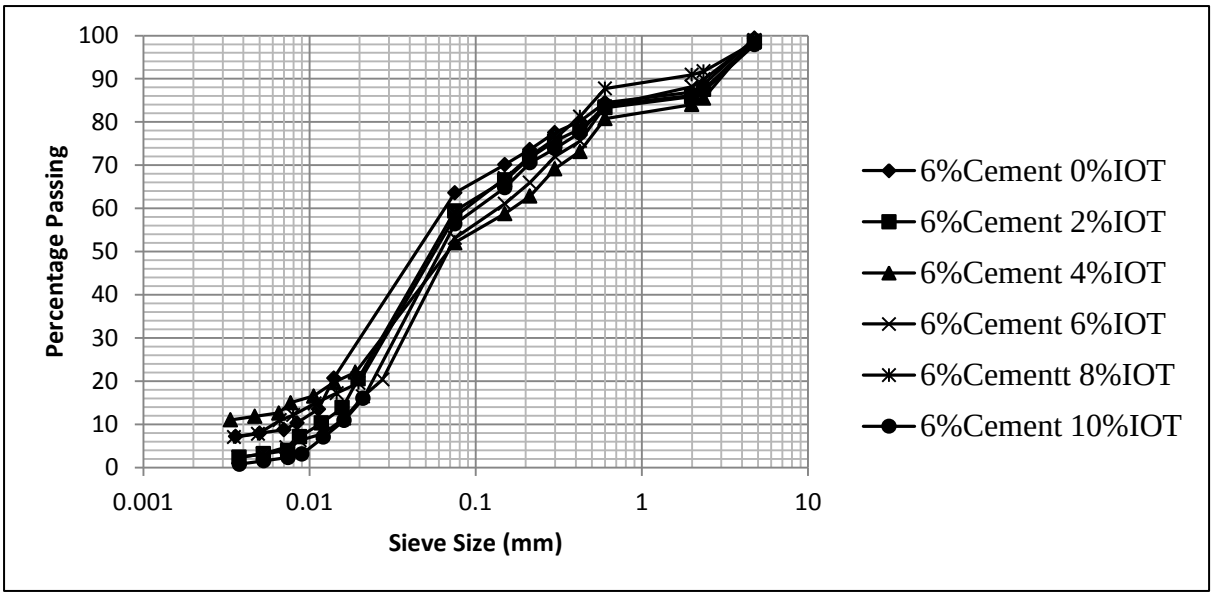


Figure 4.7: Particle size distribution curves for lateritic soil - 6 % cement – iron ore tailings mixtures.

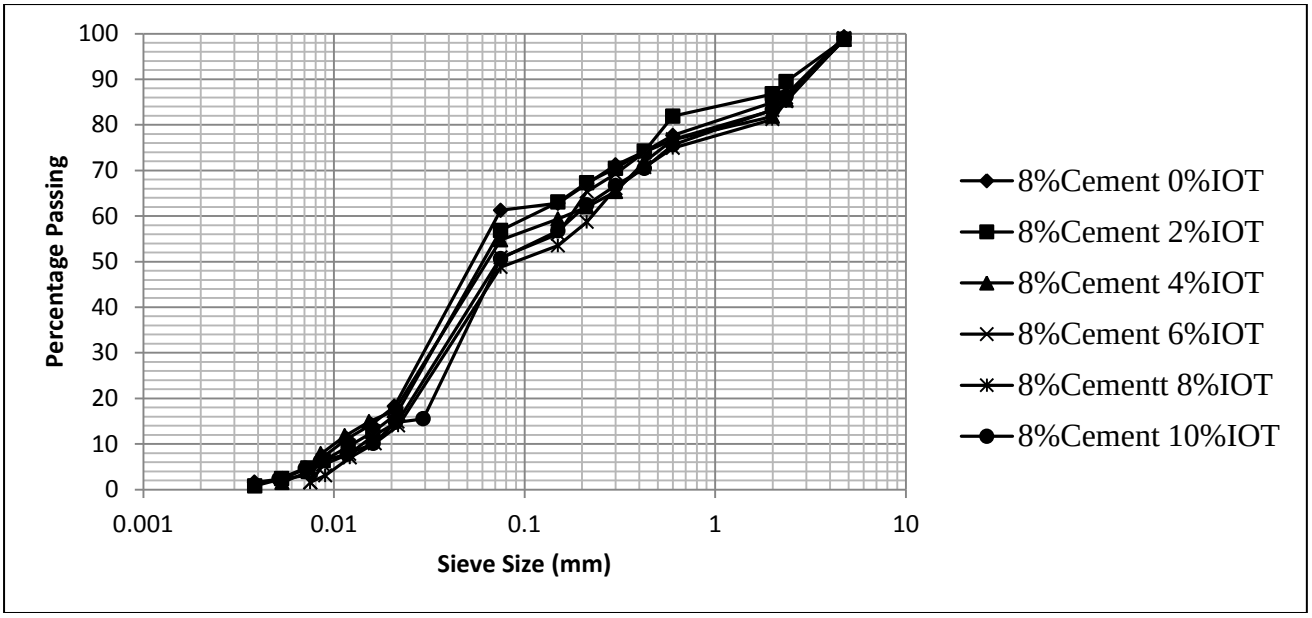


Figure 4.8: Particle size distribution curves for lateritic soil - 8 % cement – iron ore tailings mixtures.

4.2.3.2 Dry sieving

The dry sieve was carried out using the optimum moisture contents for the various soil – cement – iron ore tailings mixtures recorded for the three compactive efforts considered.

Using optimum moisture content from British Standard light compaction: The results of the particle size distribution curves obtained from the sieve analysis test conducted on the lateritic soil-cement- IOT mixtures suggest that the gradation characteristics of the lateritic soil was enhanced. It can be inferred from the results that the percentage of fines reduced from the 7.6 % for the natural soil to 3.7 % at 0 % cement/ 6 % IOT, and 1.4 % at 4 % cement/ 4 % IOT. Similar trends were observed for the various cement - IOT contents considered. The reduction in the amount of clay sized particles was as a result of flocculation and agglomeration of the soil – cement – IOT mixture. With increase in cement and IOT contents, the quantity of free silt and clay progressively reduced and coarser material was formed (see Figures 4.9 – 4.13). This is in agreement with the findings reported by Kedzi

(1979) and Amadi (2010a). The increase in the quantity of coarser particles could be attributed to moisture availability for pozzolanic reaction and hydration of free lime and silica in the additives. The high moulding moisture content associated with BSL compaction energy level facilitated the agglomeration of the soil particles to form macro structural particles. Water content plays an important role in soil - mine tailings mixtures (Ramesh *et al.*, 2013). The initial reduction in the percentage of fines may be due to pozzolanic reaction and hydration accompanying it that led to formation of coarser particles. The stabilized soil became more flocculated and agglomerated, resulting in coarser particles composed of pseudo silt to sand sizes (Osula, 1991; Obeahon, 1993; Amadi, 2010a; Sarkar *et al.*, 2012; Al karagooly, 2012; Portelinha *et al.*, 2012). Detailed test results are shown in Tables A7 in the Appendix A.

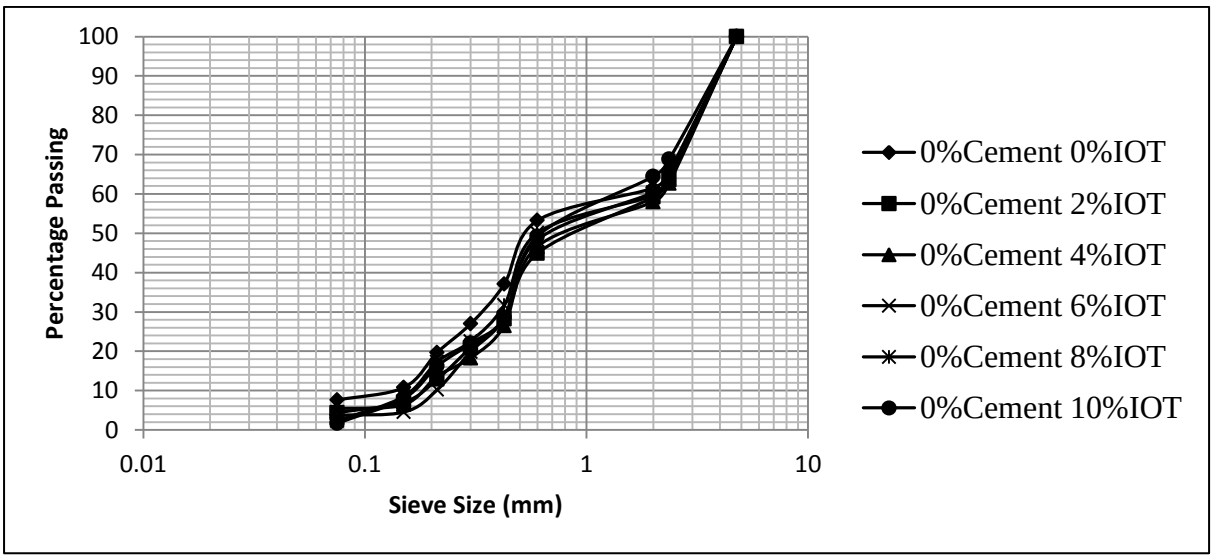


Figure 4.9: Particle size distribution curves for lateritic soil - 0 % cement - iron ore tailings mixtures (BSL compaction).

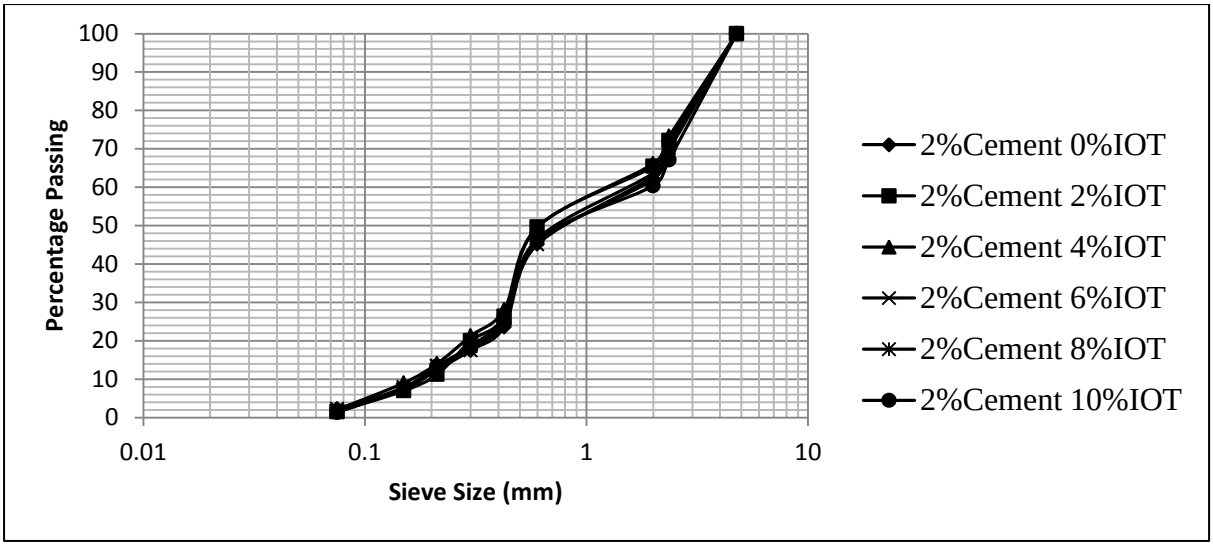


Figure 4.10: Particle size distribution curves for lateritic soil – 2 % cement – iron ore tailings mixtures (BSL compaction)

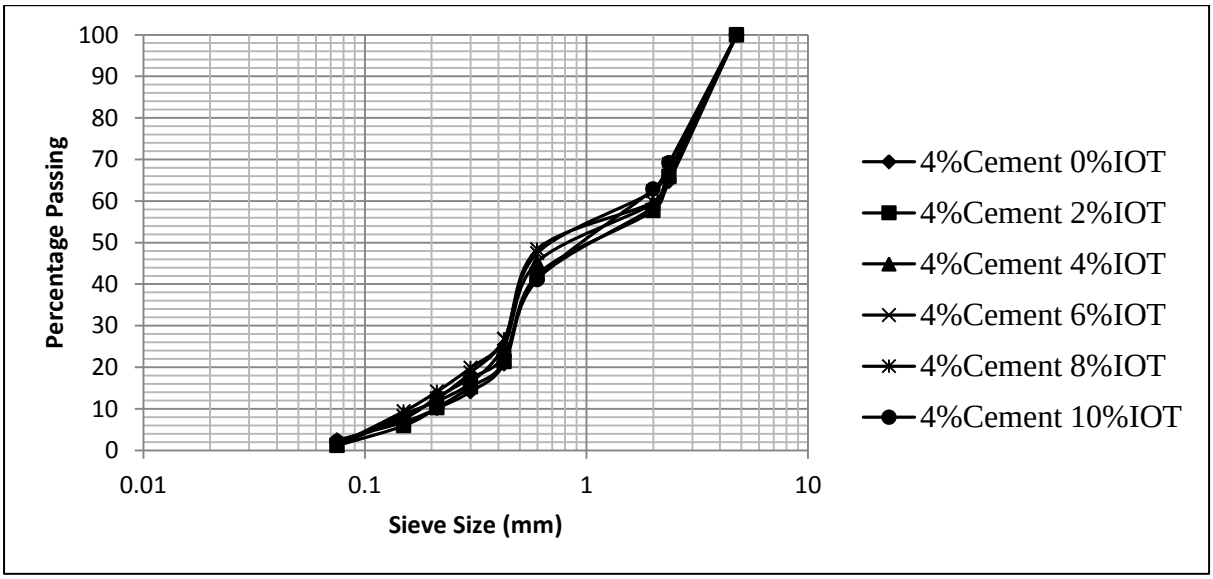


Figure 4.11: Particle size distribution curves for lateritic soil – 4 % cement – iron ore tailings mixtures (BSL compaction).

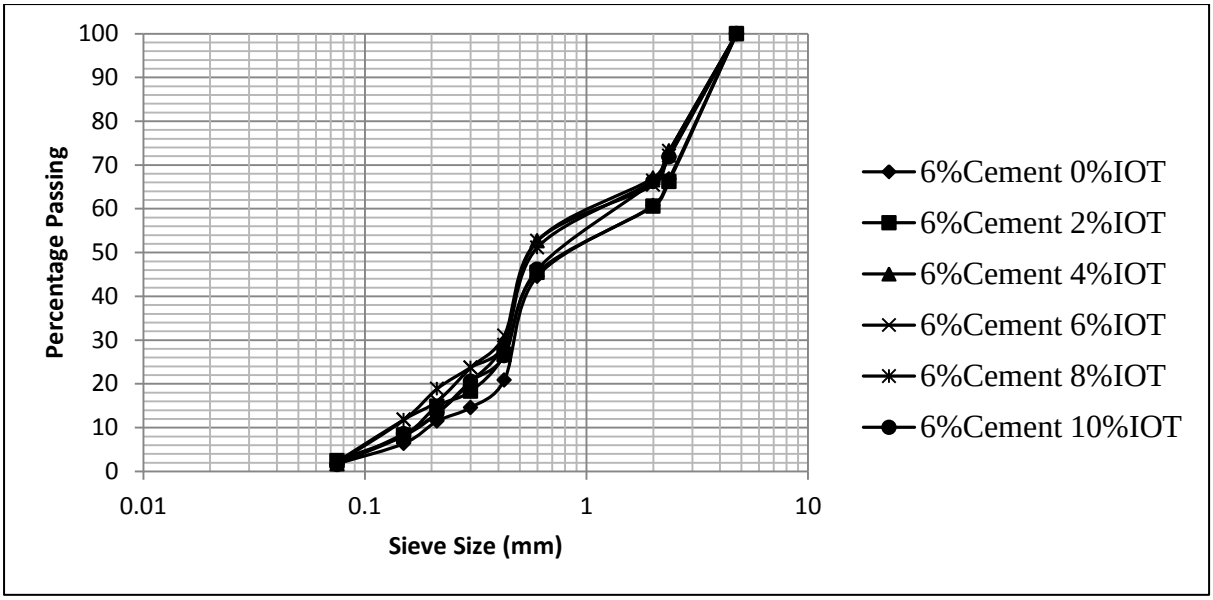


Figure 4.12: Particle size distribution curves for lateritic soil – 6 % cement – iron ore tailings mixtures (BSL compaction).

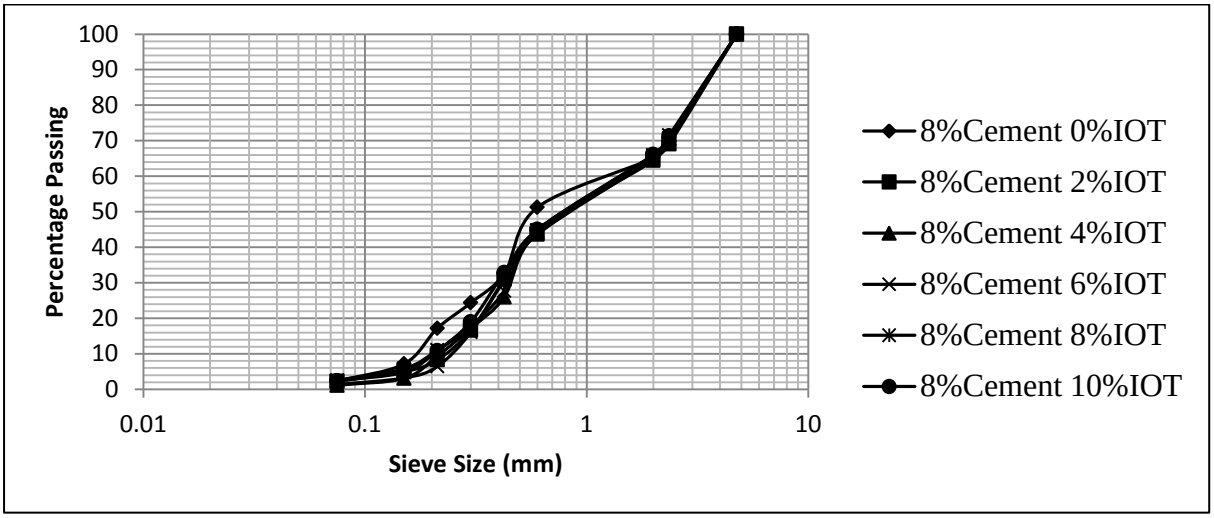


Figure 4.13: Particle size distribution curves for lateritic soil – 8 % cement – iron ore tailings mixtures (BSL compaction).

Using optimum moisture content from West African Standard compaction: The particle size distribution curve of the stabilized lateritic soil for WAS compaction is shown in Figures 4.14 – 4.18. It was observed that the available moulding moisture content facilitated the agglomeration of the soil particles to form macro structural particles. The results showed that the percentage of fines reduced from the 7.0 % for the natural soil to 2.5 % at 0 % cement/ 6 % IOT, and 1.8 % at 8% cement/ 4 % IOT. Similar trend was observed for the various

cement - IOT contents considered. The initial reduction in the percentage of fines may be due to pozzolanic reaction and hydration accompanying it that led to formation of coarser particles (Clare and O'Reilly, 1960; Osula, 1991; Obeahon, 1993; Al karagooly, 2012; Portelinha *et al.*, 2012).

The moulding moisture content for WAS compactive effort decreased when compared with BSL compaction. Detailed test results are shown in Table A8 in the Appendix A.

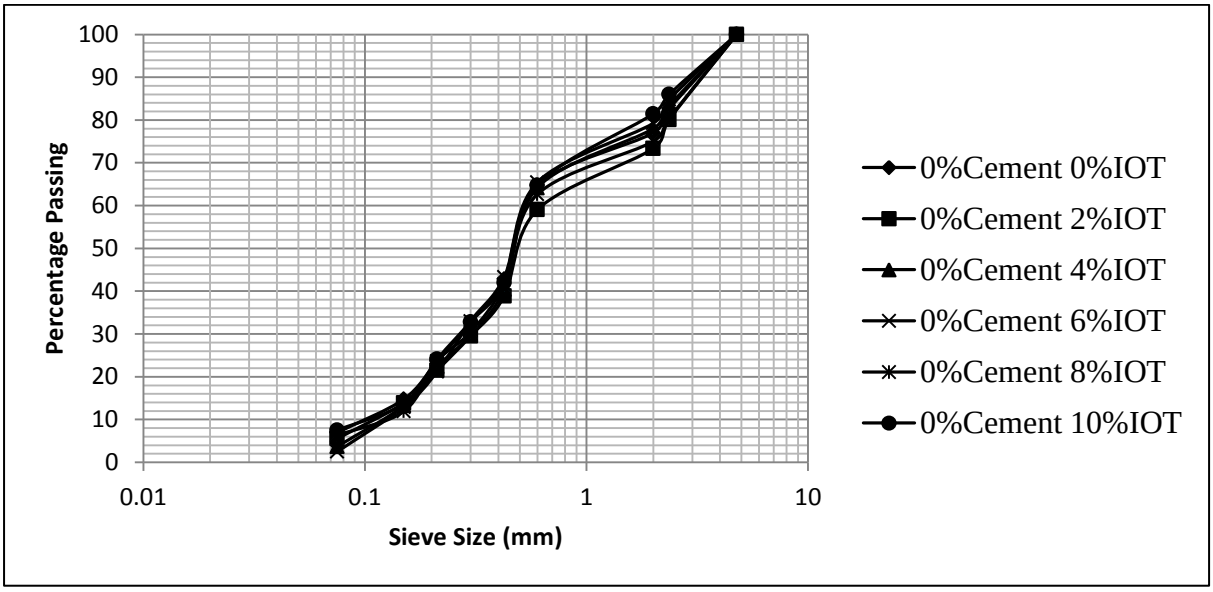


Figure 4.14: Particle size distribution curves for lateritic soil – 0 % cement – iron ore tailings mixtures (WAS compaction)

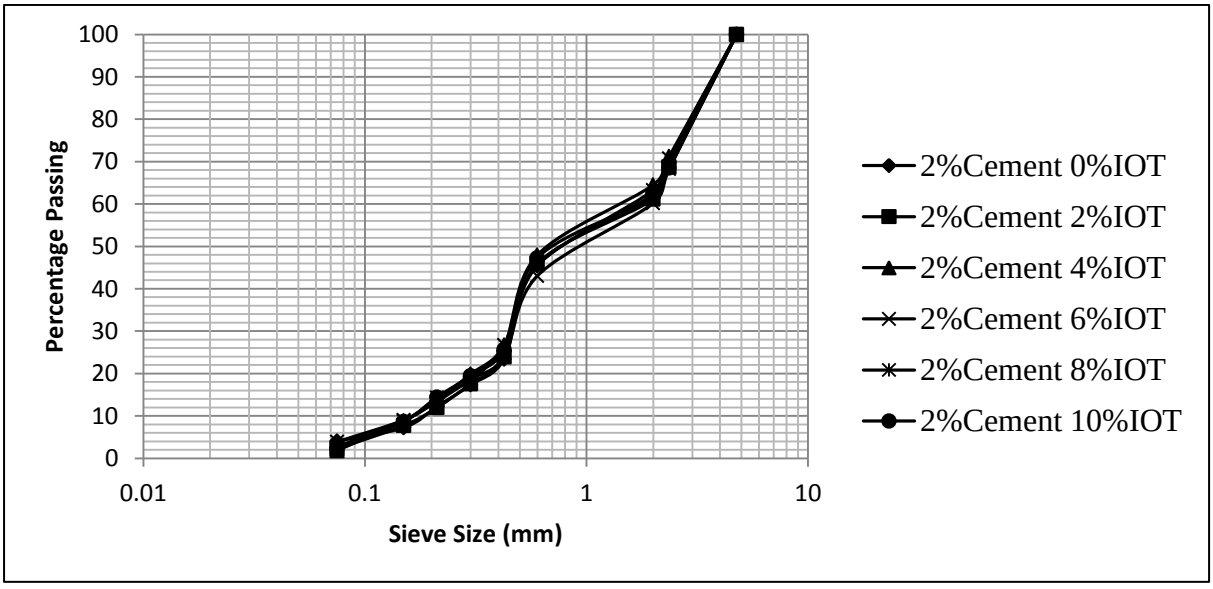


Figure 4.15: Particle size distribution curves for lateritic soil – 2 % cement – iron ore tailings mixtures (WAS compaction)

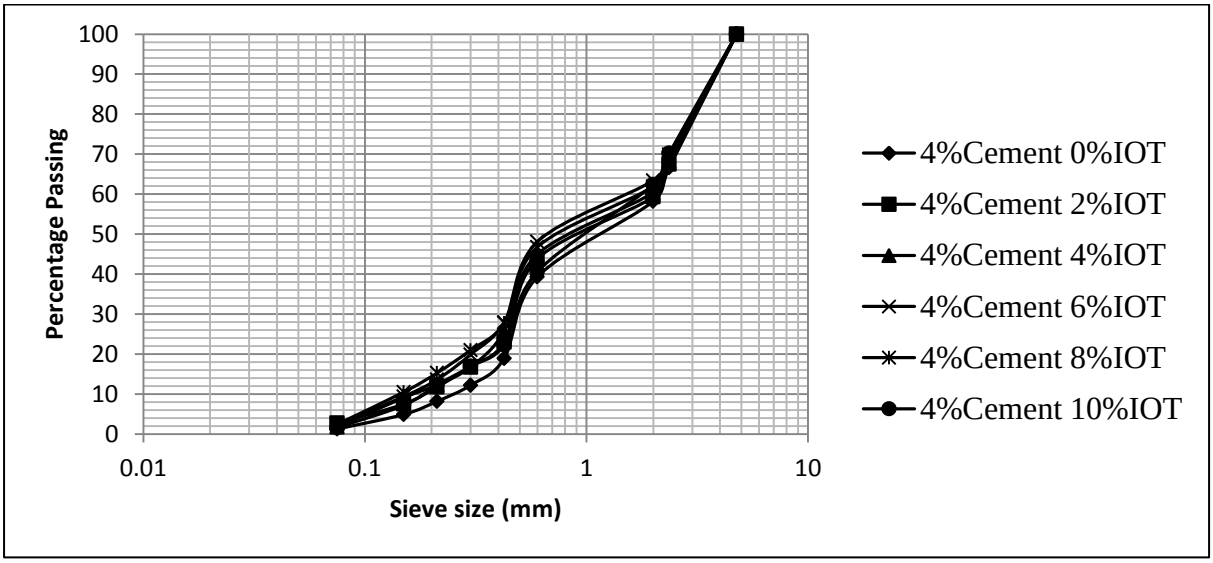


Figure 4.16: Particle size distribution curves for lateritic soil – 4 % cement – iron ore tailings mixtures (WAS compaction)

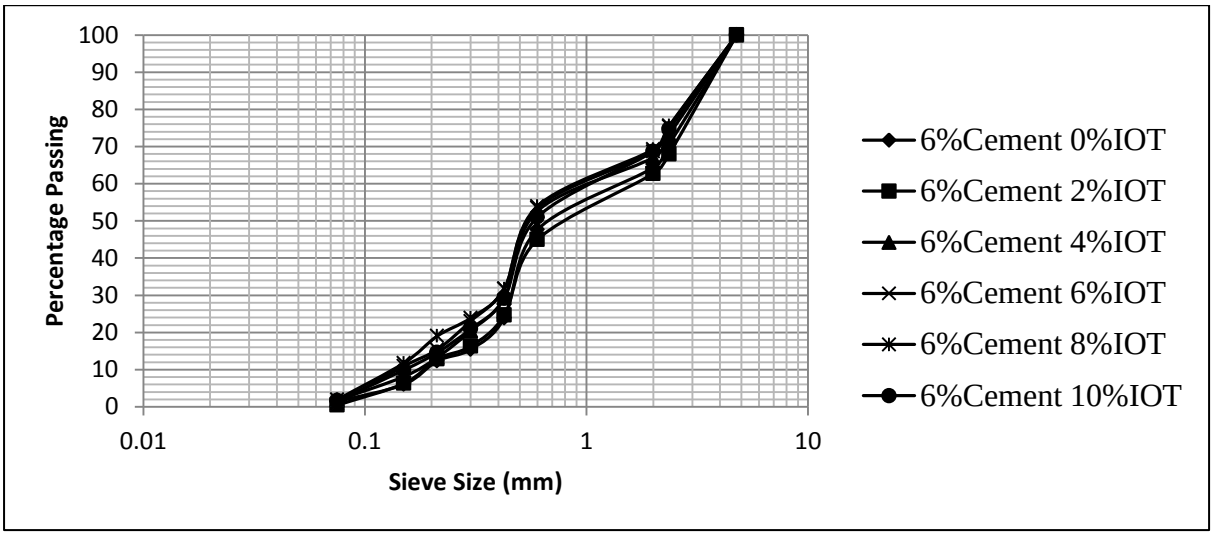


Figure 4.17: Particle size distribution curves for lateritic soil – 6 % cement – iron ore tailings mixtures (WAS compaction).

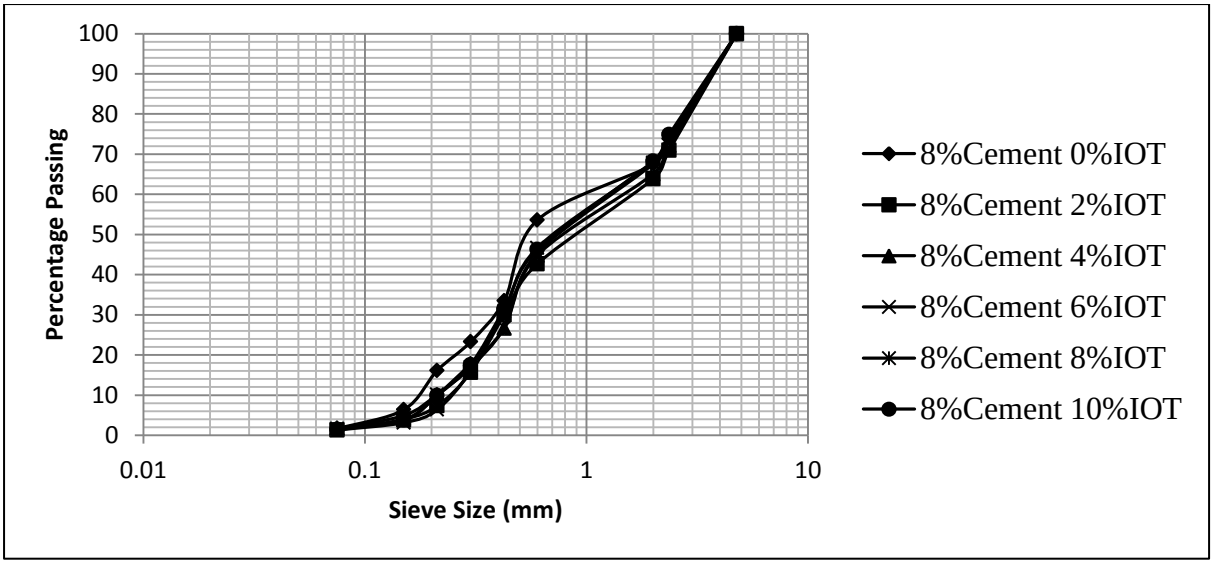


Figure 4.18: Particle size distribution curves for lateritic soil – 8 % cement – iron ore tailings mixtures (WAS compaction).

Using optimum moisture content from British Standard heavy compaction: The particle size distribution curves of the stabilized lateritic soil for BSH compaction are shown in Figures 4.19 – 4.23. It was observed that the available moulding moisture content facilitated the agglomeration of the soil particles to form macro structured particles. It can be deduced from the results that the percentage of fines reduced from the 11.1 % for the natural soil up to 9.8 % at 0 % cement / 6% IOT, and thereafter increased to 12.0 % at 0 % cement/ 10 % IOT treatment. Similar trend was observed for the various cement - IOT contents considered. The initial reduction in the percentage of fines up to 6 % IOT content (see Figures 4.19 – 4.23) and thereafter increased at 10% IOT content could be due to excess IOT that flocculated the soil particles but did not take part in their agglomeration. It could also be due to pozzolanic and hydration reaction that resulted in the formation of coarser particles. The results are consistent with the findings reported by Clare and O'Reilly (1960), Osula (1991), Obeahon (1993), Amadi (2010a) and Al karagooly (2012).

In general, the low moulding moisture content associated with BSH compactive effort (when compared with WAS and BSL compactions) reduced the agglomeration of the soil

particle with increase in the percentage of the additives. Thus, the percentage of fines is higher at BSH optimum moisture content treatments than at WAS and BSL. This may not be unconnected with the excess IOT that did not take part in the hydration process due to insufficient moisture. Detailed test results are shown in Tables A9 in the Appendix A.

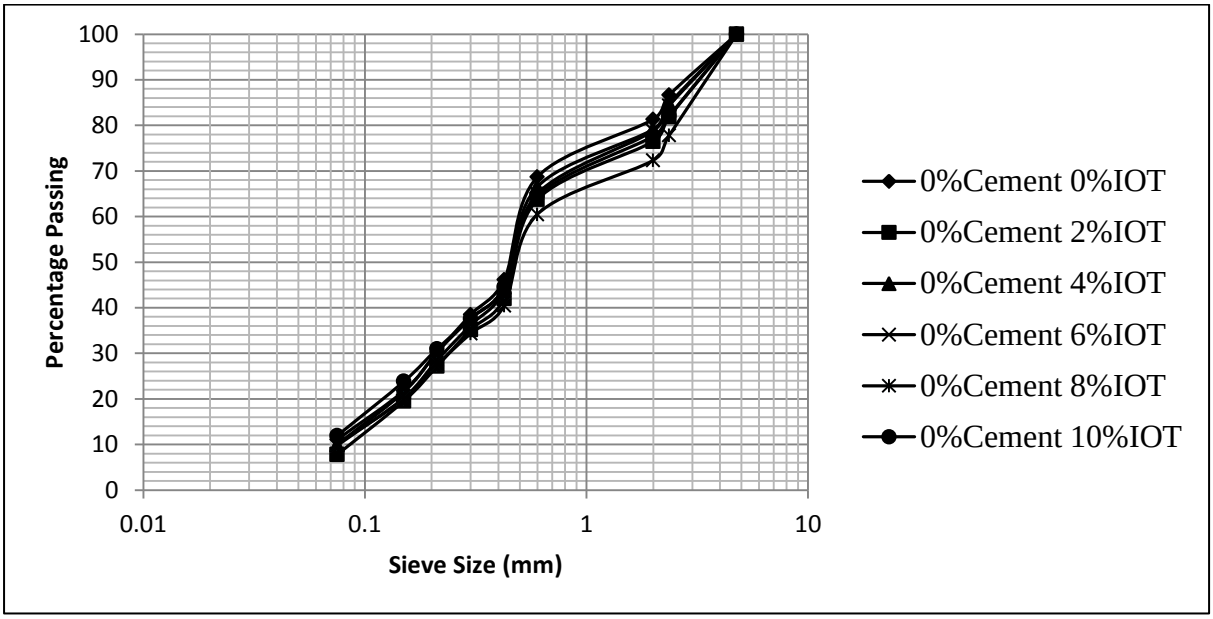


Figure 4.19: Particle size distribution curves for lateritic soil – 0 % cement – iron ore tailings mixtures (BSH compaction)

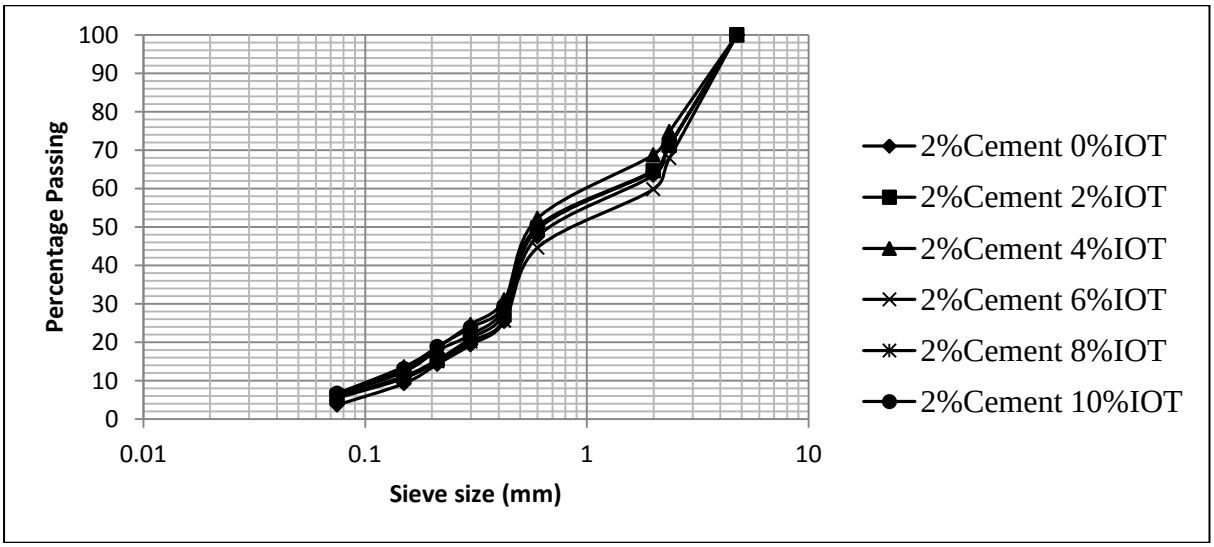


Figure 4.20: Particle size distribution curves for lateritic soil – 2 % cement – iron ore tailings mixtures (BSH compaction)

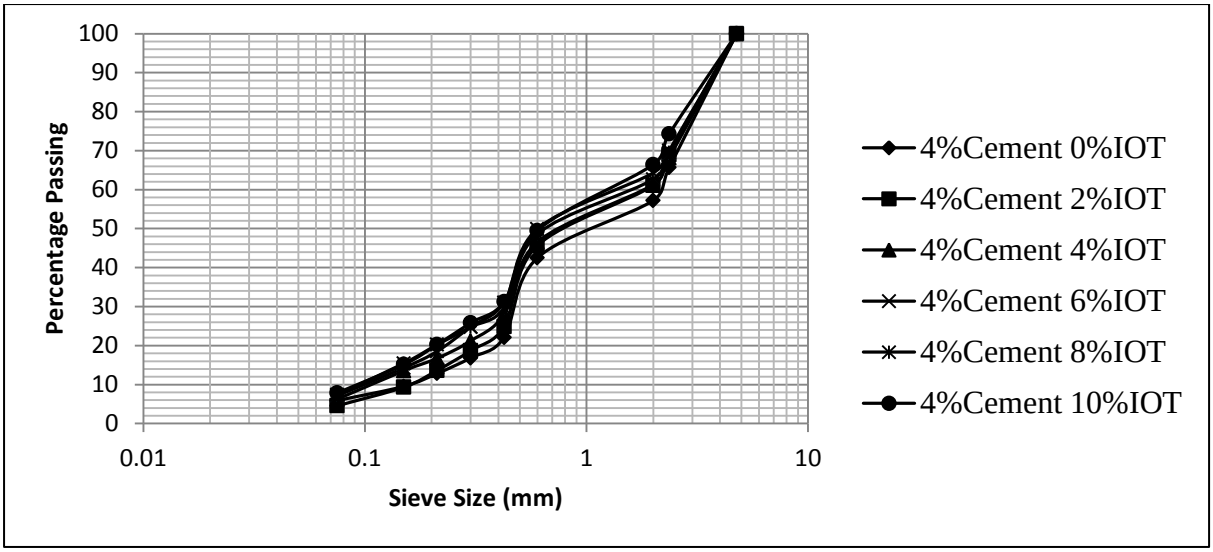


Figure 4.21: Particle size distribution curves for lateritic soil – 4 % cement – iron ore tailings mixtures (BSH compaction)

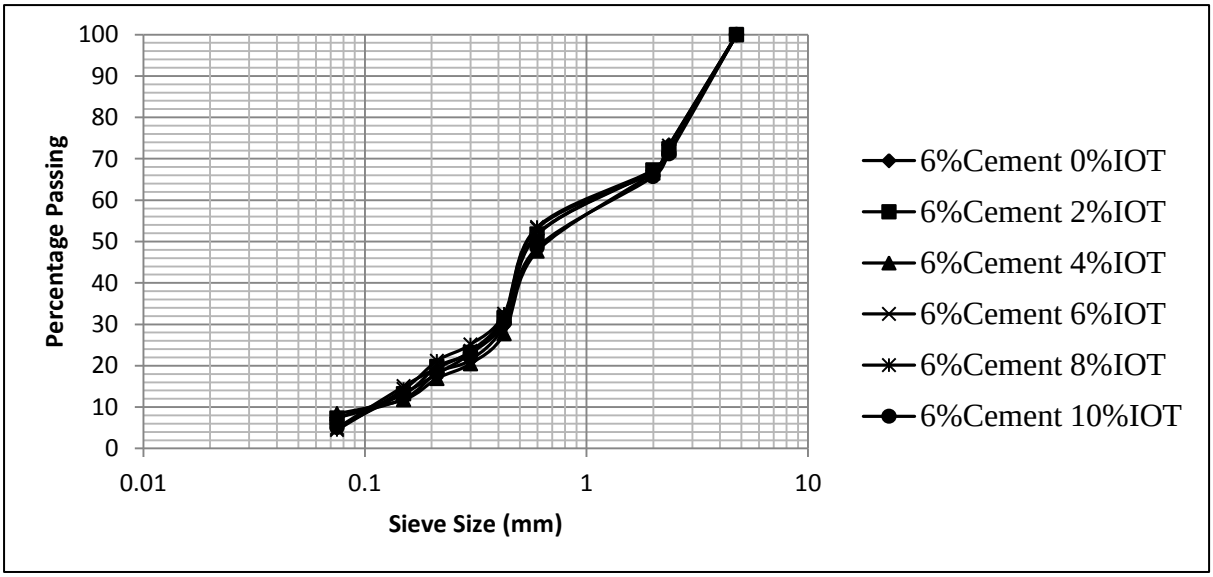


Figure 4.22: Particle size distribution curves for lateritic soil – 6 % cement – iron ore tailings mixtures (BSH compaction)

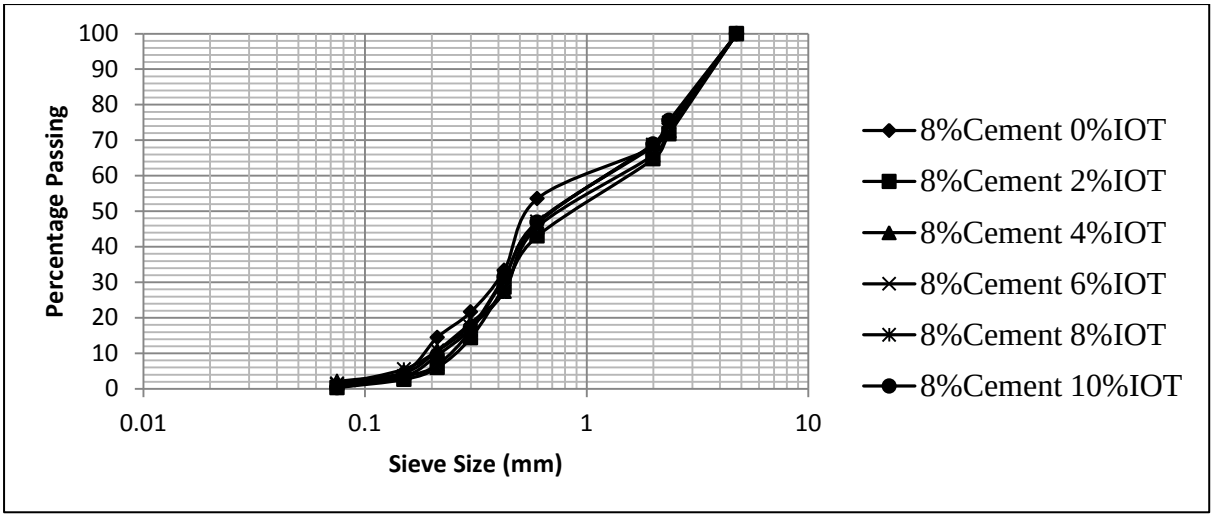


Figure 4.23: Particle size distribution curves for lateritic soil – 8 % cement – iron ore tailings mixtures (BSH compaction)

4.2.4 Atterberg limits

4.2.4.1 Liquid limit

The effect of iron ore tailings content on the liquid limit of the cement stabilized lateritic soil is shown in Figure 4.24. The results show a general decrease in the liquid limit values with increase in cement and IOT contents. The decrease may be attributed to flocculation and agglomeration arising from cation exchange reactions whereby Ca^{2+} in the additives reacted with ions of lower valence in the clay structure. This finding is in agreement with the findings reported by Obeahon (1993), Osinubi and Umar (2003), Osinubi and Alhassan (2008), Al-Zoubi (2008), Ramesh *et al.*, (2013) Yohanna (2015) and Etim (2015). The addition of cement and iron ore tailings introduced calcium for its strength which caused a decrease in the repulsive force of the soil mixture; thereby needing more water to take the soil to its dynamic shear strength (Osinubi, 1995). In other words, first calcium hydrate is dissolved and the resulting OH combined with Si and Al in the clay fraction and hydroxides with Ca^{2+}, silicate and aluminate are produced (Bell, 1996). The experimental studies reported in literature (Nelson and Miller, 1992; Lawton, 1996; Feng, 2002; Al-Rawas *et al.*,

2002) generally show that the addition of cement to clay soils reduces the liquid limit. Similar trend was reported by Zaman *et al.* (1992), Al-Refeai, *et al.* (1998), Phanikumar *et al*. (2004), Brooks *et al.* (2011) and Alkaragooly (2012). Detailed test results are shown in Tables A10 in the Appendix A.

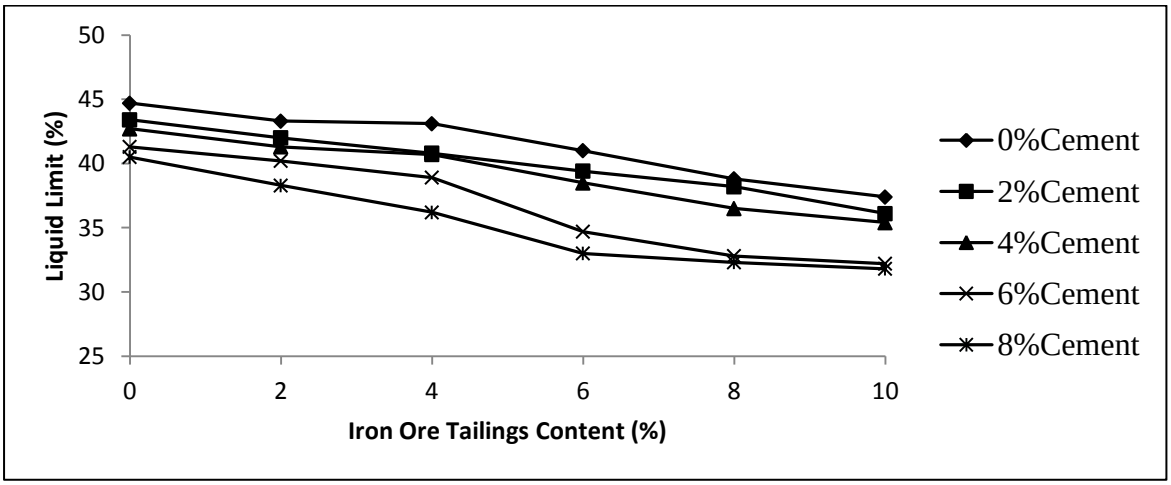


Figure 4.24: Variation of liquid limit of lateritic soil – cement mixtures with iron ore tailings content.

The result of the two – way analysis of variance (ANOVA) performed on the liquid limit result is presented in Table 4.6. The result shows that the effects of cement (F_{CAL} = 59.618 > F_{CRIT} = 2.866) and iron ore tailings (F_{CAL} = 80.583 > F_{CRIT} = 2.711) on lateritic soil were statistically significant with iron ore tailings having a more pronounced effect than cement. Detailed test results are shown in Tables A51 in the Appendix A

Table 4.6 Two-way analysis of variance results for liquid limit of lateritic soil – cement – iron ore tailings mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Liquid Limit	Cement	4	59.618	1.49E-12	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	80.583	7.87E-11	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.4.2 Plastic limit

The variation of plastic limit of lateritic soil – cement mixtures with iron ore tailings content is shown in Figure 4.25. In general, the plastic limit of the natural soil increased from 22.5 % to a peak value of 23.6 % at 0 % cement / 6 % iron ore tailings treatment and thereafter a slight decrease in the plastic limit was recorded at higher iron ore tailings content. This increment might not be unconnected with the flocculation and agglomeration of the clay particles occasioned by cation exchange at the surface due to the introduction of the additives (cement and IOT) into the soil matrix. This trend is similar to the findings reported for lateritic soil treated with IOT by Yisa (2013). It could also be attributed to the availability of silica and alumina from the IOT that further enhanced cation exchange between clay particles of the soil and calcium ions from the IOT. Meanwhile, the slight decrease at higher percentages of IOT could be as a result of the non-plastic nature of iron ore tailings. The observed decrease of plastic limit may also be attributed to cation exchange reaction that liberated adsorbed water particles in the soil leading to the flocculation and agglomeration of the soil (Osinubi, 1995). The results of decrease in plastic limit of treated soils were also reported in literature by Amadi, (2010a), Ramesh *et al.* (2013) and Osinubi *et al.* (2015). Detailed test results are shown in Tables A11 in the Appendix A.

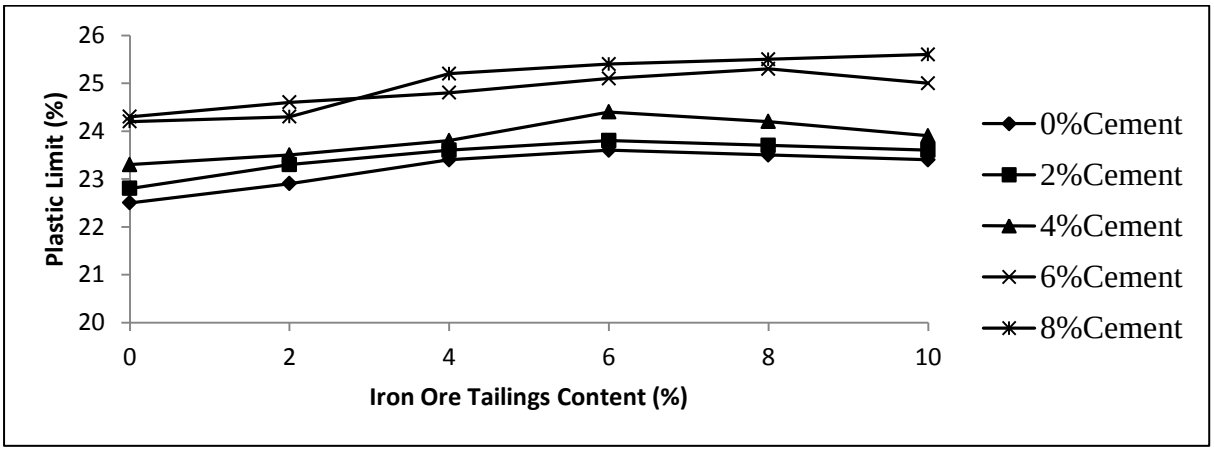


Figure 4.25: Variation of plastic limit of lateritic soil – cement mixtures with iron ore tailings content.

The results of the analysis of variance (ANOVA) of plastic limit (see Table 4.7) shows that the effects of cement (F_{CAL}= 144.568>F_{CRIT} = 2.866) and iron ore tailings (F_{CAL}= 32.194>F_{CRIT} = 2.711) on lateritic soil were statistically significant with cement having a more pronounced effect than iron ore tailings. Detailed test results are shown in Tables A52 in the Appendix A.

Table 4.7: Two-way analysis of variance for plastic limit results of lateritic soil –cement – iron ore tailings mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Plastic Limit	Cement	4	144.57	1.86E-14	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	32.194	6.58E-09	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.4.3 Plasticity index

The variation of plasticity index of lateritic soil - cement mixtures with iron ore tailings is shown in Figure 4.26. The reduction in liquid limit and increase in plastic limit resulted in a general decrease in the plasticity index values. Plasticity index value of 22.2 % was recorded for the natural soil. This value reduced to 14 % at 0 % cement / 10 % IOT treatment.

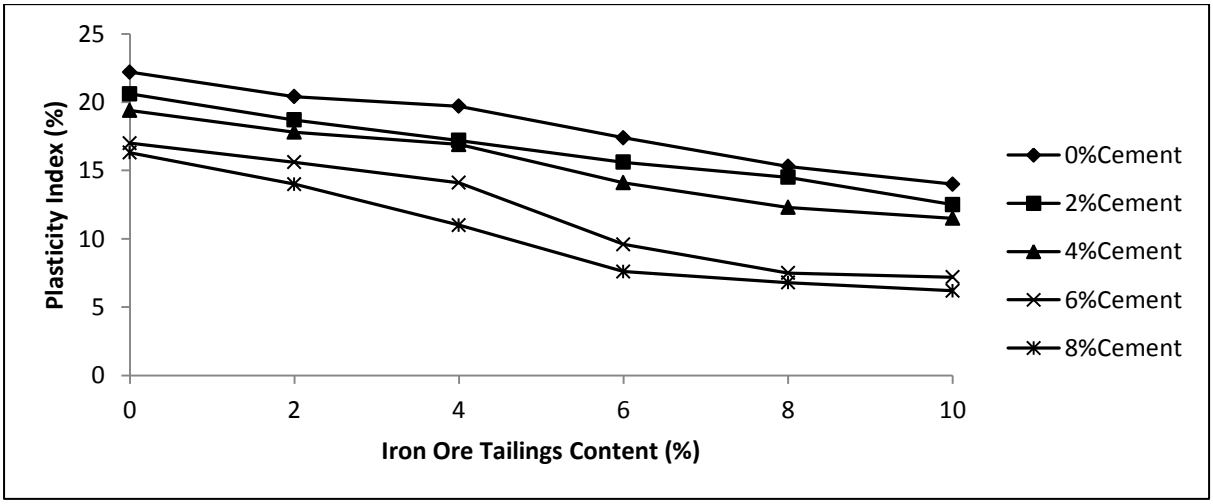


Figure 4.26: Variation of plasticity Index of lateritic soil – cement mixtures with iron ore tailings content.

On treatment with 2, 4, 6 and 8 % cement - up to 10 % IOT content, it was observed that plasticity index (PI) decreased from 20.6 to 12.5 %, 19.4 to 11.5 %, 17 to 7.2 % and 16.3 to 6.2 %, respectively, the decrease in the plasticity index is indicative of improvement of the natural soil. This reduction in plasticity index is in agreement with the findings reported by Olugbenga *et al.* (2011) and Yisa, (2013). Detailed test results are shown in Tables A14 in the Appendix A.

The analysis of variance (ANOVA) of plasticity index results (see Table 4.8) shows that the effects of cement (F_{CAL} = 94.359 > F_{CRIT} = 2.866) and iron ore tailings (F_{CAL} = 90.369 > F_{CRIT} = 2.711) on lateritic soil were statistically significant with the effect of cement being more pronounced than that of iron ore tailing. Detailed test results are shown in Tables A4.53 in the Appendix A.

Table 4.8 Two-way analysis of variance for plasticity index results of lateritic soil –cement – iron ore tailings mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Plasticity Index	Cement	4	94.359	1.093E-12	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	90.369	5.006E-13	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.3.4 Linear shrinkage

The variation of linear shrinkage of lateritic soil - cement mixtures with iron ore tailings content is shown in Figure 4.27. The results show that the linear shrinkage decreased with increase in the additives. The linear shrinkage decreased from 7.81 % for the natural soil to 4.69 % at 10 % iron ore tailings content. Upon treatment with 2, 4, 6 and 8 % cement and up to 10 % iron ore tailing content, the linear shrinkage progressively decreased. This trend is consistent with the report of other researchers (Ola 1991; Osinubi 1995, 1999; Buhler and Cerato 2007). However, the decrease in the linear shrinkage is more pronounced at lower contents of cement (0 % and 2 %). The results also reveal that the soils treated with cement –

iron ore tailing blend give rise to soils with lesser shrinkage when compared to those treated with iron ore tailing alone. Detail test results are shown in Table A15 in the Appendix A.

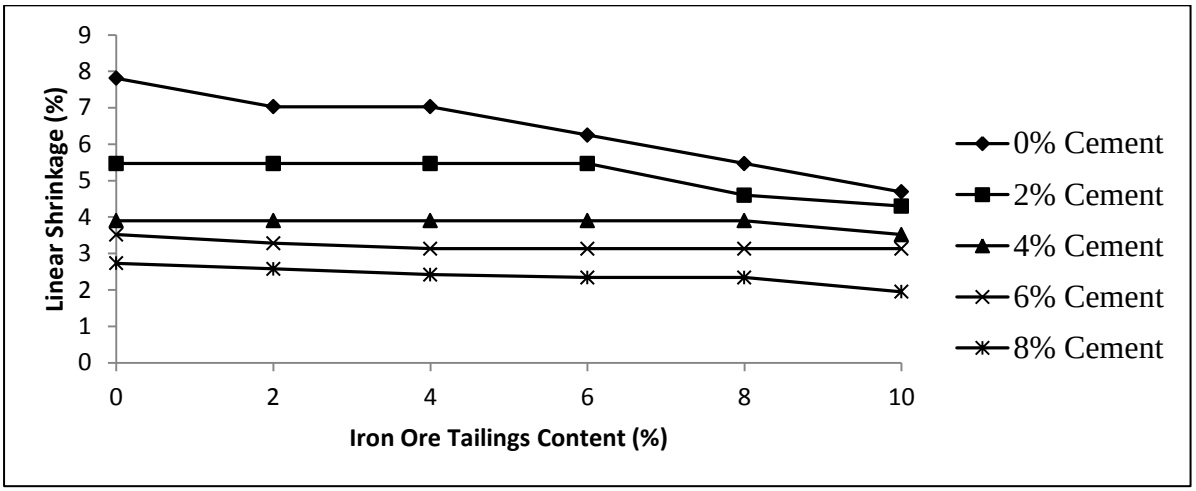


Figure 4.27: Variation of linear shrinkage of lateritic soil - cement mixture with iron ore tailings content

The results of the two-way analysis of variance (ANOVA) performed on linear shrinkage results (Table 4.9) shows that the effects of cement (F_{CAL} = 72.435 > F_{CRIT} = 2.866) and iron ore tailings (F_{CAL} = 4.350 > F_{CRIT} = 2.711) on lateritic soil were statistically significant with cement having a more pronounced effect. Detailed test results are shown in Tables A54 in the Appendix A.

Table 4.9 Two-way analysis of variance for linear shrinkage results of lateritic soil –cement – iron ore tailings mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Linear Shrinkage	Cement	4	72.435	1.302E-11	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	4.350	0.0076705	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.3 Compaction Characteristics

Many of the engineering properties of a soil are dependent on the moisture and density at which the soil is compacted (Osinubi and Toro, 1997). Therefore, it is necessary to

achieve the desired relative density of 95 % or more on field relative to that obtained in the laboratory.

4.3.1 Maximum dry density

4.3.1.1 Effect of additives on maximum dry density

The variation of maximum dry density (MDD) of lateritic soil – cement mixtureswith iron ore tailings content for BSL, WAS and BSH compactions are presented in Figures 4.28 – 4.30. It was observed that MDD values increased with increase in iron ore tailings content for the three compactive efforts considered. For BSL compaction, MDD increased from a value of 1.61 Mg/m^3 for the natural soil to 1.68 Mg/m^3 at 0 % cement/ 10 % IOT. The peak value of 1.77 Mg/m^3 was recorded at 8 % cement - 10 % iron ore tailings treatment (see Figure 4.28). Test results also showed an increase in MDD with increase in cement content.

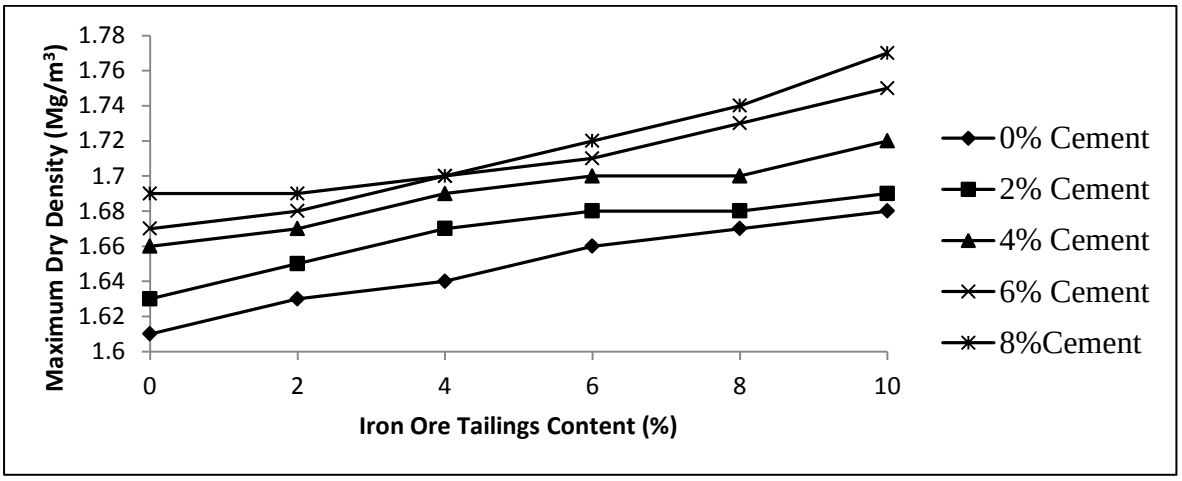


Figure 4.28: Variation of maximum dry density of lateritic soil–cement mixtures with iron ore tailings content (BSL compaction)

The trend observed for WAS and BSH compactions were similar to that of the BSL compaction. For WAS and BSH compactions, MDD values increased from 1.67 and 1.77 Mg/m^3 for the natural soil to peak values of 1.81 and 1.91 Mg/m^3 both at 8 % cement - 10 % iron ore tailings treatments, respectively (see Figures 4.29 and 4.30). Phanikumar *et al.*

(2004), Jadhao and Nagarnik (2008), Kumar and Puri (2013) as well as Osinubi *et al.* (2015) reported similar trend of increasing maximum dry densities in their respective researches.

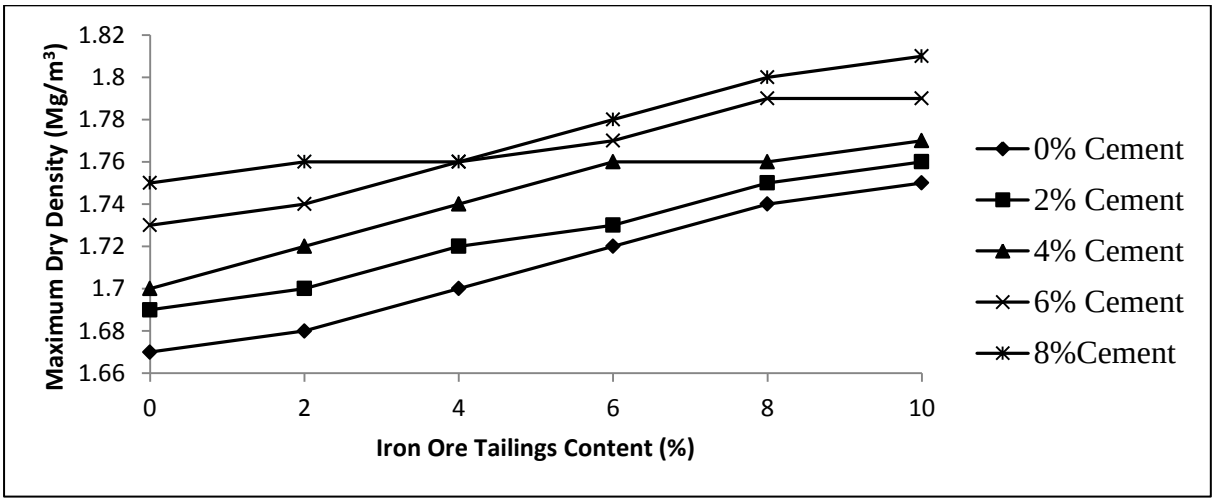


Figure 4.29: Variation of maximum dry density of lateritic soil–cement mixtures with iron ore tailings content (WAS compaction)

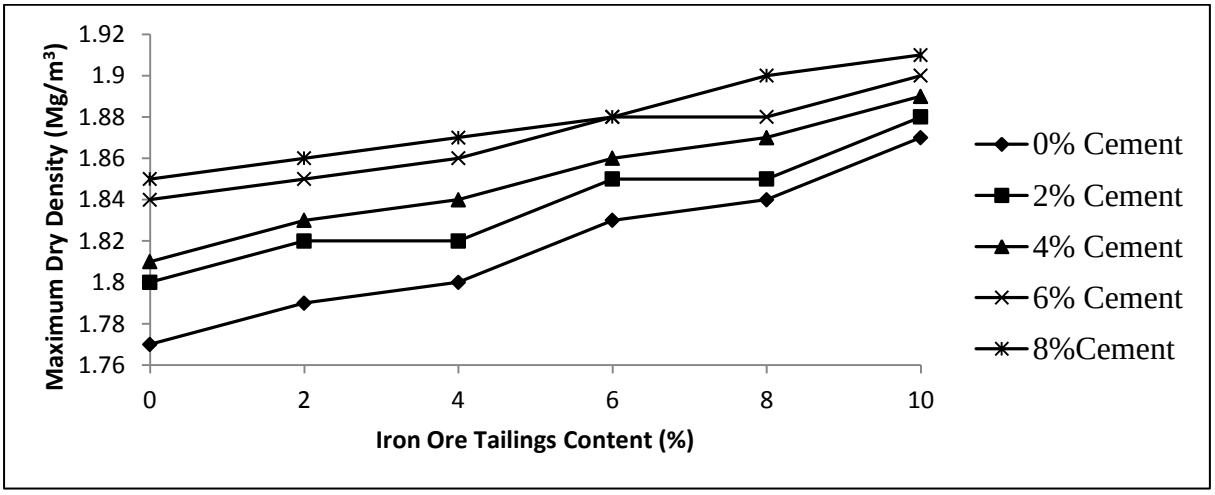


Figure 4.30: Variation of maximum dry density of lateritic soil–cement mixtures with iron ore tailings content (BSH compaction)

The increase in MDD recorded for the compactive efforts considered, may be due to flocculation and agglomeration of the clay particles primarily due to cation exchange and in addition the particles filling the voids within the soil matrix (O'Flaherty, 1988; Osinubi, 2000; Moses, 2006; Oriola and Moses, 2010). The increase in MDD could also be as a result of IOT which has a higher specific gravity (3.31) replacing the soil particles which has a lower specific gravity of 2.52 thus resulting in the formation of a mixture with higher specific

gravity and higher MDD as reported by Ishola (2014), Osinubi *et al*. (2015). Detailed test results are given in Tables A14 – 16 in the Appendix A.

The result of the two - way analysis of variance (ANOVA) performed on the MDD result for BSL, WAS and BSH compaction (see Table 4.10) showed that the effects of cement (F_{CAL} = 79.82, 124.53, 79.74 > F_{CRIT} = 2.87) and iron ore tailings (F_{CAL} = 54.49, 100.86, 84.61 > F_{CRIT} = 2.71) on lateritic soil were statistically significant.

Table 4.10: Two-way analysis of variance for maximum dry density of lateritic soil - cement – iron ore tailings mixtures

Property		Source of variation	Degree of freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	MDD	Cement	4	79.81	5.28E-12	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	54.49	5.77E-11	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	MDD	Cement	4	124.53	7.79E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	100.86	1.76E-13	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	MDD	Cement	4	79.74	5.32E-12	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	84.61	9.36E-13	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are shown in Tables A55 – 57 in the Appendix A.

4.3.1.2 Effect of compactive effort on maximum dry density

The variations of maximum dry density of lateritic soil – cement – iron ore tailings mixtures with compaction energy are presented in Figures 4.31 – 4.35. The results indicate a general increase in MDD with increase in compaction energy in the order of BSL, WAS and BSH compaction energy levels.

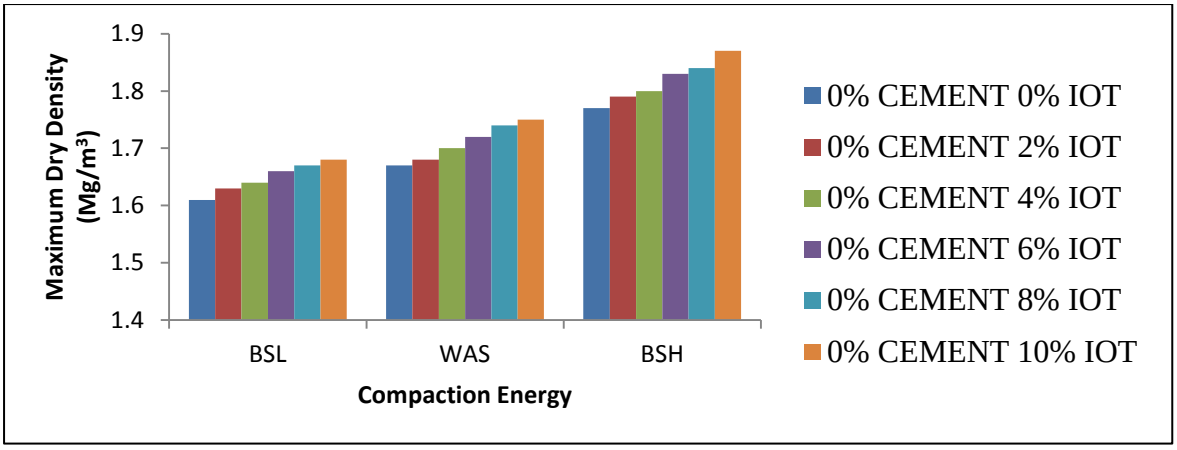


Figure 4.31: Variation of maximum dry density of lateritic soil – 0 % cement – iron ore tailings mixtures with compaction energy

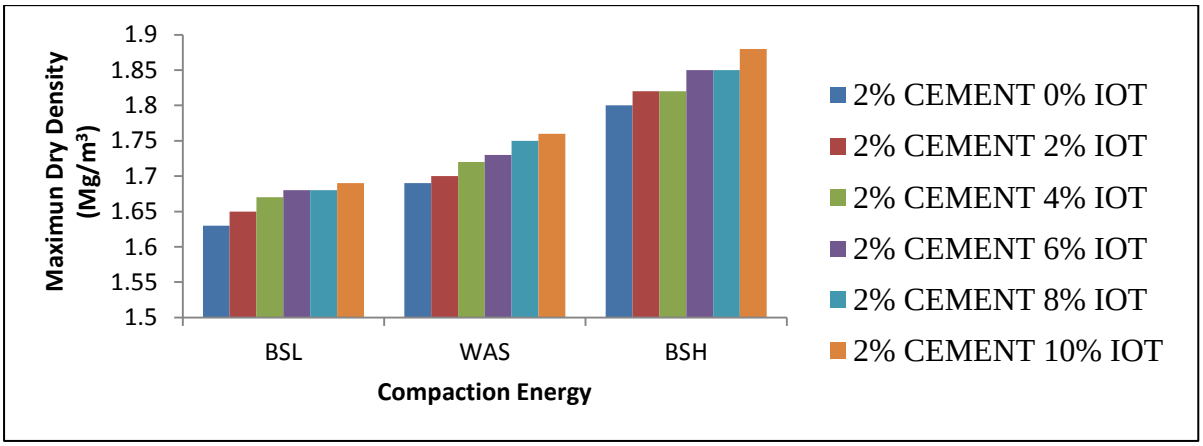


Figure 4.32: Variation of maximum dry density of lateritic soil – 2 % cement – iron ore tailings mixtures with compaction energy

The MDD values recorded at 4 % cement / 6 % IOT treatment were 1.7 Mg/m^3 for BSL, 1.76 Mg/m^3 for WAS and 1.86 Mg/m^3 for BSH compaction energies (see Figure 4.33).

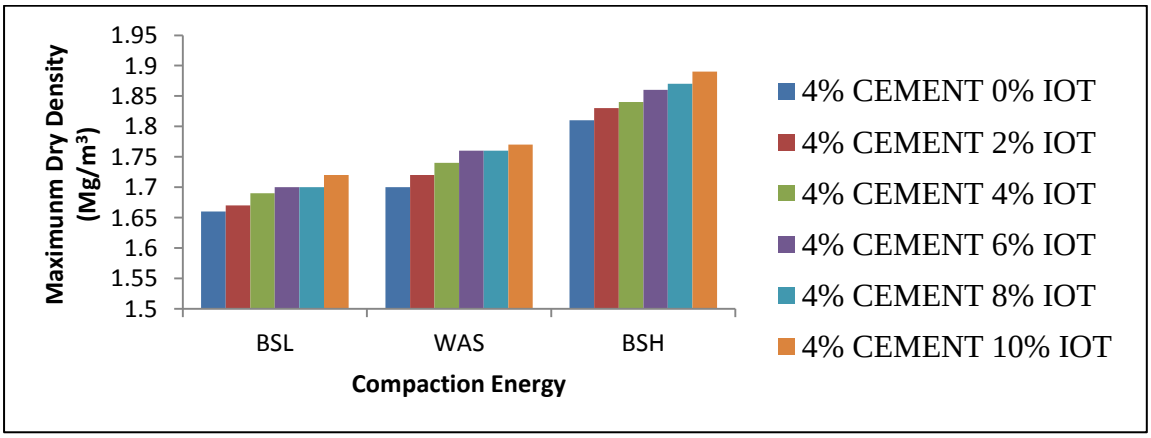


Figure 4.33: Variation of maximum dry density of lateritic soil – 4 % cement – iron ore tailings mixtures with compaction energy

The maximum dry density values for 6 % cement / 6 % IOT treatment were 1.71 Mg/m^3, 1.77 Mg/m^3 and 1.88 Mg/m^3 for BSL, WAS and BSH compactions, respectively (see Figure 4.34).

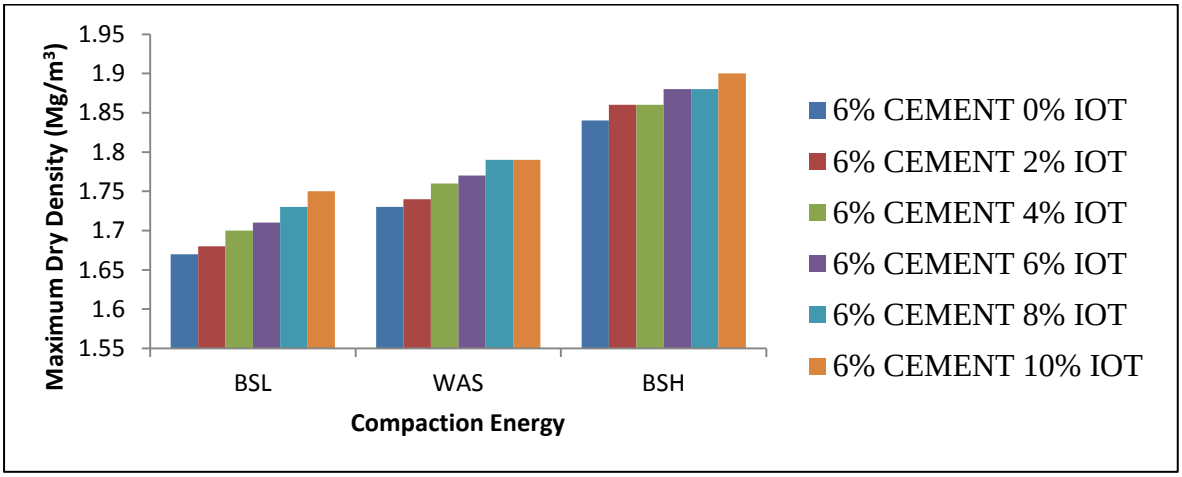


Figure 4.34: Variation of maximum dry density of lateritic soil – 6 % cement – iron ore tailings mixtures with compaction energy

Similarly, 1.72 Mg/m^3, 1.78 Mg/m^3 and 1.88 Mg/m^3 were the MDD values for BSL, WAS and BSH compactions in that order at 8 % cement / 6 % IOT (see Figure 4.35).

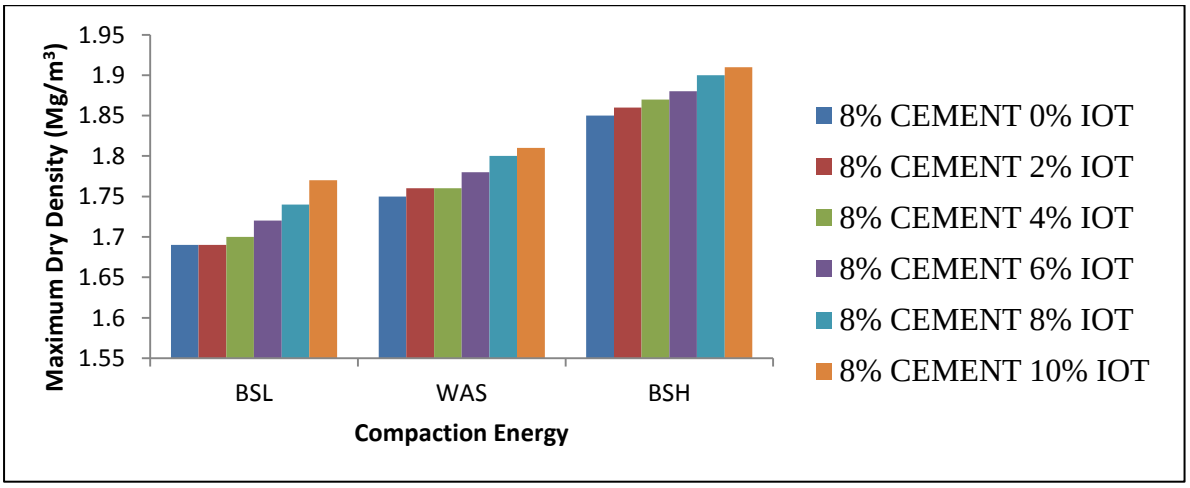


Figure 4.35: Variation of maximum dry density of lateritic soil – 8 % cement – iron ore tailings mixtures with compaction energy

Similar trend were observed for the various cement – IOT treatments considered. The observed increase in MDD with higher compactive effort was probably because, it was easier

to breakdown flocculated aggregates, destroy shear planes and eliminate large pores, at higher compactive efforts (Osinubi, 1999). The observed trend is in agreement with the findings reported by Osinubi (1998a), Mustapha (2006), Alhassan (2006), Yohanna (2015) and Etim (2015).

4.3.1.3 Regression analysis for maximum dry density

Regression analysis is a statistical test which establishes the relationship between the dependent variable and the independent variables. The extent to which the independent variables influence the dependent variable is a function of the coefficient of each parameter in the resultant regression equation.

The following geotechnical properties were considered for this analysis: cement content, iron ore tailings content, sand, silt and clay fractions as independent variables. The specific gravity was also considered while the compactive effort was used as a deterministic parameter. The compactive effort index values of –1, 0 and 1 for British Standard light, West African Standard and British Standard heavy compactive efforts were used.

The resultant equation obtained from the regression analysis performed on the maximum dry density (MDD) of the soil showed that MDD was influenced by the grading properties, specific gravity and compactive effort applied. This agrees with earlier research findings that the behaviour of lateritic 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, Gidigasu (1976).

The regression Equation (4.1) revealed the extent to which these parameters influenced MDD 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. The positive coefficient for cement content, iron ore tailing content, clay, silt and sand could be associated with the reduction in

the voids within the soil matrix leading to the increase in the maximum dry density. The coefficient of multiple determinations (R^2) shows a strong relationship between maximum dry density and the parameters with R^2 value of 0.968

The regression Equations is

$$MDD = 1.169 + 0.00689C + 0.00650IOT + 0.00288Sa + 0.00321Si + 0.00307Cl + 0.08430Gs + 0.082CE \quad (4.1)$$

where; MDD = Maximum dry density, C = Cement content, IOT = Iron ore tailings content, Cl = Clay, Si = Silt, Sa = Sand, Gs = Specific gravity, CE = Compactive effort.

Detailed test results are shown in table 4.11

Table 4.11 Regression analysis for maximum dry density of lateritic soil – cement – iron ore tailings mixtures

Dependent variable	Independent variable	Coefficients	p-value	Adjusted R^2	F
MDD	Intercept	1.169222067	0.013690884	0.9678	7.66013E-60
	Cement content	0.006886168	0.000229955		
	Iron ore tailings content	0.006503977	6.52339E-07		
	Sand	0.002883921	0.565947379		
	Silt	0.003210276	0.53406965		
	Clay	0.003074753	0.549406963		
	Specific gravity	0.084304445	0.281037614		
	Compactive effort	0.082	2.06173E-60		

4.3.2 Optimum moisture content

4.3.2.1 Effect of additives on optimum moisture content

The variation of optimum moisture content (OMC) of lateritic soil - cement mixtures with iron ore tailings content for BSL, WAS and BSH compactive efforts are shown in Figs. 4.36 – 4.38. Generally, it was observed that OMC decreases with increased iron ore tailings treatment for the compaction energy levels considered. The results also showed that, the OMC decreased with increase in cement content. The decrease in the OMC could be as a result of an enhanced cation exchange reaction due to combination of free lime product of hydration of cement and the IOT admixture. This reaction resulted in the decrease in the thickness of the double layer thereby causing flocculation. As the clay flocculated under this action, water, which had become separated from the particles concentrated in the voids between the bonded particles thus decreasing the OMC (Mustapha, 2006). Also, the observed decrease in OMC may not be unconnected with self – desiccation in which all the water was used up thus resulting in low hydration. When there was no water movement to or from the soil – cement – iron ore tailing 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). Detailed test results are shown in Tables A17 – 19 in the Appendix A.

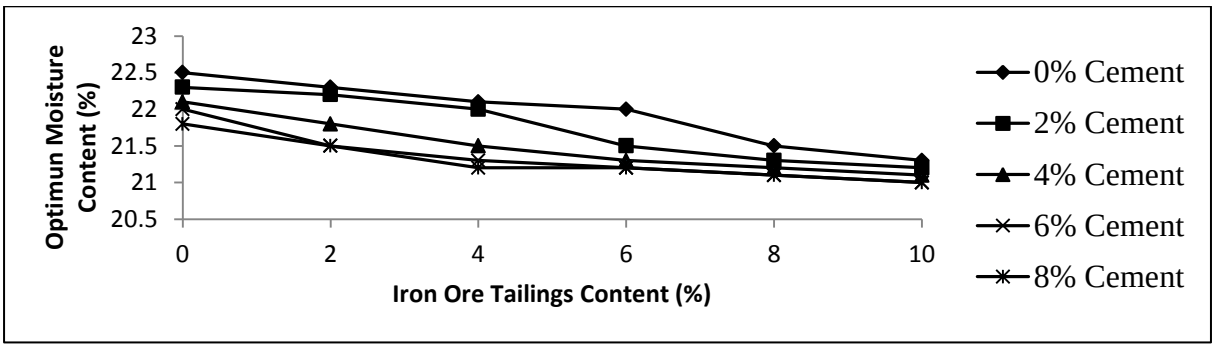


Figure 4.36: Variation of optimum moisture content of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

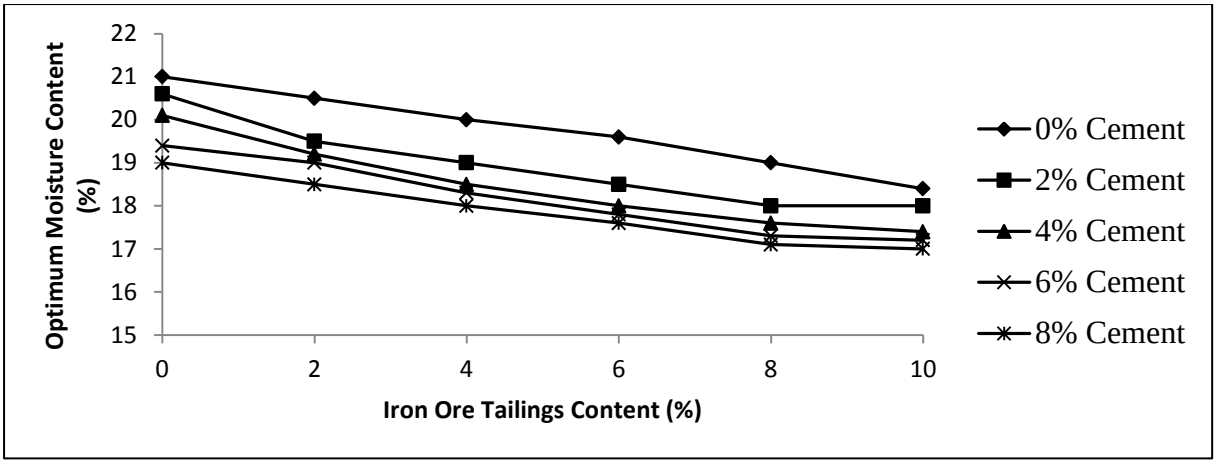


Figure 4.37: Variation of optimum moisture content of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

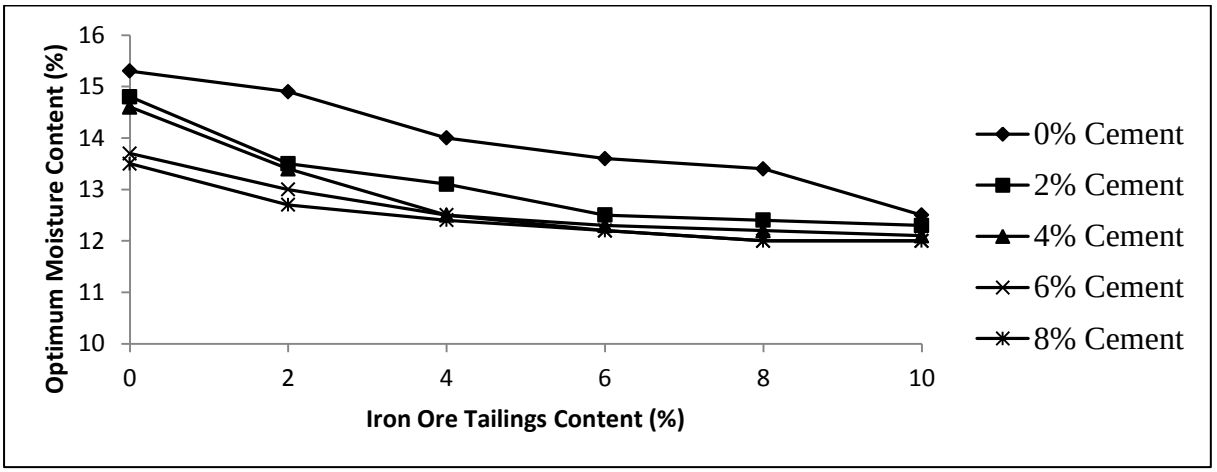


Figure 4.38: Variation of optimum moisture content of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction)

The result of the two - way analysis of variance (ANOVA) performed on OMC results for BSL, WAS and BSH compactions (see Table 4.12) shows that the effects of cement (F_{CAL} = 26.27, 118.23, 27.94 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 42.76, 156.59, 44.89 > F_{CRIT} = 2.71) on lateritic soil were statistically significant.

Table 4.12 Two-way analysis of variance for optimum moisture content of lateritic soil – cement with iron ore tailings mixtures

Property		Source of variation	Degree of freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	OMC	Cement	4	26.27	1.03E-07	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	42.76	5.27E-10	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	OMC	Cement	4	118.23	1.28E-13	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	156.59	2.52E-15	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	OMC	Cement	4	27.94	6.16E-08	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	44.89	3.39E-10	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are given in Tables A58 – 60 in the Appendix A.

4.3.2.2 Effect of compactive effort on optimum moisture content

The variations of the OMC of lateritic soil – cement – iron ore tailings with compaction energy are presented in Figures 4.39 – 4.43. It was observed that generally OMC decreased with increase in compaction energy in the order of BSL, WAS and BSH compaction energy levels.

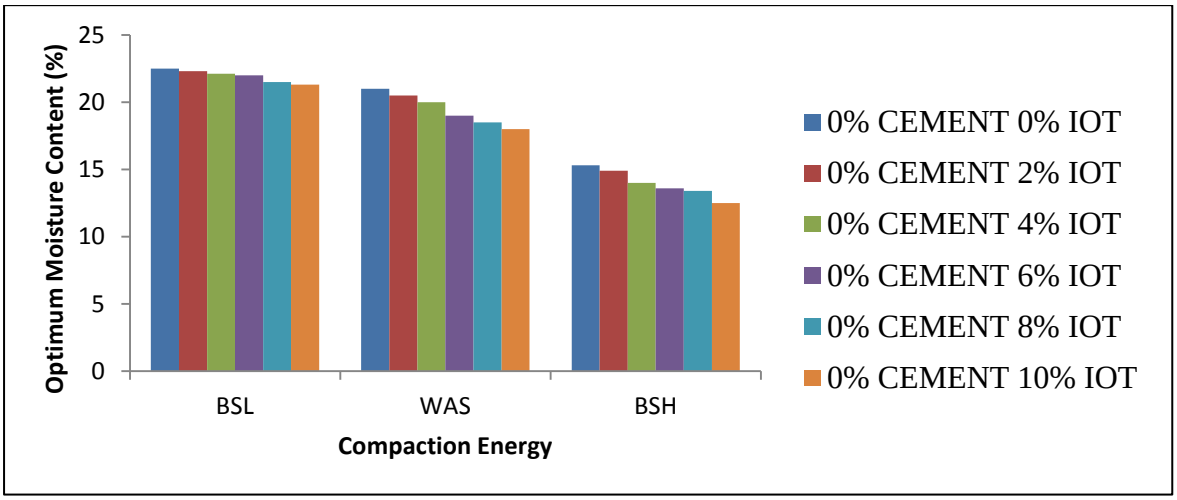


Figure 4.39: Variation of optimum moisture content of lateritic soil – 0 % cement – iron ore tailings mixtures with compaction energy

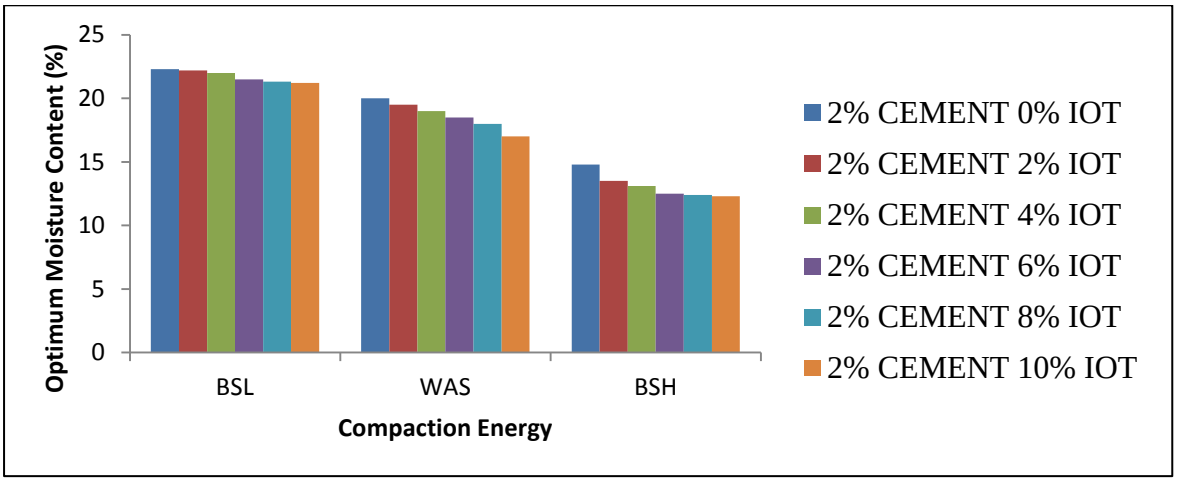


Figure 4.40: Variation of optimum moisture content of lateritic soil – 2 % cement – iron ore tailings mixtures with compaction energy

The OMC values recorded at 4 % cement / 6 % IOT treatment were 21.3 % for BSL, 17.5 % for WAS and 12.3 % for BSH compaction energies (see Figure 4.41).

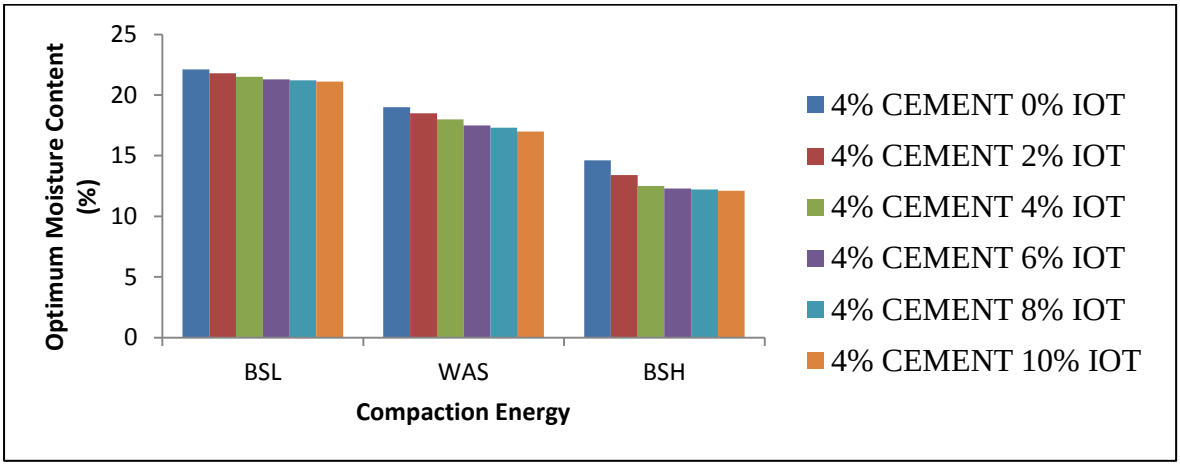


Figure 4.41: Variation of optimum moisture content of lateritic soil – 4 % cement – iron ore tailings mixtures with compaction energy

The optimum moisture content values for 6 % cement / 6 % IOT treatment were 21.2 %, 17.3 % and 12.2 % for BSL, WAS and BSH compactions respectively (see Figure 4.42).

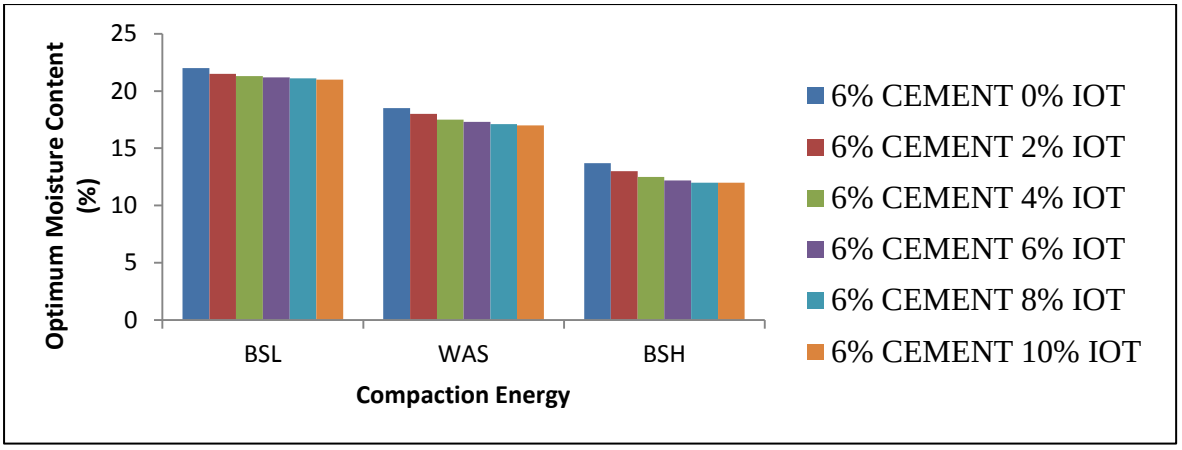


Figure 4.42: Variation of optimum moisture content of lateritic soil – 6 % cement – iron ore tailings mixtures with compaction energy

Similarly, 21.2 %, 17.2 % and 12.2 % were the OMC values recorded for BSL, WAS and BSH compactions, respectively, at 8 % cement / 6 % IOT treatment (see Figure 4.43).

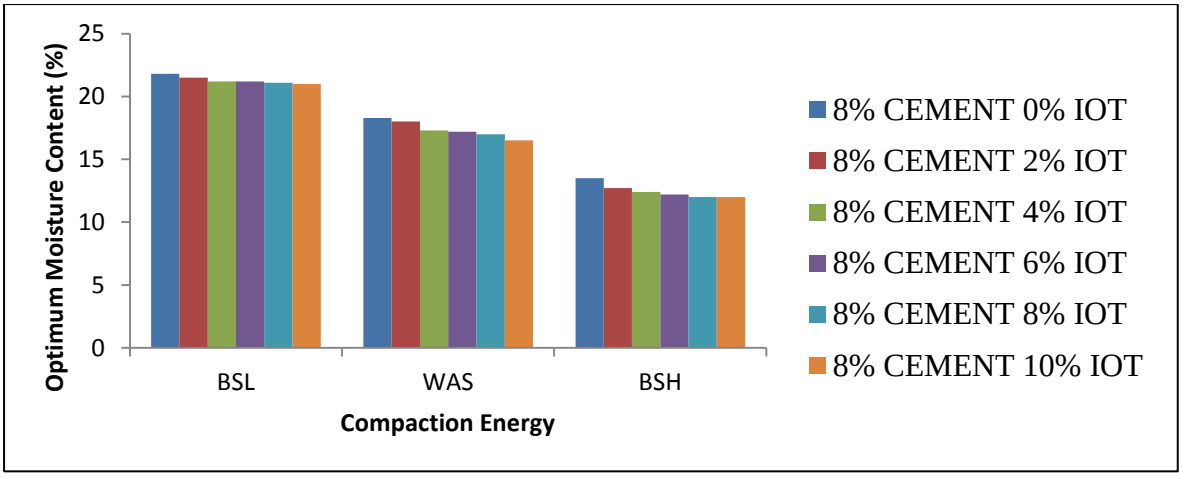


Figure 4.43: Variation of optimum moisture content of lateritic soil – 8 % cement – iron ore tailings mixtures with compaction energy

The decrease in OMC with higher compactive effort according to Osinubi (1999) is not unconnected to the ease with which flocculated aggregates are broken down, shear planes destroyed and large poles eliminated at higher compaction energies. Detailed test results are shown in Tables A17 – 19 in the Appendix A.

4.3.2.3 Regression analysis for optimum moisture content

The results of regression analysis for optimum moisture content showed that the optimum moisture content was also influenced by the grading properties, specific gravity and compactive effort applied. The geotechnical properties considered for these analyses include the percentages of sand, silt and clay fractions alongside their respective specific gravities. The regression equation showed that the optimum moisture content of the stabilised soil is influenced by the clay, silt and sand fractions present in the soil, iron ore tailings content, cement content, specific gravity as well as compactive effort. The positive coefficient of clay, silt and sand fractions 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 coefficient of multiple determination value (R^2) showed a strong relationship between optimum moisture content and the parameters with R^2 value of 0.957. Generally the coefficient of multiple determination values (R^2) of 0.968 for maximum dry density and 0.957 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

$$\mathrm{OMC} = 26.140 - 0.00816\mathrm{C} - 0.0839\mathrm{IOT} + 0.10091\mathrm{Sa} + 0.11904\mathrm{Si} + 0.11834\mathrm{Cl} - 7.07894\mathrm{Gs} - 4.29167\mathrm{CE} \quad (4.2)$$

where; OMC = Optimum moisture content, C = Cement content, IOT = Iron ore tailing content, Cl = Clay, Si = Silt, Sa = Sand, Gs = Specific gravity, CE = Compactive effort. Detailed test results are shown in Table 4.13

Table 4.13 Regression analysis for optimum moisture content of lateritic soil – cement – iron ore tailings mixtures

Dependent variable	Independent variable	Coefficients	p-value	Adjusted R^2	F
OMC	Intercept	26.14012428	0.312343928	0.957139752	9.30192E-55
	Cement content	-0.008157365	0.934536548		
	Iron ore tailings content	-0.083904446	0.212779275		
	Sand	0.100910807	0.716823788		
	Silt	0.119043889	0.677120133		
	Clay	0.118336809	0.677382948		
	Specific gravity	-7.078936547	0.103921493		
	Compactive effort	-4.291666667	1.85243E-58		

4.4 Strength Characteristics

4.4.1 Unconfined compressive strength

Over the years, unconfined compressive strength (UCS) test has been the most common and suitable method of evaluating the strength of stabilized soil. It is the main test recommended for the determination of the required amount of additive to be used in the stabilization of soil (Singh, 1991). According to Ola (1983), it is an important factor in the evaluation of the design criteria for the use of soil as a pavement material.

4.4.1.1 Effect of iron ore tailings on unconfined compressive strength

The variation of UCS of lateritic soil – cement mixtures with iron ore tailings content for BSL, WAS and BSH compactions and the different curing periods considered are shown in Figures 4. 44 – 4.52. The UCS of lateritic soil – cement mixtures increased with up to 6 % IOT content and thereafter decreased. For BSL compaction it was observed that after 7 days

curing period the UCS value increased. Peak UCS values of 996.1, 2590.4, 3783.6, and 3578.8 kN/m^2 were recorded for 2, 4, 6 and 8 %cement / 6 % IOT content, respectively (see Figure 4.44).

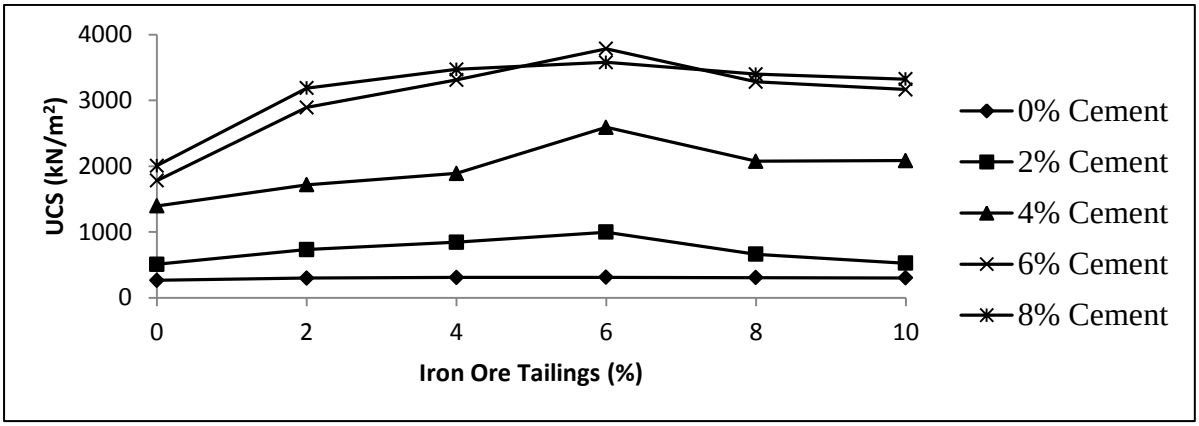


Figure 4.44: Variation of unconfined compressive strength (7 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

The observed trend at BSL compaction energy was similar to those for WAS and BSH compaction energy levels with the peak UCS values occurring at the 6% IOT at specific cement contents after 7 days curing period. However, the peak UCS values at these energy levels are higher than those in the BSL compaction energy (see Figures 4.45 and 4.46). Also, it was observed that addition of up to 4 % cement, there was sharp increase in UCS values (see Figures 4.44 - 4 52). Thus, 4 % cement appears to be a 'transition binder content' while at 6 % and 8 % cement content the strength values appear to be close to each other for all values of IOT content, regardless of compactive effort.

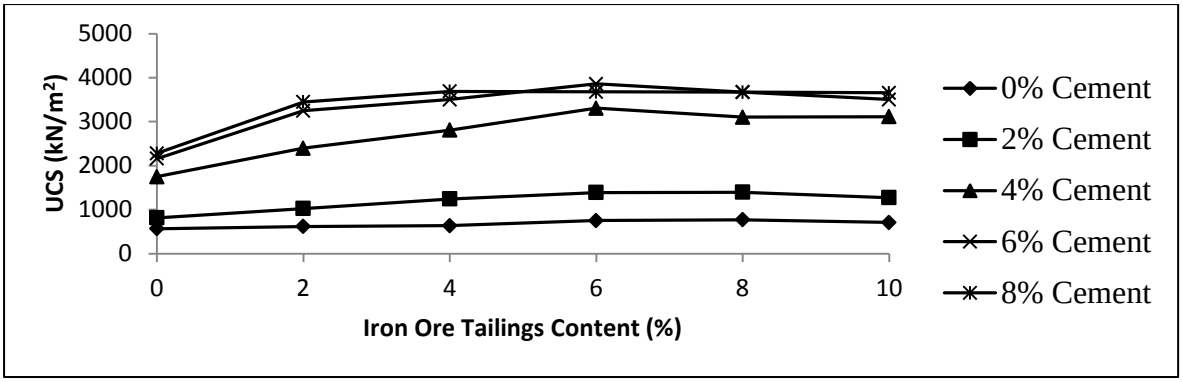


Figure 4.45: Variation of unconfined compressive strength (7 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

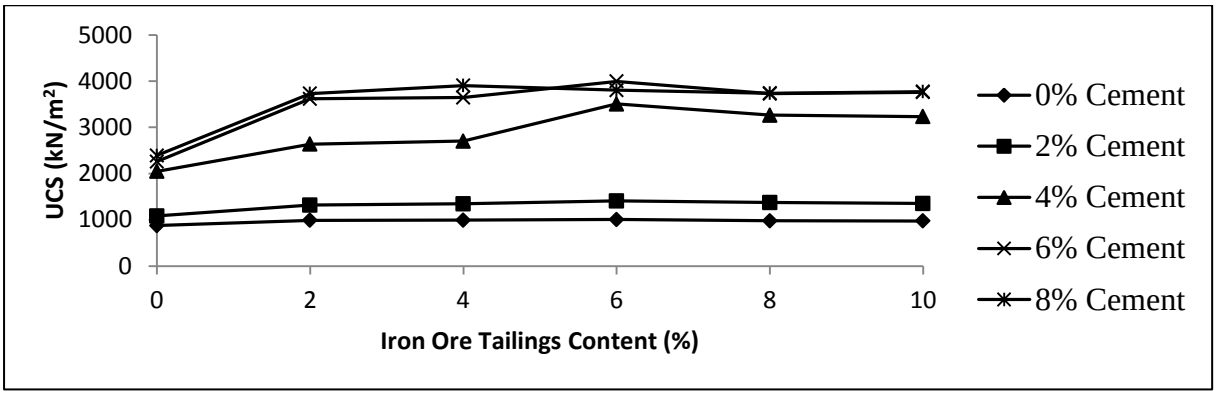


Figure 4.46: Variation of unconfined compressive strength (7 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction)

Similar trend was observed for both 14 and 28 days curing period, at BSL, WAS and BSH compaction energies (see Figures 4.47 – 4.52).

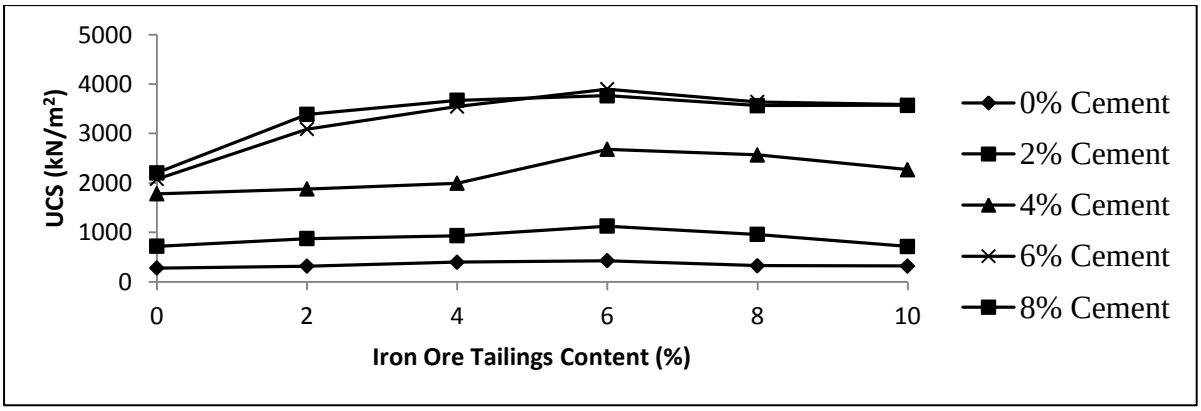


Figure 4.47: Variation of unconfined compressive strength (14 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

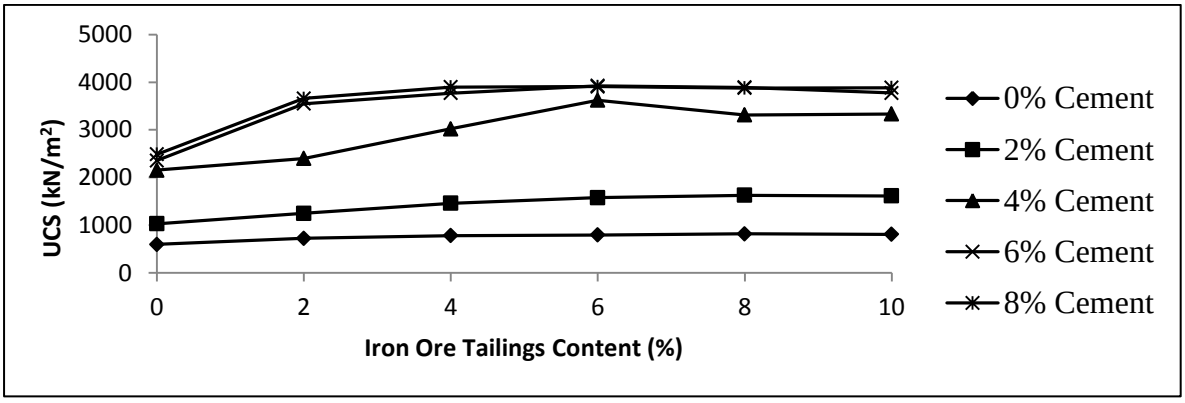


Figure 4.48: Variation of unconfined compressive strength (14 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

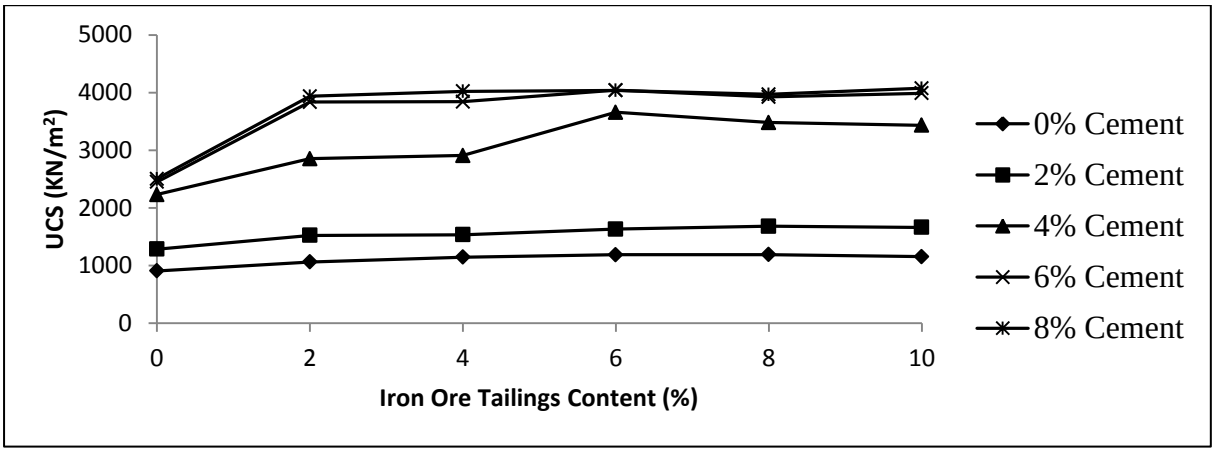


Figure 4.49: Variation of unconfined compressive strength (14 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction).

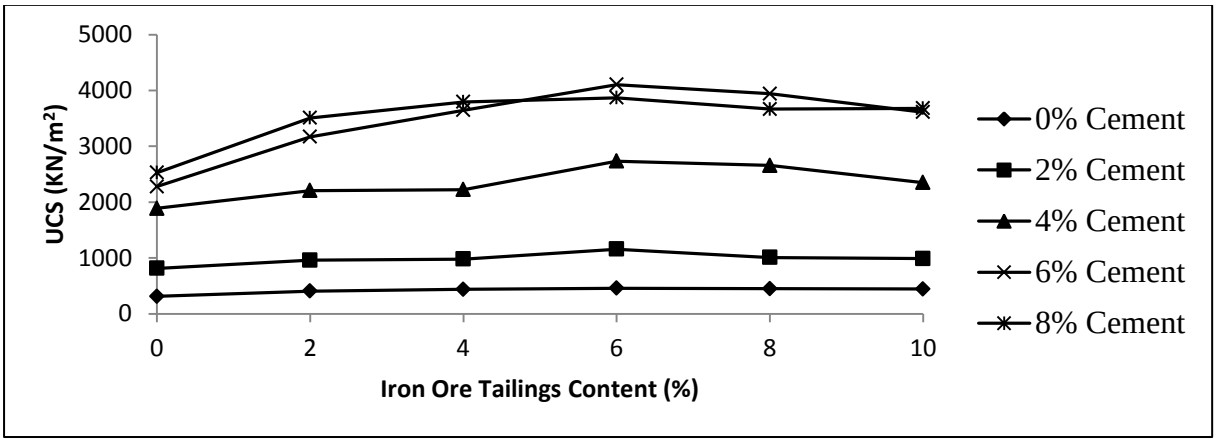


Figure 4.50: Variation of unconfined compressive strength (28 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

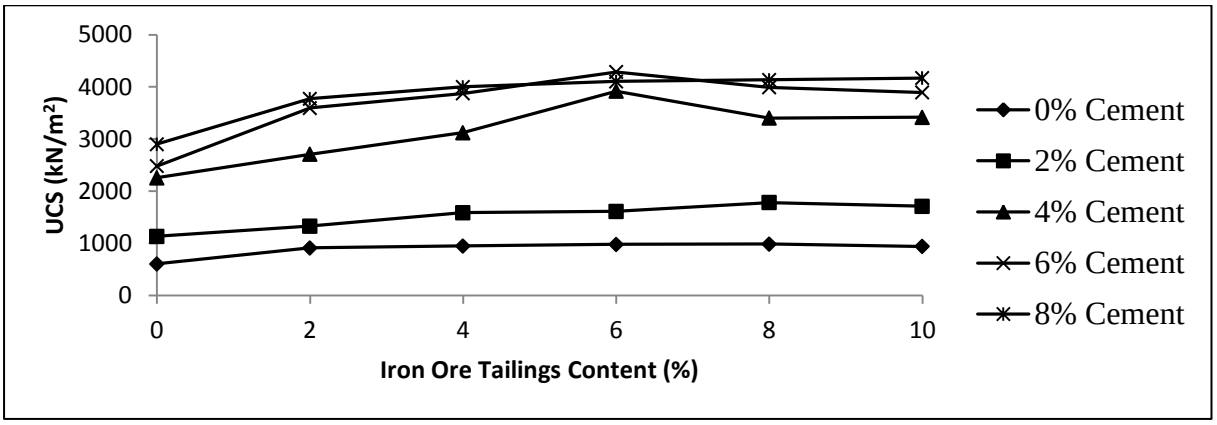


Figure 4.51: Variation of unconfined compressive strength (28 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

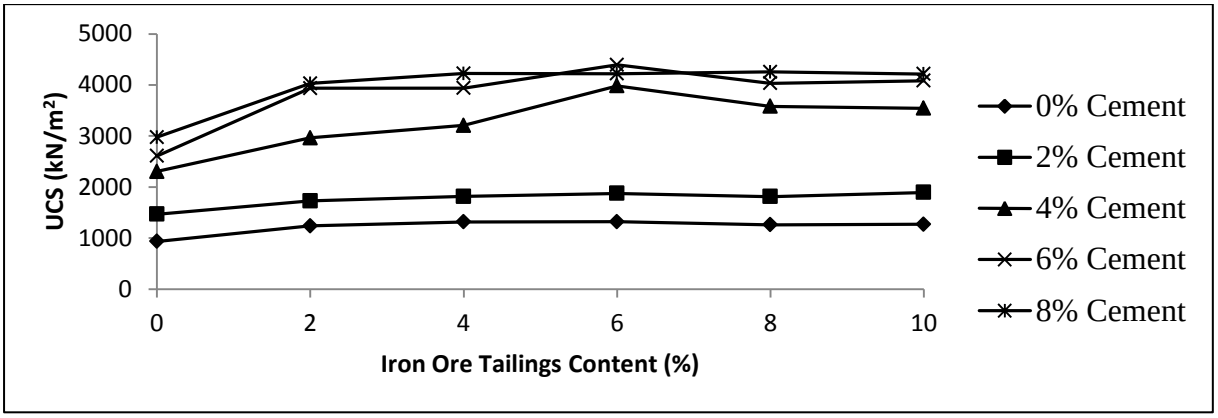


Figure 4.52: Variation of unconfined compressive strength (28 days curing period) of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction)

The pozzolanic reaction between the lime librated from the hydration of cement and the pozzolanic IOT to form secondary cementitious materials may be responsible for the increase in strength (Osinubi and Medubi, 1997a). The subsequent decrease in UCS values beyond 6 % iron ore tailing content for all cement contents and compactive efforts considered may be due to insufficient water required to complete the pozzolanic reaction (Osinubi, 1999). Also, greater fraction of iron ore tailing occupying the soil matrix beyond 6% IOT causes the reduction in the UCS. Detailed test results are given in Tables A20 – 28 in the Appendix A.

4.4.1.2 Effect of compaction energy on the unconfined compressive strength

The UCS increased with increase in compaction energy in the order of BSL, WAS and BSH compaction energies. This observed trend was noted from the resultant peak UCS values recorded at the three compactive efforts considered in this study. For 7 days curing period, the maximum peak UCS values of 3783.64, 3860.97 and 3993.14 kN/m^2 were recorded for BSL, WAS and BSH compaction energies respectively (see Figure 4.53)

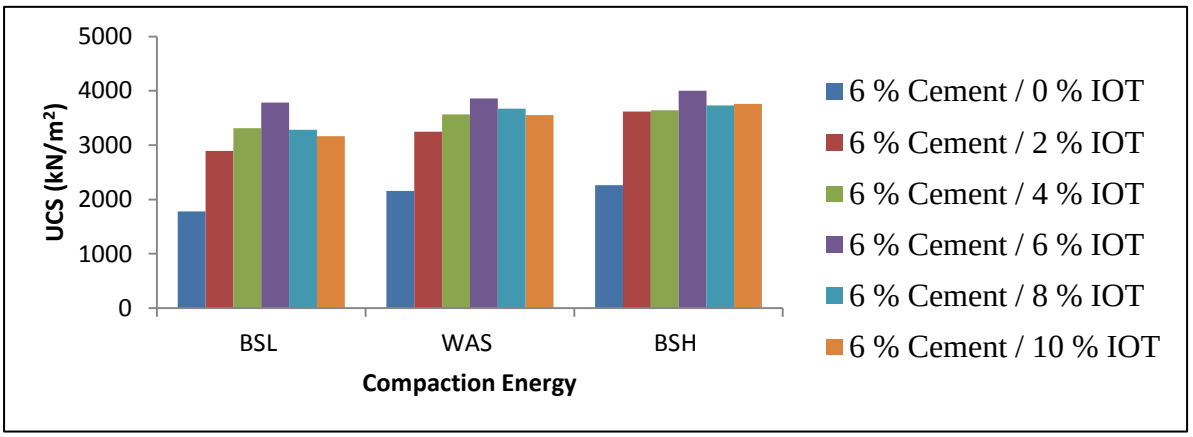


Figure 4.53: Variation of unconfined compressive strength (7 days curing period) of lateritic soil – 6% cement – iron ore tailings mixtures with compactive efforts

The 14 days curing period has peak UCS values of 3897.71, 3922.86 and 4041.17 kN/m2 for the respective compaction energies of BSL, WAS and BSH (see Figure 4.54).

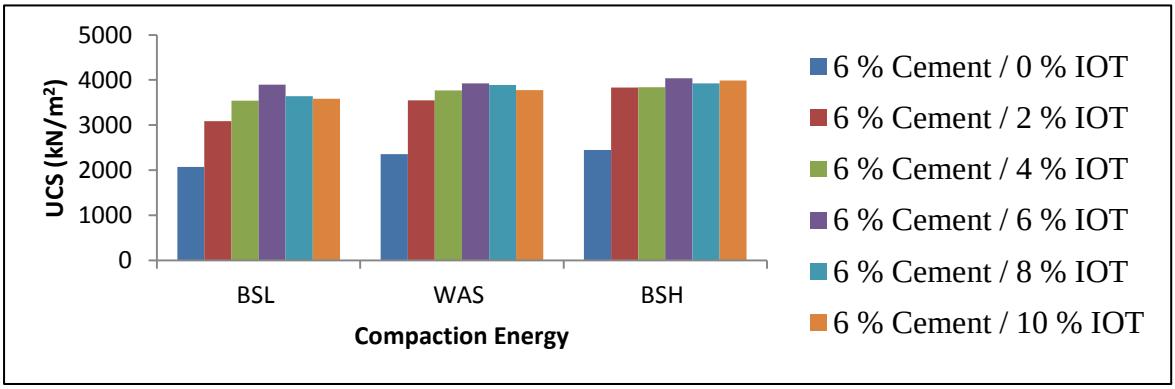


Figure 4.54: Variation of unconfined compressive strength (14 days curing period) of lateritic soil – 6% cement – iron ore tailings mixtures with compactive efforts

Higher peak UCS values of 4105.28, 4286.5 and 4392.21 kN/m^2 were recorded at BSL, WAS and BSH compactions respectively, after 28 days curing period (see Figure 4.55). The increase could be due to increase in maximum dry densities recorded for the three compactive efforts considered (Mustapha, 2006). Similar trends were observed for the various soil – cement – IOT mixtures.

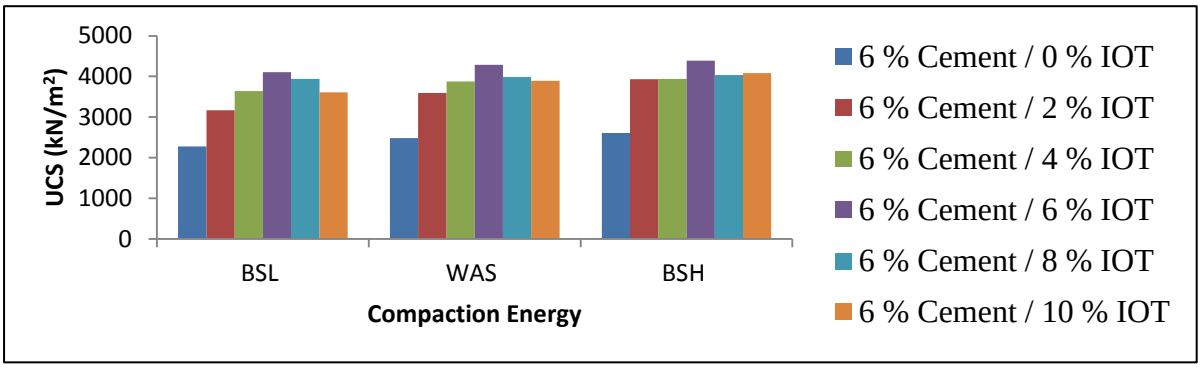


Figure 4.55: Variation of unconfined compressive strength (28 days curing period) of lateritic soil – 6% cement – iron ore tailings mixtures with compactive efforts

4.4.1.3 Effect of curing period on the unconfined compressive strength

The effects of curing period on the unconfined compressive strength of the soil – cement – IOT mixtures for BSL, WAS and BSH compactive efforts are shown in Figures 4.56 – 4.58. The results show that UCS values increased with increase in curing period. The 7, 14 and 28 days peak UCS values of 3783.64, 3897.71 and 4105.28 kN/m^2 , respectively, were recorded for specimens compacted with BSL energy (see Figure 4.56).

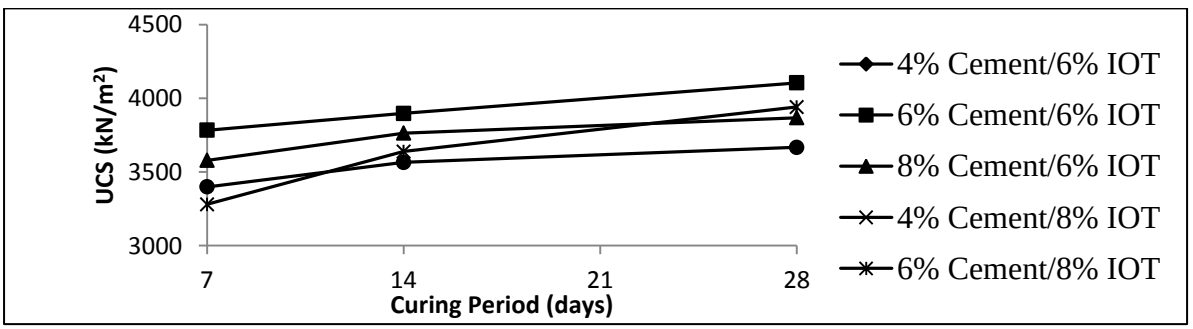


Figure 4.56: Variation of unconfined compressive strength of lateritic soil – cement – iron ore tailngs mixtures with curing period (BSL compaction)

For WAS compaction, the peak UCS values recorded at 7, 14 and 28 days were 3860.97, 3922.86 and 4286.5 kN/m^2 respectively. The highest UCS values of 3993.14, 4041.17 and 4392.21 were recorded at the BSH compaction after 7, 14 and 28 days of curing respectively (see Figures 4.57 and 4.58).

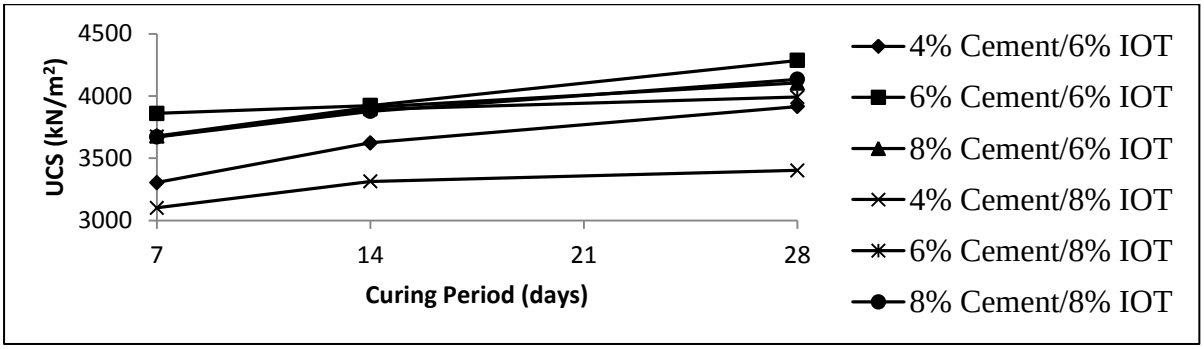


Figure 4.57: Variation of unconfined compressive strength of lateritic soil – cement – iron ore tailings mixtures with curing period (WAS compaction)

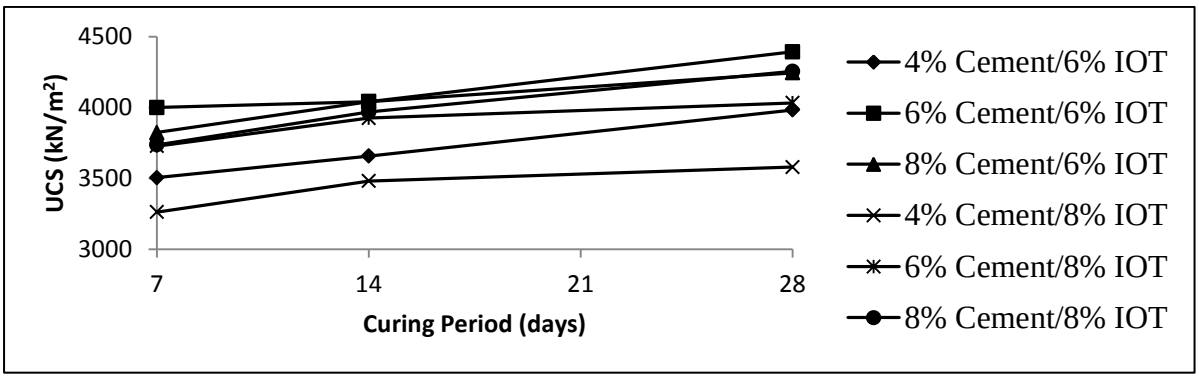


Figure 4.58: Variation of unconfined compressive strength of lateritic soil – cement – iron ore tailings mixtures with curing period (BSH compaction)

The trend of increase in UCS values with curing period can be attributed to time dependent strength gain of the mixture due to pozzolanic reaction. The strength gain was due to the availability of water that enhanced hydration reaction between lime liberated from the hydration reaction of cement and the iron ore tailing to form secondary cementation compounds (Diamond *et a*l., 1964; Sloane, 1965; Ormsby and Kinter, 1973a, b; Choquette et al., 1987; Osinubi and Medubi, 1997a; Mohamed and Anita 1998; Mohamed *et al* 2001; Mustapha 2006). Detailed test results are given in Tables A20 – 28 in the Appendix A.

The result of the two – way analysis of variance (ANOVA) of the 7-day UCS results (see Table 4.14) shows that for BSL, WAS and BSH compactive efforts, the effects of cement (F_{CAL} = 110.19, 138.63, 100.72 > F_{CRIT} = 2.87) and iron ore tailings (F_{CAL} = 6.70, 11.69, 7.39 > F_{CRIT} = 2.71) on lateritic soil were statistically significant.

Table 4.14: Two-way analysis of variance for unconfined compressive strength (7 days curing period) of lateritic soil – cement – iron ore tailings mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	7 Days curing	Cement	4	110.19	2.51E-13	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	6.70	0.0008089	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	7 Days curing	Cement	4	138.63	2.78E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	11.69	2.21E-05	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	7 Days curing	Cement	4	100.72	5.90E-13	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	7.39	0.0004545	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are given in Tables A61 – 63 in the Appendix A.

The result of the two – way analysis of variance (ANOVA) performed on the 14-days UCS results (Table 4.15) shows that for BSL,WAS and BSH compactions, the effects of cement (F_{CAL} = 121.91, 139.67, 116.72 > F_{CRIT} = 2.87) and iron ore tailing (F_{CAL} = 6.03, 10.75, 9.66 > F_{CRIT} = 2.71), respectively, on lateritic soil were statistically significant.

Table 4.15: Two - way analysis of variance for unconfined compressive strength (14 days curing period) of lateritic soil - cement – iron ore tailings mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	14 days curing	Cement	4	121.91	9.56E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	6.03	0.001473	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	14 days curing	Cement	4	139.67	2.59E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	10.75	3.98E-05	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	14 day curing	Cement	4	116.72	1.45E-13	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	9.66	8.26E-05	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are shown in Tables A64 – 66 in the Appendix A.

Similarly, the two – way analysis of variance (ANOVA) of the 28-day UCS results for BSL, WAS and BSH compactions (see Table 4.16) shows that the effects of cement (F_{CAL} = 159.85, 174.76, 142.10 > F_{CRIT} = 2.87) and iron ore tailing (F_{CAL} = 6.68, 13.42, 11.59 > F_{CRIT} = 2.71), respectively, on lateritic soil were statistically significant.

Table 4.16: Two-way analysis of variance for unconfined compressive strength (28 days curing) of lateritic soil – cement – iron ore tailings mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	28 days curing	Cement	4	159.85	7.05E-15	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	6.68	0.000825	2.71	$F_{CAL}>F_{CRIT}$, Significant
WAS	28 day curing	Cement	4	174.76	2.97E-15	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	13.42	8.19E-06	2.71	$F_{CAL}>F_{CRIT}$, Significant
BSH	28 day curing	Cement	4	142.10	2.19E-14	2.87	$F_{CAL}>F_{CRIT}$, Significant
		IOT	5	11.59	2.35E-05	2.71	$F_{CAL}>F_{CRIT}$, Significant

Detailed test results are shown in Tables A67 – 69 in the Appendix A.

4.4.1.4 Comparison of (UCS) results with recommended standard

Road Note 31(1993) recommends the range of 3000 – 6000 kN/m^2 for specimen cured for 7 days, as a road base for heavily trafficked roads (CB1) and the range of 1500 – 3000 kN/m^2 as a road base for lightly trafficked roads (CB2). Also, Singh (1991) recommends UCS of 1720 kN/m^2 for specimen cured for 7 days for lightly trafficked road bases (CB2) and from 2750 – 3450 kN/m^2 for heavily trafficked road bases (CB1). In the same vein, the Nigerian General Specifications (1997) also recommended 1720 kN/m^2 as criterion for lightly trafficked road bases when specimens are cured for 7 days. Adopting 3450 kN/m^2 as the UCS value recommended for heavily trafficked road bases, which is in the range of both Road Note 31 and Singh (1991), only peak UCS values of 3783.64 kN/m^2 at 6% cement/ 6% IOT, 3578.84 kN/m^2 at 8% cement/ 6% IOT as well as 3470.72 kN/m^2 at 8% cement/ 4% IOT are adequate for (CB1) for road base at BSL compaction level. At WAS compaction level, 6% cement admixed with 4% up to 10% IOT and 8% cement admixed with 4% up to 10% IOT are adequate for heavily trafficked (CB1) road bases, with the peak values of 3860.97 kN/m^2 at 6% cement/ 6% IOT and 3688.68 kN/m^2 at 8% cement/ 4% IOT. Similarly, for BSH compaction energy, 4% cement/ 6% IOT, 6% cement admixed with 2% up to 10% IOT and 8% cement admixed with 2%, 4%, 6%, 8% and 10% IOT were adequate, with peak values of 3993.14 kN/m^2 at 6% cement/ 6% IOT and 3903.74 kN/m^2 at 8% cement/ 4% IOT blend.

For 1720 kN/m^2 recommended for light traffic (CB2) road bases by Road Note 31 (1993), Singh (1991) and Nigerian General Specifications (1997) after 7 days of curing, all samples treated with 4%, 6% and 8% cement with varying IOT blend from 2% up to 10% IOT were adequate for the three compactive efforts considered in this study.

4.4.1.5 Regression analysis for unconfined compressive strength

The geotechnical properties considered as the independent variable for this analysis include the cement content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter, the UCS is considered as the dependent variable. The extent to which these parameters influence the unconfined compressive strength after 28 days curing of the stabilized soil which is a function of the coefficient of each parameter is shown in Equation (4.3). The regression equations showed that the unconfined compressive strength of the treated soil is influenced by the cement content, iron ore tailing content, compactive effort, the plasticity index as well as the percentage of fines. The coefficient of multiple determination value (R^2) shows a strong relationship between UCS of the treated soil and the parameters with R^2 value of 0.88. The formation of crystalline product of pozzolanic reactions is responsible for strength gain in cement stabilized soil and the strength gain is time dependent and may continue for a long period of time (Mallela *et al.,* 2004; Osinubi and Medubi, 1997a).

The regression equation is

$$\mathrm{UCS} = 3890.69 + 285.8\mathrm{C} + 4.86\mathrm{IOT} - 21.92\mathrm{PF} - 75.35\mathrm{PI} + 335.88\mathrm{CE} \qquad (4.3)$$

$R^2 = 0.881$

where:

UCS = Unconfined compressive strength after 28 days curing

C = Cement content, IOT = Iron ore tailing content, PF = Percentage fine, Pl = Plasticity index, CE = Compactive effort. Detailed test results are shown in Table 4.17

Table 4.17 Regression analysis for unconfined compressive strength of lateritic soil – cement – iron ore tailings mixtures

Dependent variable	Independent variable	Coefficients	p-value	Adjusted R^2	F
UCS	Intercept	3890.690407	0.010371548	0.880694727	2.6271E-38
	Cement content	285.7989694	8.40591E-06		
	Iron ore tailings content	4.857502495	0.922139844		
	Percentage fine	-21.92441639	0.036078707		
	Plasticity index	-75.35053179	0.143617329		
	Compactive effort	335.8798333	1.05998E-07		

4.4.1.6 7 days curing and 7 days soaking periods

The variation of unconfined compressive strength (7 days curing + 7 days soaking) of lateritic soil - cement mixtures with iron ore tailings content is shown in Figures 4.59 – 4.61. In general, the UCS (7 days curing + 7 days soaking) values increased with higher compactive efforts and additives (cement and IOT) contents. The UCS values recorded for BSL compaction increased from 130.21 kN/m^2 for the natural soil to a peak value 3402.04kN/m^2 at 6 % cement - 6 % iron ore tailing treatment and thereafter reduced to 2783.83 kN/m^2 for 6 % cement 8 % iron ore tailing treatment. For WAS and BSH compaction the UCS value increased from 244.91 and 335.35 kN/m^2 to 3569.5 and 3737.14 kN/m^2, respectively, at 6 % cement - 6 % iron ore tailings treatment. Beyond this treatment no significant increase in UCS values were recorded due to the same reason as earlier mentioned. It is pertinent to state that the UCS values for the soaked specimens are lower compared to those obtained for 7 and 14 days curing periods probably due to the ingress of

water that resulted in loss of strength. Detailed test results are shown in Tables A29 – 31 in the Appendix A.

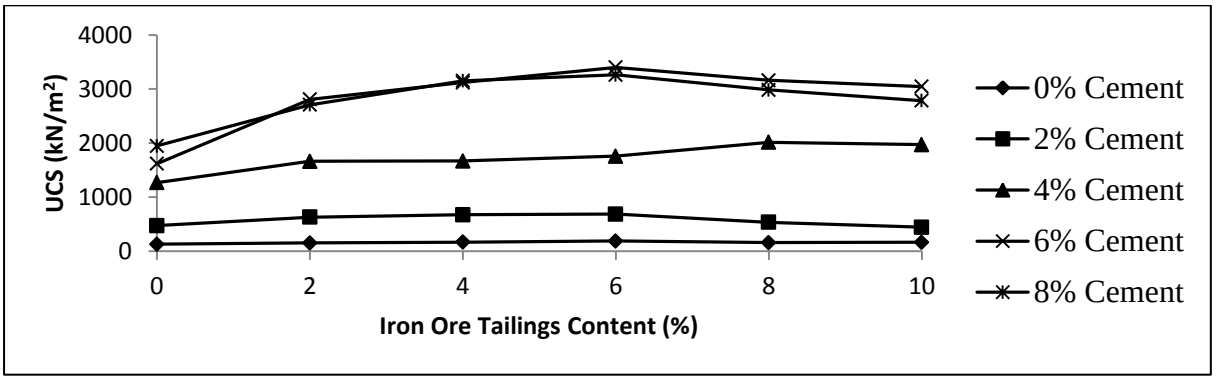


Figure 4.59: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of lateritic soil - cement mixtures with iron ore tailings content (BSL compaction)

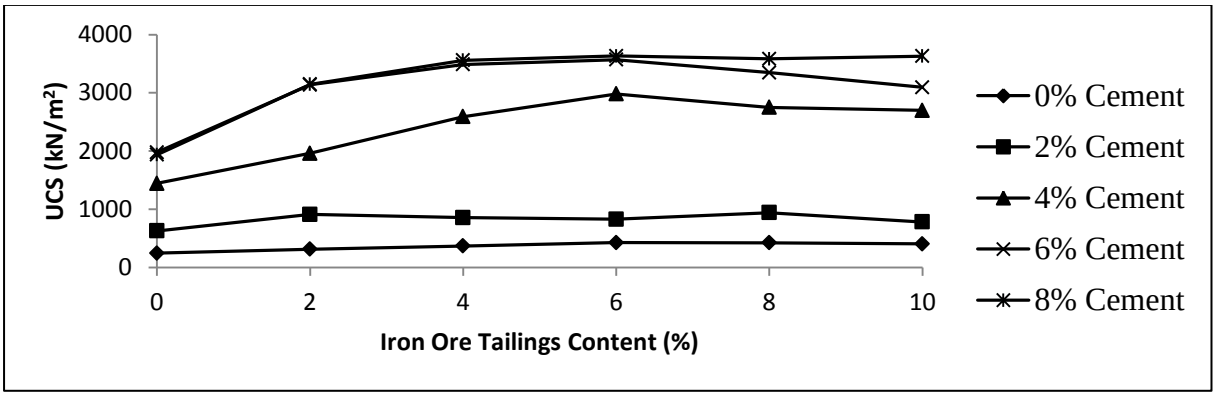


Figure 4.60: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of lateritic soil - cement mixtures with iron ore tailings content (WAS compaction)

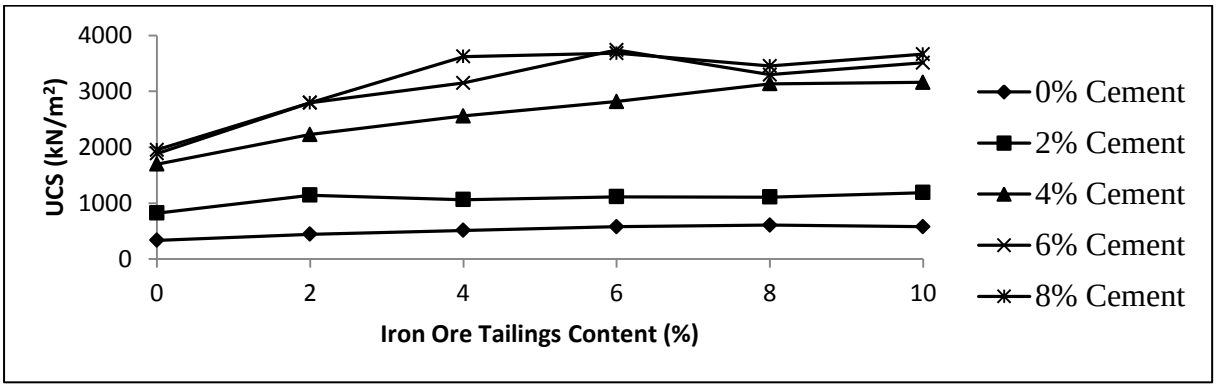


Figure 4.61: Variation of unconfined compressive strength (7 days curing + 7 days soaking) of lateritic soil - cement mixtures with iron ore tailings content (BSH compaction)

The two – way analysis of variance (ANOVA) of the 7-day curing and 7 days soaking UCS results for BSL,WAS and BSH compaction (Table 4.18) shows that the effects of

cement (F_{CAL} = 114.36, 107.04, 89.72 > F_{CRIT} = 2.87) and iron ore tailing (F_{CAL} = 4.77, 7.65, 8.69 > F_{CRIT} = 2.71), respectively, on lateritic soil were statistically significant.

Table 4.18 Two - way analysis of variance for unconfined compressive strength (7 days curing + 7 days soaking) of lateritic soil - cement – iron ore tailings mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	7c + 7s	Cement	4	114.36	1.76E-13	2.87	Fcal>Fcrit, significant
		IOT	5	4.77	0.004955	2.71	Fcal> Fcrit, significant
WAS	7c + 7s	Cement	4	107.04	3.31E-13	2.87	Fcal> Fcrit, significant
		IOT	5	7.65	0.000368	2.71	Fcal> Fcrit, significant
BSH	7c + 7s	Cement	4	89.72	1.76E-12	2.87	Fcal> Fcrit, significant
		IOT	5	8.69	0.000166	2.71	Fcal> Fcrit, significant

***NB: 7c + 7s** = 7 days curing + 7 days soaking*

Detailed test results are given in Tables A70 – 72 in the Appendix A.

4.5 Deformation Characteristics

4.5.1 Stress strain relationship

The variation of deviator stress with strain for the natural and stabilized soil is shown in Figures 4.62 – 4.76 for the various cement/IOT treatment with curing period and compactive effort as indicated. The shear stress of the various lateritic soil – cement – IOT mixtures is determined by subjecting three samples of each treatment to the unconfined compressive stress tests and the deviator stress determined at the point at which failure had occurred. The average value of the three samples represents the shear stress value for the given lateritic soil – cement – IOT mixtures. It was observed from test results that the shearing stress increases with increase in compactive efforts, additives as well as the curing periods.

For the BSL compaction energy, the shear stress value of 263.98 kN/m^2 recorded for the natural soil increased to 299.19 kN/m^2, 307.28 kN/m^2 and 310.37 kN/m^2 at 2 %, 4 % and 6 % IOT blend, respectively, after 7 days curing period. However, slight decreases in shear stress values were observed at 8 and 10 % IOT both having 305.6 and 300 kN/m^2 , respectively (see Figure 4. 62).

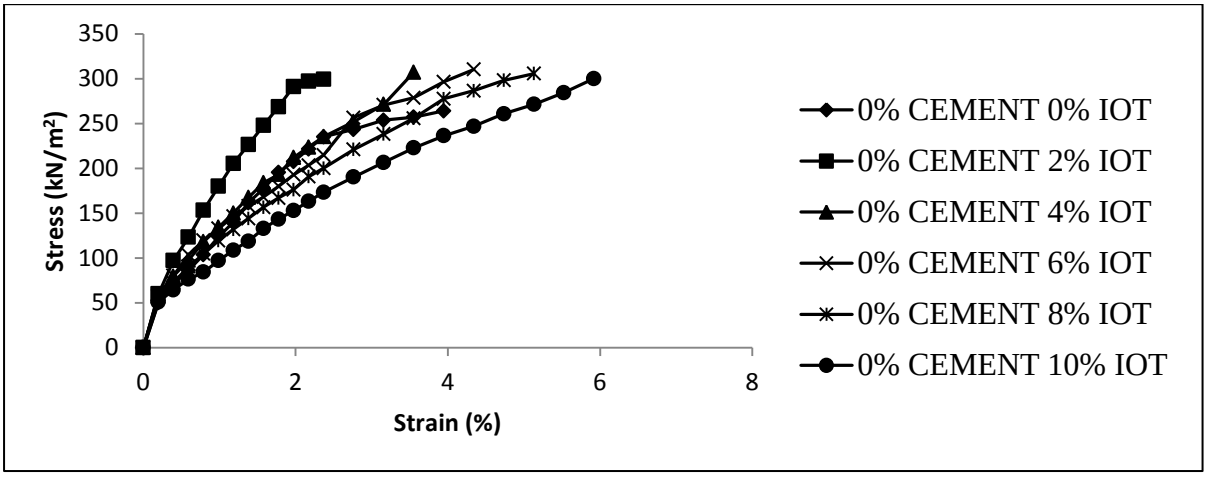


Figure 4.62: Stress-strain graph for lateritic soil – 0 % cement (7 days curing period) for varying iron ore tailings content (BSL compaction)

Increases in shear stress were also noticed with increase in cement contents with varying IOT contents after 7 days of curing. The deviator stress value increased from 996.14 kN/m^2 at 2 % cement/ 6 % IOT to 2590.38 kN/m^2 at 4 % cement/ 6 % IOT, 3783.64 kN/m^2 at 6 % cement/ 6 % IOT where it peaked then dropped to 3573 kN/m^2 at 8 % cement/ 6 % IOT (see Figures 4.63 – 4. 66). Similar trends were observed for all the varying cement/IOT lateritic soil mixtures.

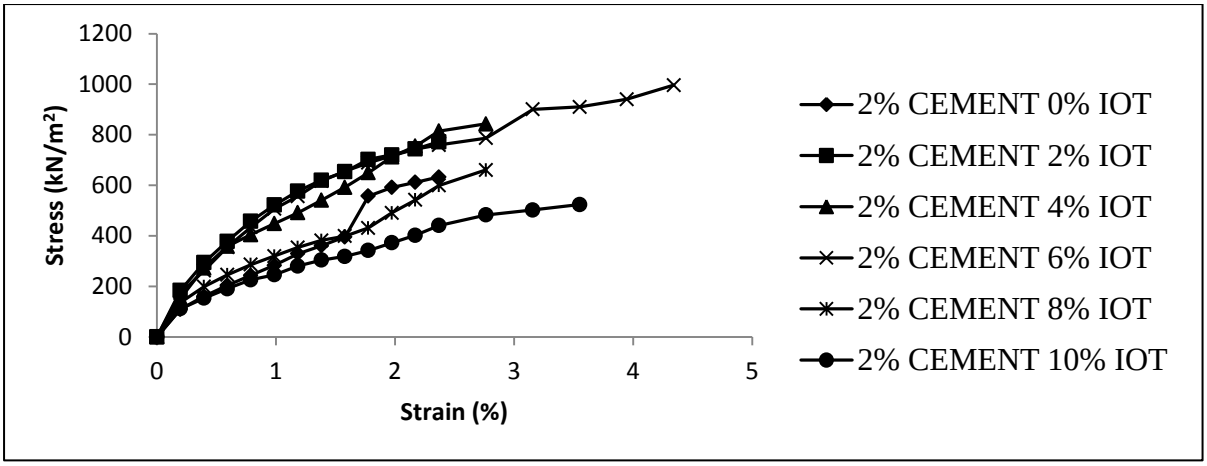


Figure 4.63: Stress-strain graph for lateritic soil – 2 % cement mixture (7 days curing period) for varying iron ore tailings content (BSL compaction)

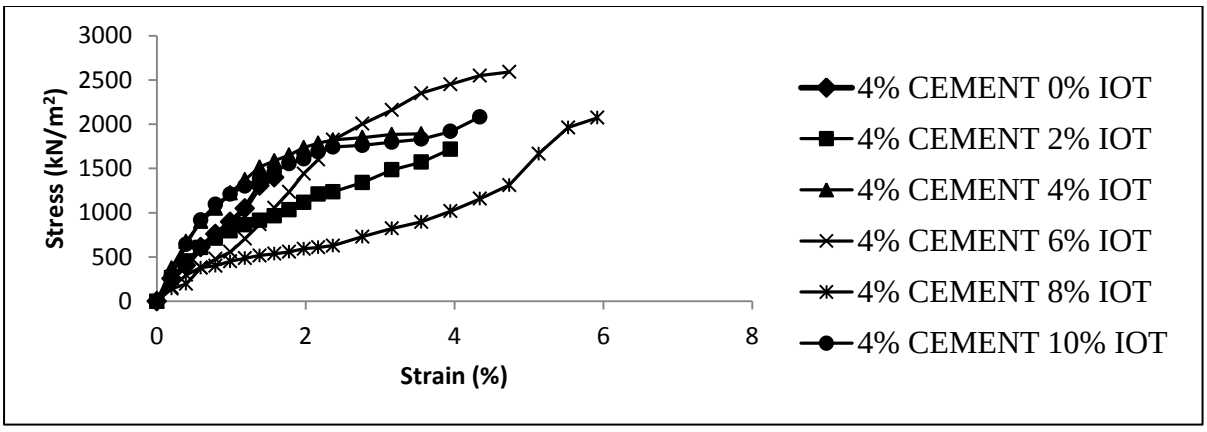


Figure 4.64: Stress-strain graph for lateritic soil – 4 % cement mixture (7 days curing period) for varying iron ore tailings content (BSL compaction)

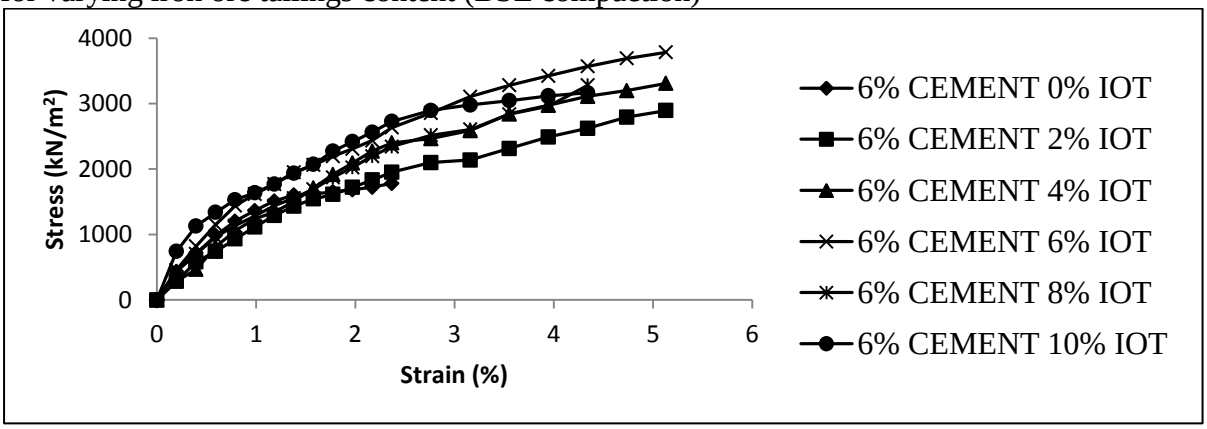


Figure 4.65: Stress-strain graph for lateritic soil – 6 % cement mixture (7 days curing period) for varying iron ore tailings content (BSL compaction)

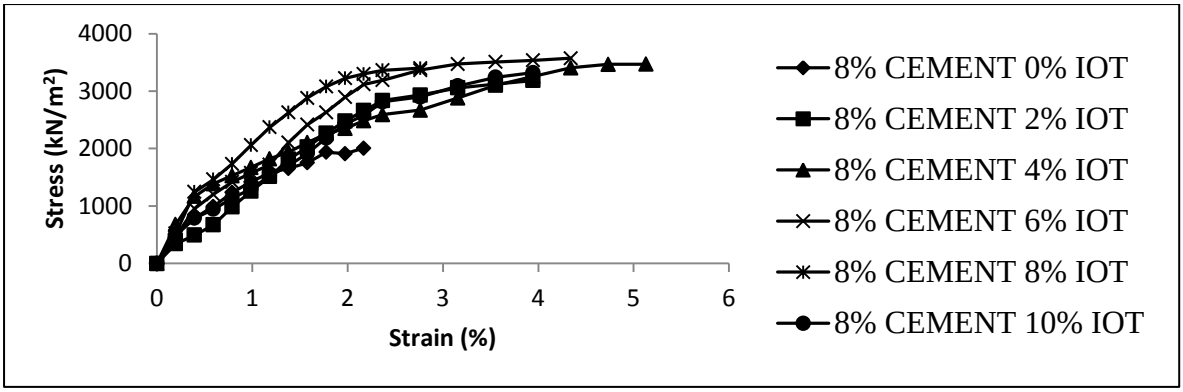


Figure 4.66: Stress-strain graph for lateritic soil – 8 % cement mixture (7 days curing period) for varying iron ore tailings content (BSL compaction)

At WAS compaction level, it was also observed that increase in IOT contents resulted to increase in shear stress values at varying specific cement contents. The shear stress increased from 1023.3 kN/m^2 at 2 % cement / 2 % IOT to 1244.43 kN/m^2 at 2 % cement / 4 % IOT, 1390.15 kN/m^2 at 2 % cement / 6 % IOT, and 1395.99 kN/m^2 at 2 % cement / 8 % IOT before reducing to 1270.58 kN/m^2 at 2 % cement / 10 % IOT for samples cured for 7 days (see Figure 4.67). As it was with BSL compaction, increase in cement contents also resulted to corresponding increases in the stress values. For instance, the stress value increased from 752 kN/m^2 at 0 % cement / 6 % IOT to 1390.13 kN/m^2, 3304.94 kN/m^2, 3809.97 kN/m^2 and 3678.42 kN/m^2 at 2, 4, 6 and 8 % cement, respectively, each treated with 6 % IOT content (see Figures 4.67 – 4.71). Similar trends were observed for the various lateritic soil – cement – IOT mixtures considered.

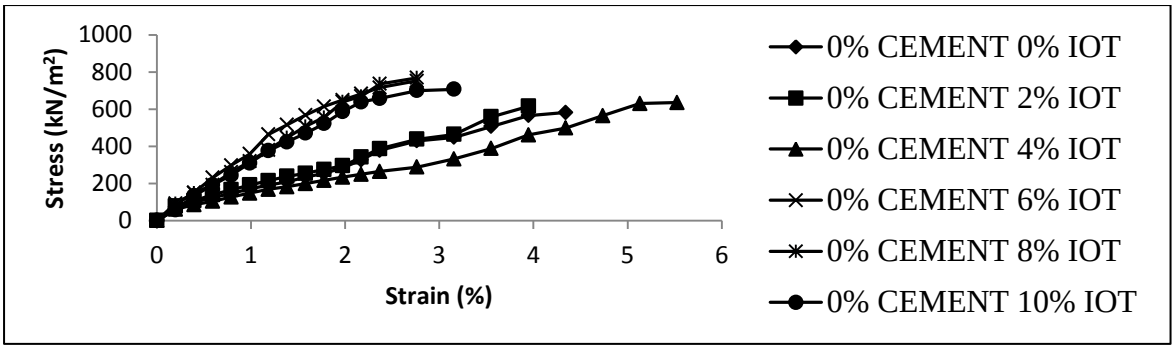


Figure 4.67: Stress-strain graph for lateritic soil – 0 % cement (7 days curing, period) for varying iron ore tailings content (WAS compaction)

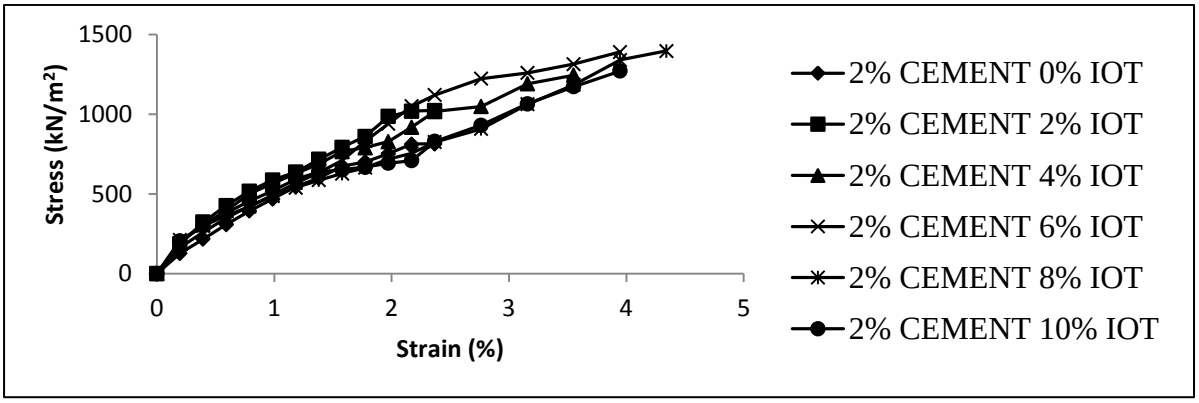


Figure 4.68: Stress-strain graph for lateritic soil – 2 % cement mixture (7 days curing period) for varying iron ore tailings content (WAS compaction)

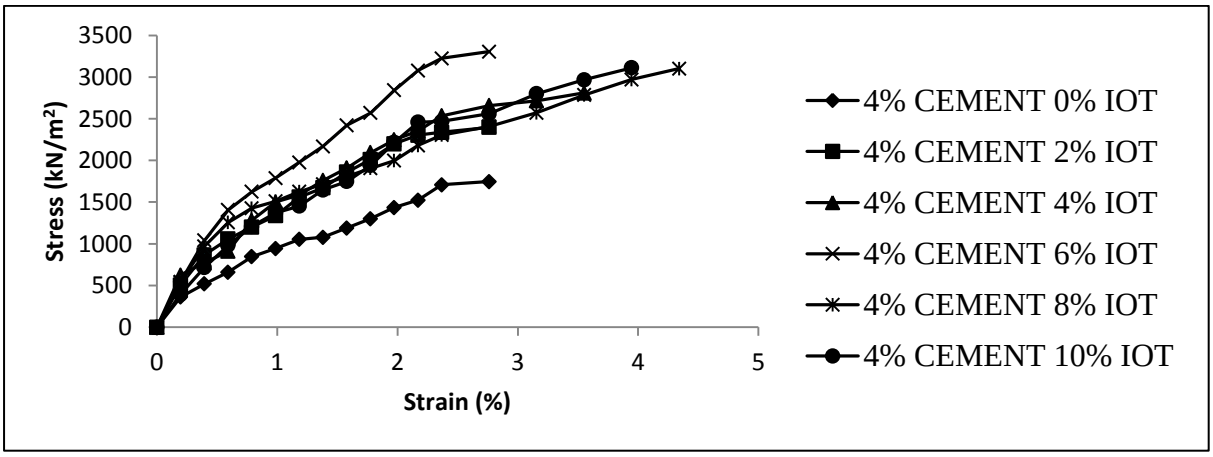


Figure 4.69: Stress-strain graph for lateritic soil – 4 % cement mixture (7 days curing period) for varying iron ore tailings content (WAS compaction)

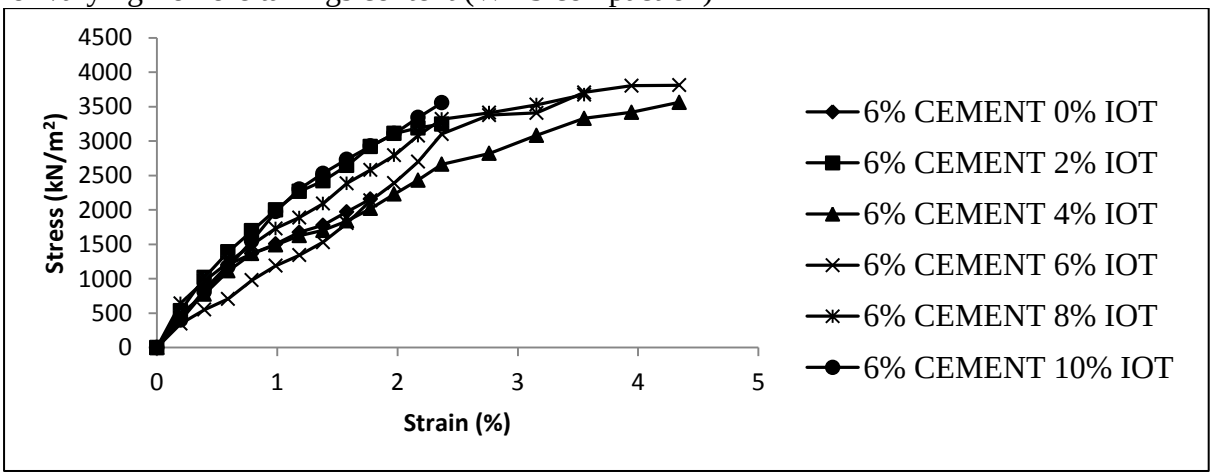


Figure 4.70: Stress-strain graph for lateritic soil – 6 % cement mixture (7 days curing period) for varying iron ore tailings content (WAS compaction)

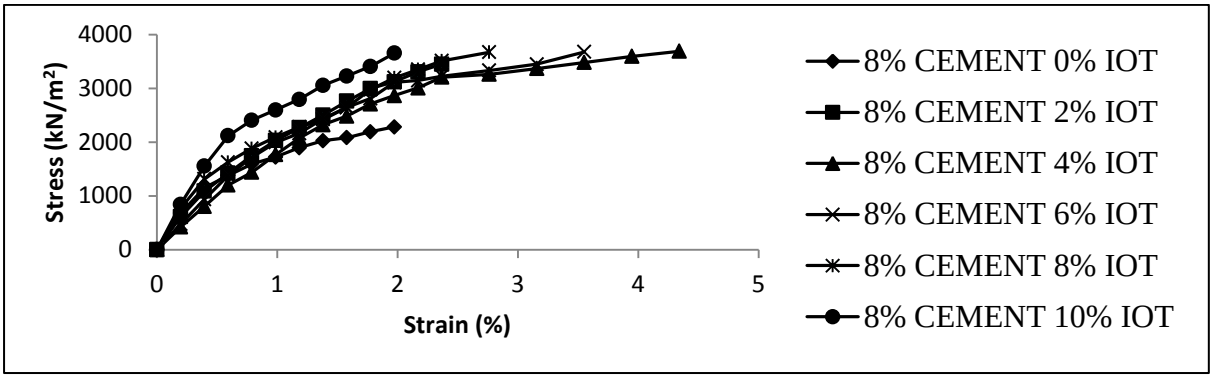


Figure 4.71: Stress-strain graph for lateritic soil – 8 % cement mixture (7 days curing period) for varying iron ore tailings content (WAS compaction)

BSH compaction also recorded similar trend of increased stress with increase in additives as observed for WAS and BSL compaction levels, though higher shear stress values were recorded as shown in Figures 4.72 - 4.76.

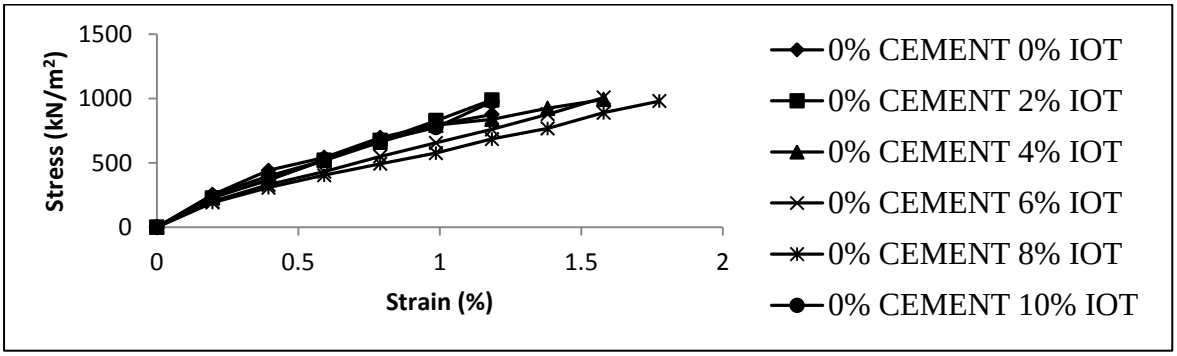


Figure 4.72: Stress-strain graph for lateritic soil – 0 % cement (7 days curing period) for varying iron ore tailings content (BSH compaction)

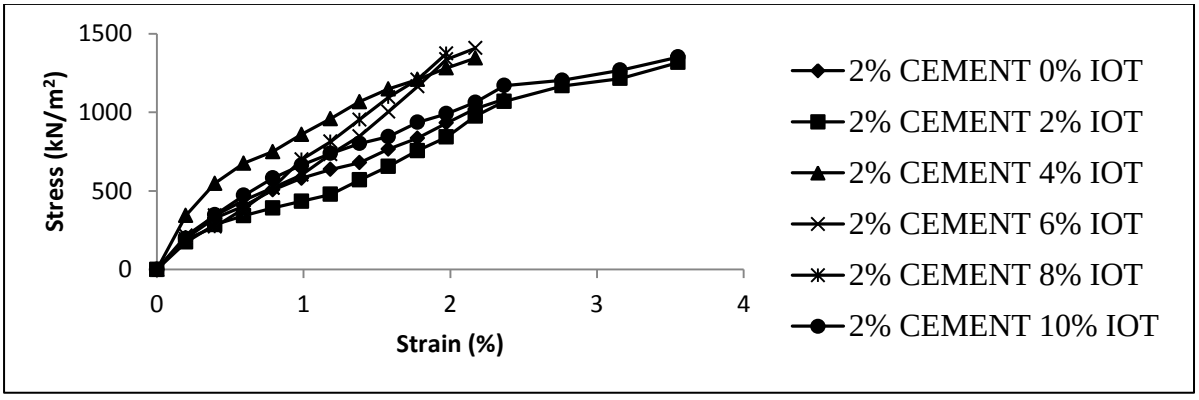


Figure 4.73: Stress-strain graph for lateritic soil – 2 % cement mixture (7 days curing period) for varying iron ore tailings content (BSH compaction)

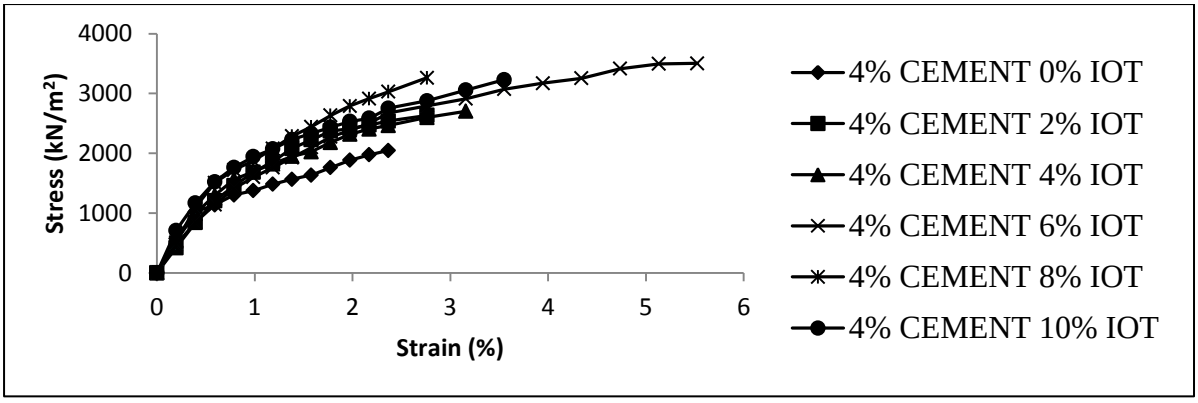


Figure 4.74: Stress-strain graph for lateritic soil – 4 % cement mixture (7 days curing period) for varying iron ore tailings content (BSH compaction)

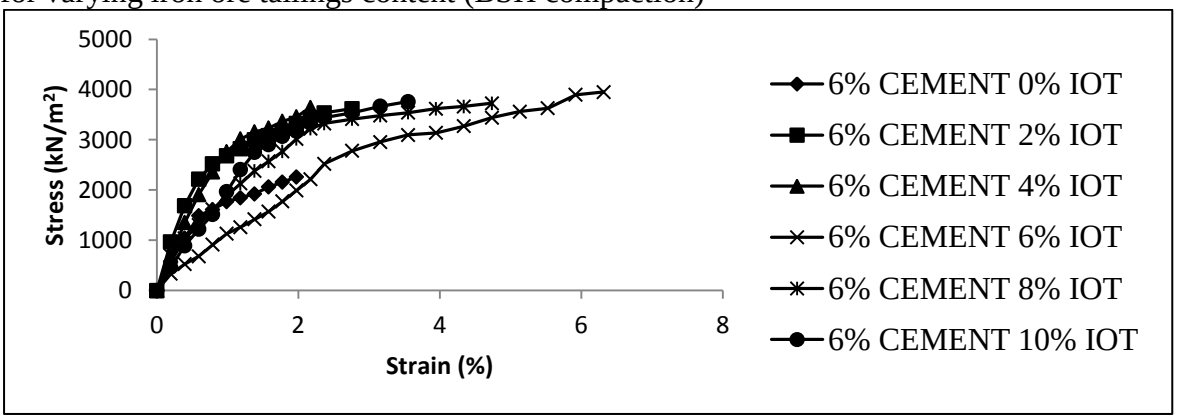


Figure 4.75: Stress-strain graph for lateritic soil – 6 % cement mixture (7 days curing period) for varying iron ore tailings content (BSH compaction)

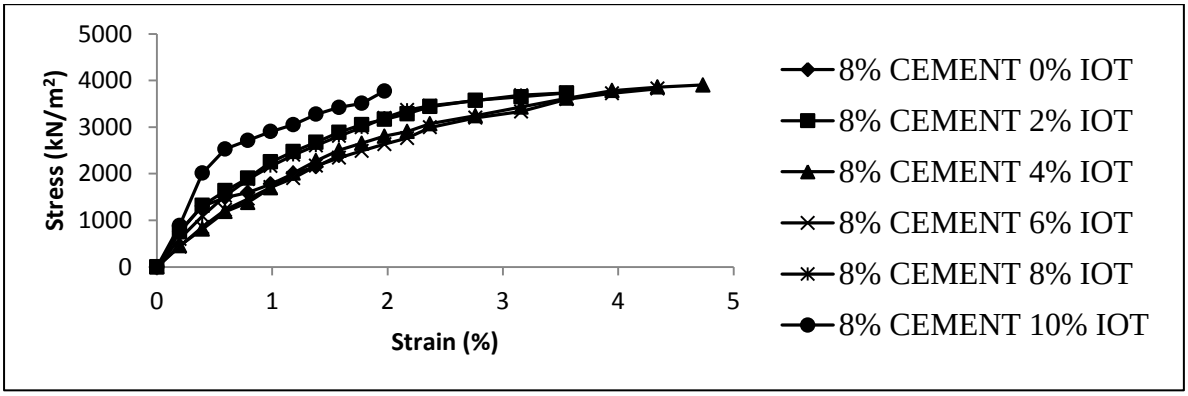


Figure 4.76: Stress-strain graph for lateritic soil – 8 % cement (7 days curing period) for varying iron ore tailings content (BSH compaction)

In general, it was observed that at higher cement and IOT contents, the resulting soil – cement – iron ore tailings mixture becomes stiffer thereby requiring high stresses to be mobilized for failure to occur. Meanwhile, at higher compactive effort, the failure mode

becomes brittle although at higher stresses values. This observed failure pattern may be as a result of changes that occur in the soil's matrix due to additives which resulted in the reduction of clay size fraction as a result of the ion exchange reaction that deposited free lime in the system. Also, the pozzolanic reaction that continues after mixing by formation of calcium silicate hydrates increases the soil strength (Eberemu and Sada, 2013).

The effect of compaction energy on the stress as observed during the course of the study revealed that, the stress increases with increase in compactive effort in the order BSL compaction – WAS compaction – BSH compaction. The soil – cement / IOT mixtures result for 6 % cement / 6 % IOT which represent the optimum blend for the various soil cement / IOT mixtures, compacted at BSL, WAS and BSH compaction energies recorded shearing stress values of 3783.64 kN/m^2, 3809.97 kN/m^2 and 3949.13 kN/m^2 in that order at 7 days curing age. Similar trend was observed for the various soils – cement – IOT blend. The increase could be as a result of increase in maximum dry densities.

The effect of curing period on the stress also showed increases in the shear stress values as the curing time increases. At BSL compaction energy, the shear stress values recorded at 7, 14 and 28 days curing period for 6 % cement / 6 % IOT treatment were 3783.64 kN/m^2, 3897.7 kN/m^2 and 4105.27 kN/m^2 respectively. 3398.8 kN/m^2, 3564.49 kN/m^2 and 3666.75 kN/m^2 were deviator stress values recorded at 7, 14 and 28 days of curing in that order at 8 % cement / 8 % IOT treatment. These values therefore suggests that increase in curing time resulted to increase in shearing stress values. WAS compaction also recorded similar behaviour, at 4 % cement / 6 % IOT content shear stress values of 3304.94 kN/m^2 for 7 days, 3623.85 kN/m^2 for 14 days and 3916.14 kN/m^2 for 28 days of curing were recorded. BSH compaction also recorded similar trend. However, higher shear stress values were achieved. The increase may also not be unconnected to the time dependent strength gain of pozzolanas. Figures 4.77 - 4.79 show the Stress-strain graph for lateritic soil –cement mixture

for varying iron ore tailings content for natural (0 % cement / 0% IOT) and optimum (6 % cement / 6 % IOT) blend for the curing period as indicated. These results suggest that the soil improved after treatment as higher yielding stress were recorded for the varying cement/IOT blend. The shear stress – strain plots for 14 and 28 days curing period are shown in Figures B1 – B30 in the appendix B.

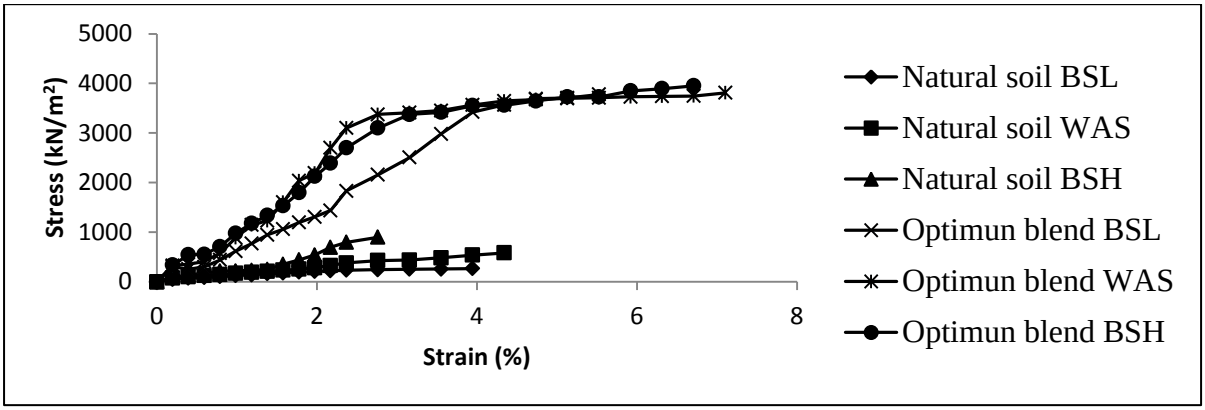


Figure 4.77: Stress-strain graph for lateritic soil –cement mixtures (7 days curing period) for varying iron ore tailings content for natural (0 % cement / 0% IOT) and optimum (6 % cement / 6 % IOT) blend

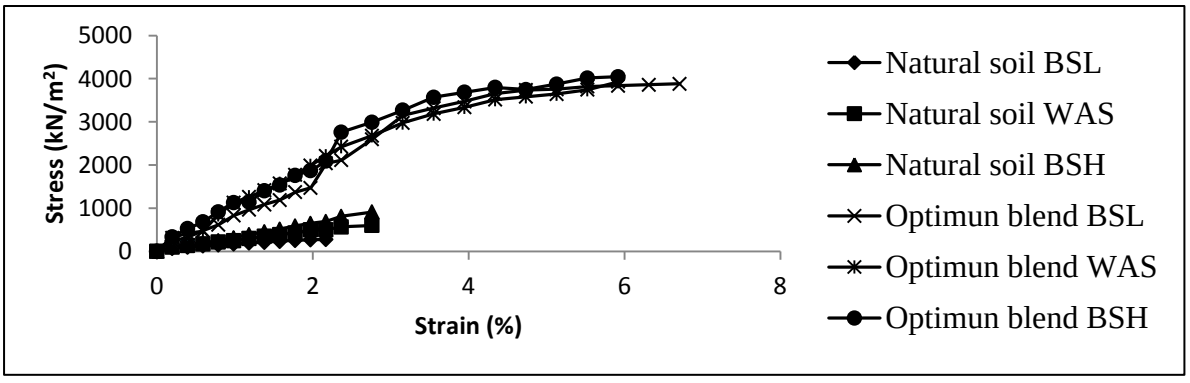


Figure 4.78: Stress-strain graph for lateritic soil –cement mixtures (14 days curing period) for varying iron ore tailings content for natural (0 % cement / 0% IOT) and optimum (6 % cement / 6 % IOT) blend

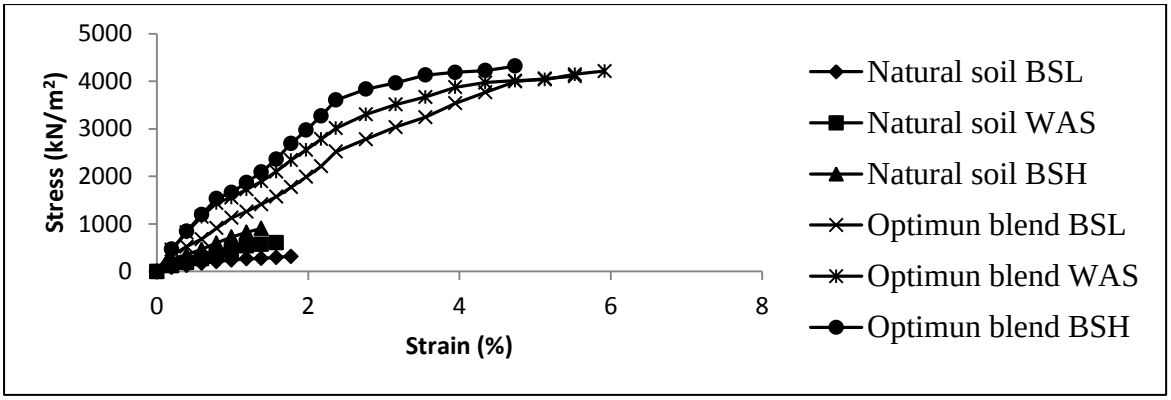


Figure 4.79: Stress-strain graph for lateritic soil –cement mixtures (28 days curing period) for varying iron ore tailings content for natural (0 % cement / 0% IOT) and optimum (6 % cement / 6 % IOT) blend

The initial decrease in shear strength may also be attributed to the formation of honey comb, flocculent or coarse-grained skeleton structures in the soil formed by flocculation and cation exchange reaction as well as broken bonds between clay particles and the reduction in voids by compaction (Sarkar *et al.,* 2012). The results obtained are consistent with the findings reported by (Lees *et al.,* 1982; Osula 1991 and Osinubi 1995). The significance of these results is that, the lateritic soil is able to withstand increased yielding stress before shearing when treated with varying IOT and specific cement contents.

4.5.2 Elastic modulus

Variation of elastic modulus of lateritic soil – cement mixture with iron ore tailings content is shown (Figures 4.80 – 4.88). Increase in IOT contents at specific cement contents, led to decrease in the elastic modulus. The elastic modulus value of 119.35 kN/m^2 recorded for natural soil decreased to 87.97 kN/m^2 at 10 % IOT contents for samples cured for 7 days and compacted at BSL compaction energy (see Figure 4.80).

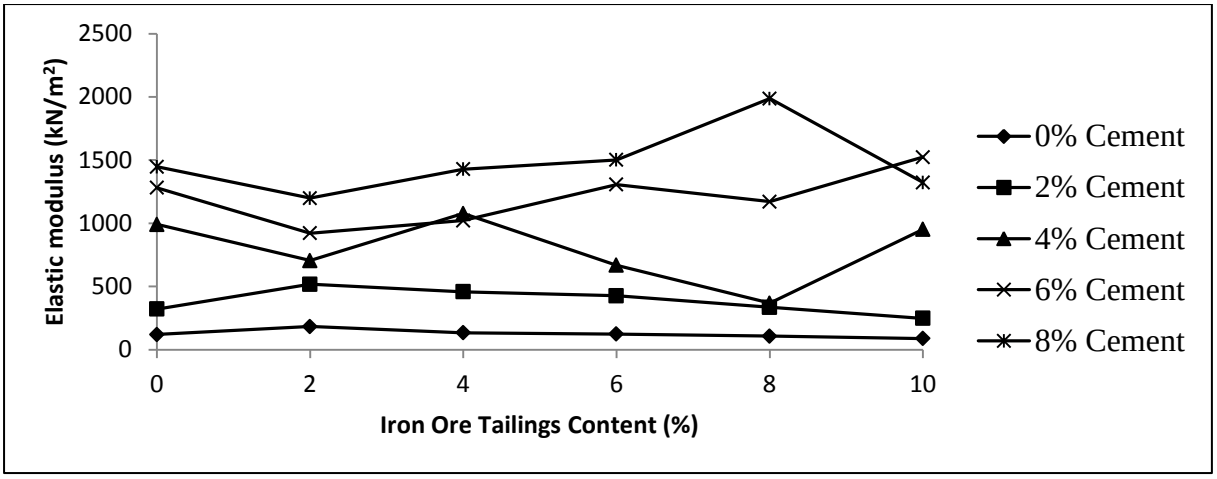


Figure 4.80: Variation of elastic modulus of lateritic soil –cement mixture (7 days curing period) with iron ore tailings content (BSL compaction)

The mean elasatic modulus value of 174.41 kN/m^2 observed at 0 % IOT decreased to 139.1 kN/m^2 when treated with 4 % IOT both cured for 7 days and compacted at WAS energy level. BSH compaction also showed similar behaviour with 957.99 kN/m^2 recorded at 0 % IOT decreased to 910.91 kN/m^2 at 10 % IOT after 7 days curing period (see Figures 4.81 and 4.82).

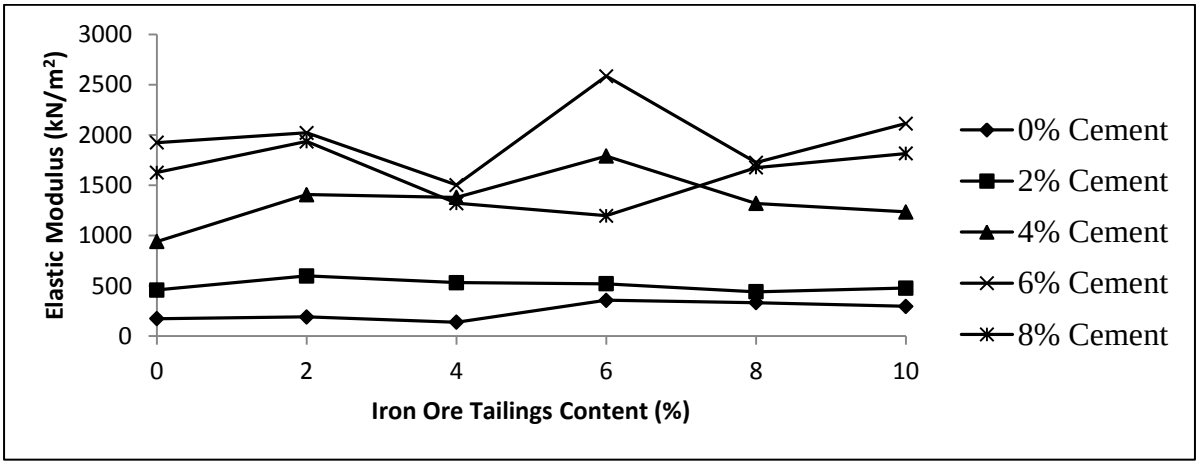


Figure 4.81: Variation of elastic modulus of lateritic soil –cement mixtures (7 days curing period) with iron ore tailings content (WAS compaction)

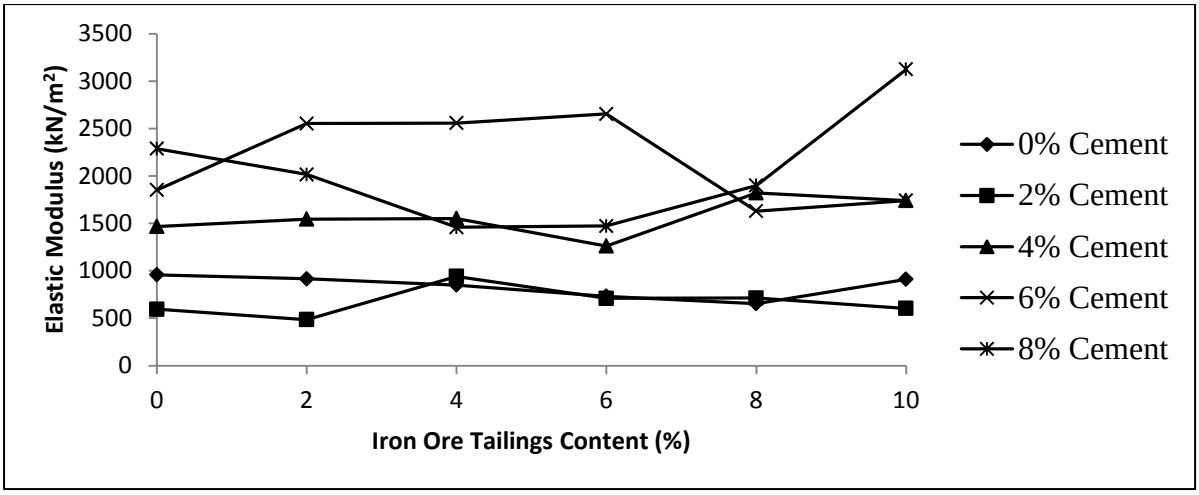


Figure 4.82: Variation of elastic modulus of lateritic soil –cement mixtures (7 days curing period) with iron ore tailings content (BSH compaction)

The decrease in the elastic modulus may be as a result of low percentage of CaO in the IOT which would have aided the hydration process. However, when cement is introduced into the system, the hydrated lime which is a by product of hydration of cement, that is released into the soil matrix complement the low CaO in the IOT. This results to the formation of secondary cementitious compounds thereby enhancing strength. Similar results were observed for 14 and 28 days curing period as shown in Figures 4.83 – 4.88 for the compactive efforts as indicated.

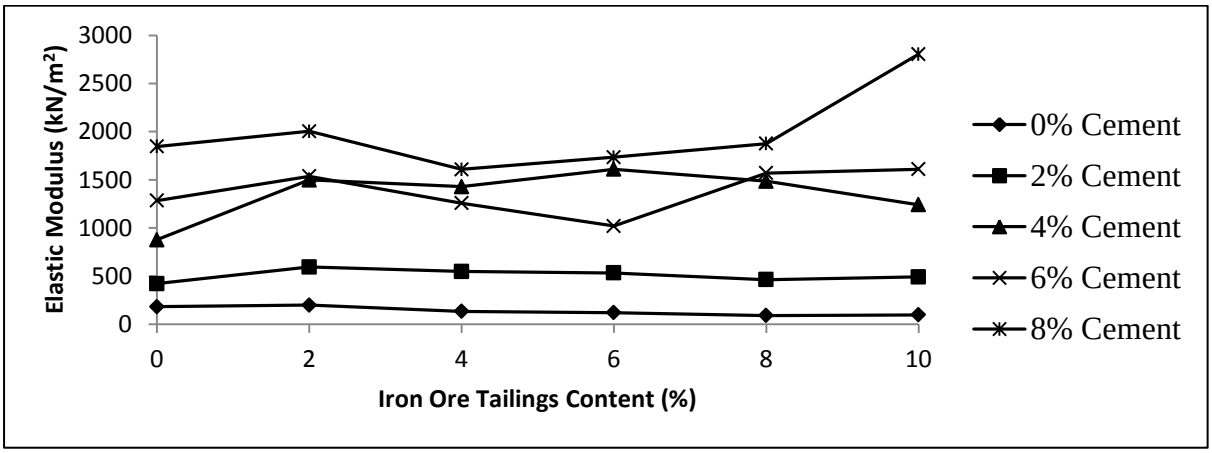


Figure 4.83: Variation of elastic modulus of lateritic soil –cement mixtures (14 days curing period) with iron ore tailings content (BSL compaction)

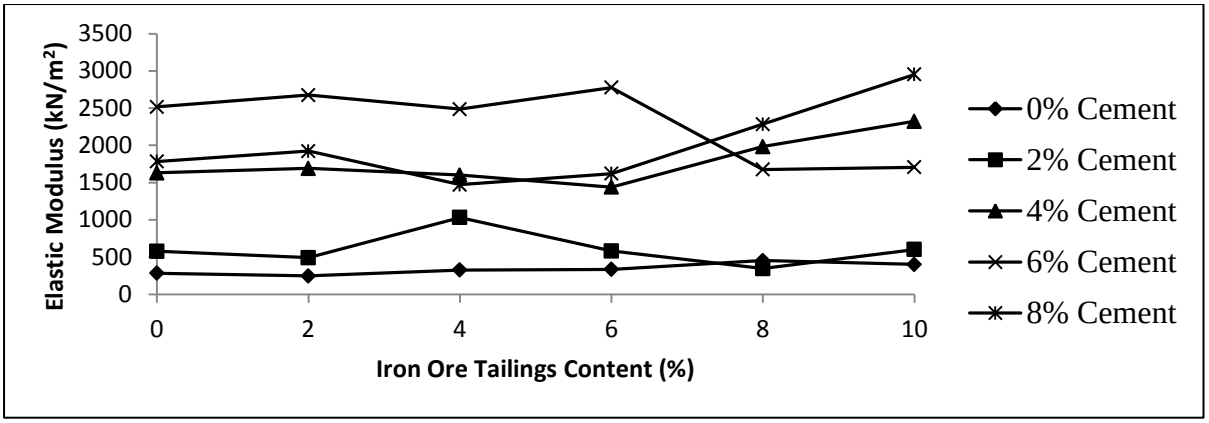


Figure 4.84: Variation of elastic modulus of lateritic soil –cement mixtures (14 days curing period) with iron ore tailings content (WAS compaction)

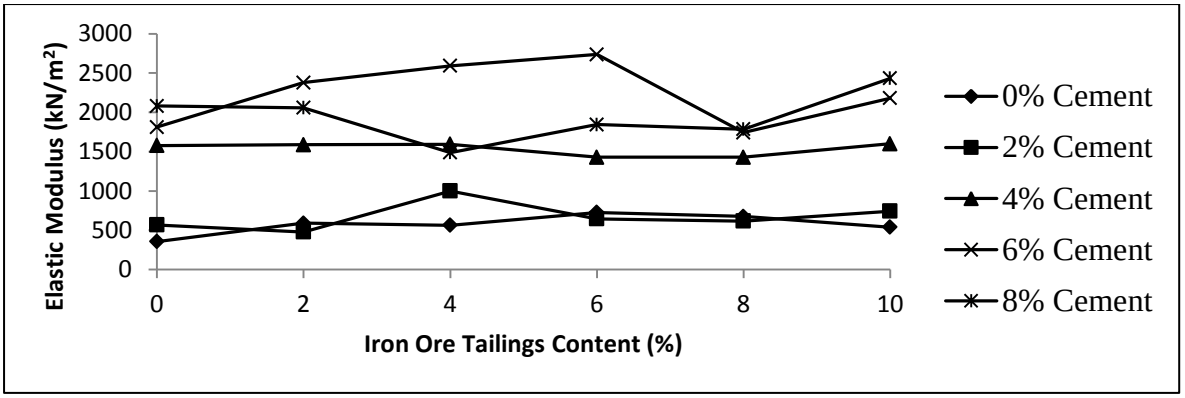


Figure 4.85: Variation of elastic modulus of lateritic soil –cement mixtures (14 days curing period) with iron ore tailings content (BSH compaction)

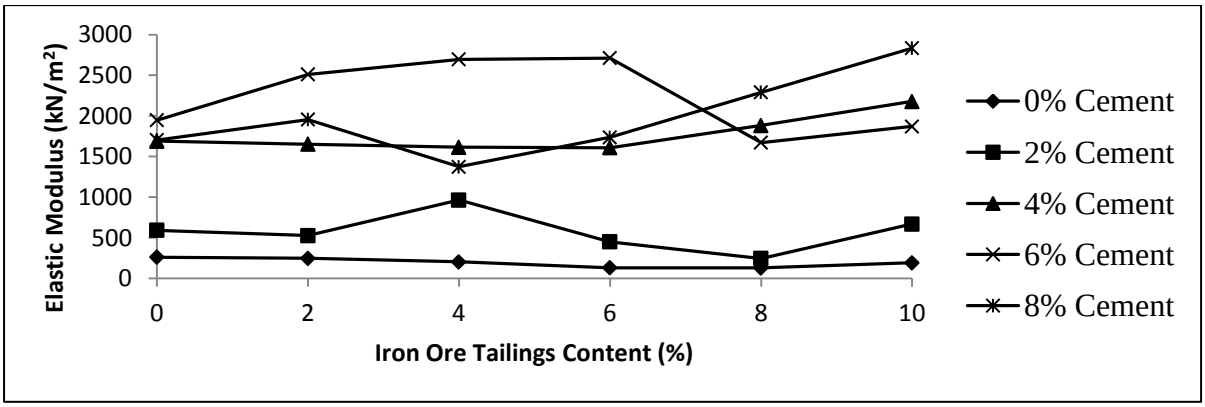


Figure 4.86: Variation of elastic modulus of lateritic soil –cement mixture (28 days curing period) with iron ore tailings content (BSL compaction)

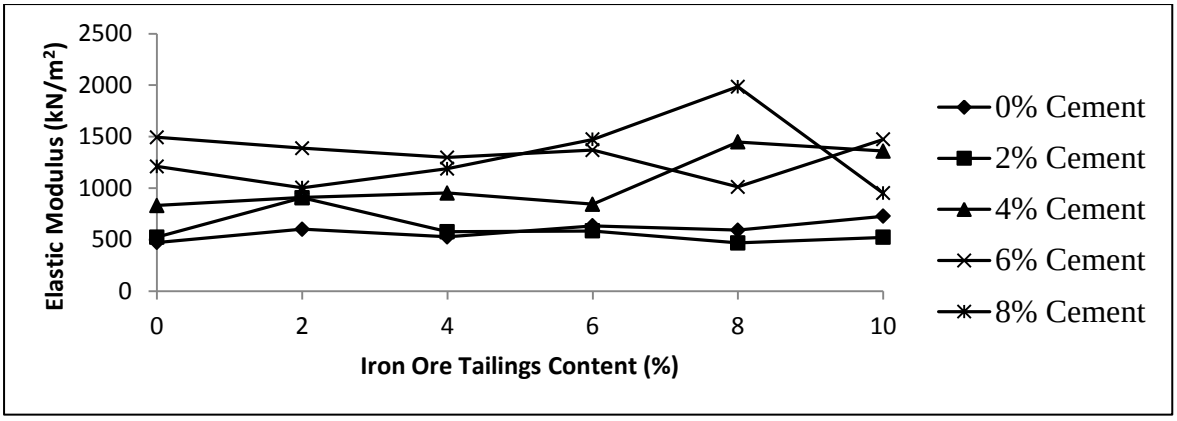


Figure 4.87: Variation of elastic modulus of lateritic soil –cement mixture (28 days curing period) with iron ore tailings content (WAS compaction)

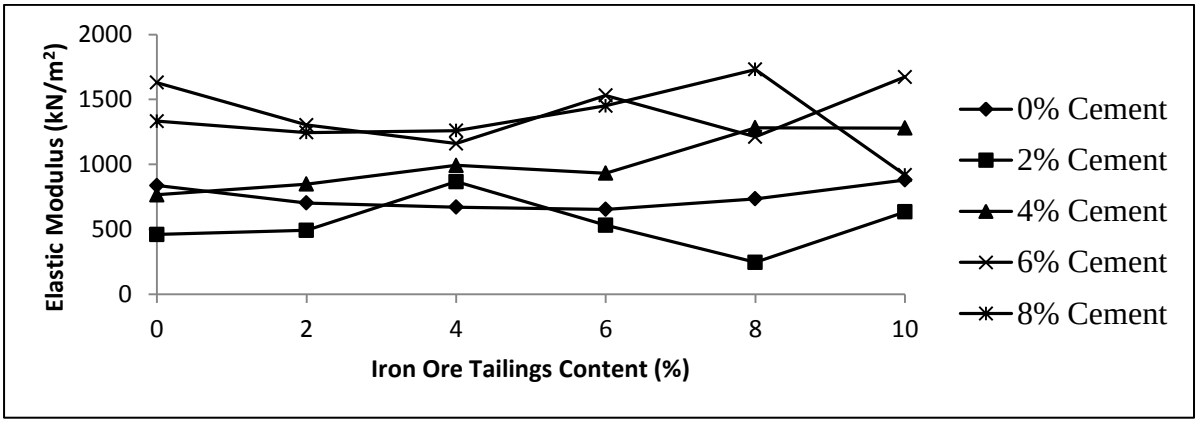


Figure 4.88: Variation of elastic modulus of lateritic soil –cement mixture (28 days curing period) with iron ore tailings content (BSH compaction)

Figures 4.89 – 4.97 show the variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content. It could be inferred from the results that for every percentage increase in the cement contents, there is a commensurate increase in the elastic modulus of soil – cement – IOT blend. For BSL compaction energy, the mean elastic modulus increase from 119.35 kN/m^2 for the natural soil to 1447. 04 kN/m^2 at 8 % cement / 0 % IOT. The 122.98 kN/m^2 recorded for 0 % cement / 6 % IOT increased to 1502.04 kN/m^2 at 8 % cement / 6 % IOT, 87.97 kN/m^2 at 0 % cement / 10 % IOT to 1523.04 kN/m^2 at 6 % cement / 10 % IOT after 7 days of curing (see Figure 4.89). Similar trend were observed for the various cement / IOT treatment.

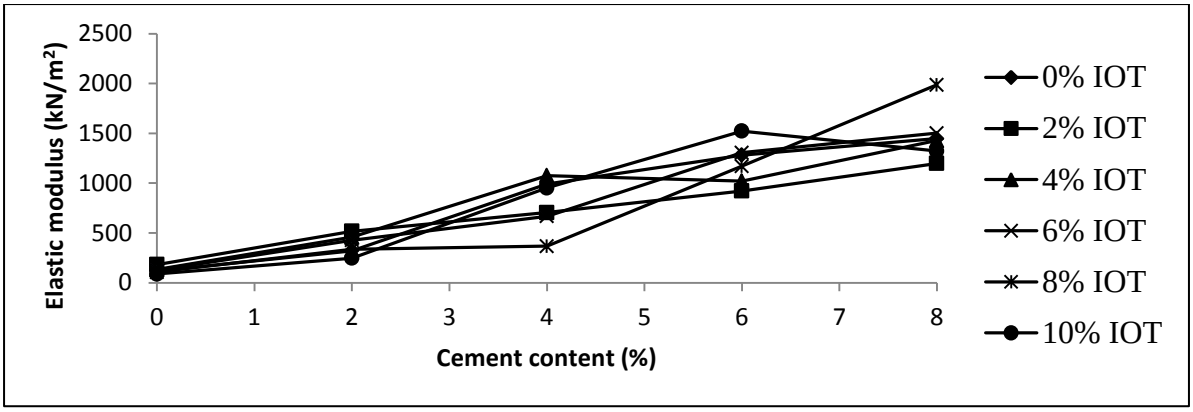


Figure 4.89: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (7 days curing, BSL).

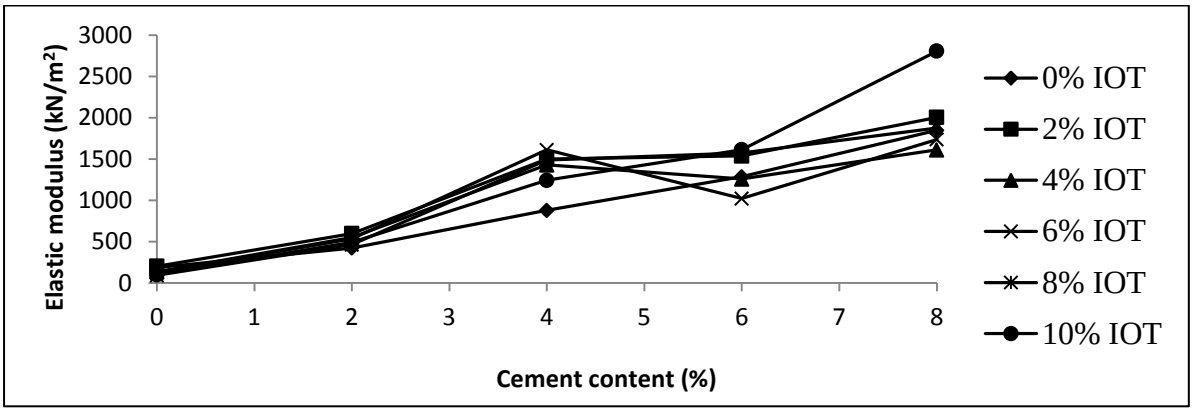


Figure 4.90: Variation of modulus of elasticity of lateritic soil – iron ore tailings content mixtures with cement content (14 days curing, BSL)

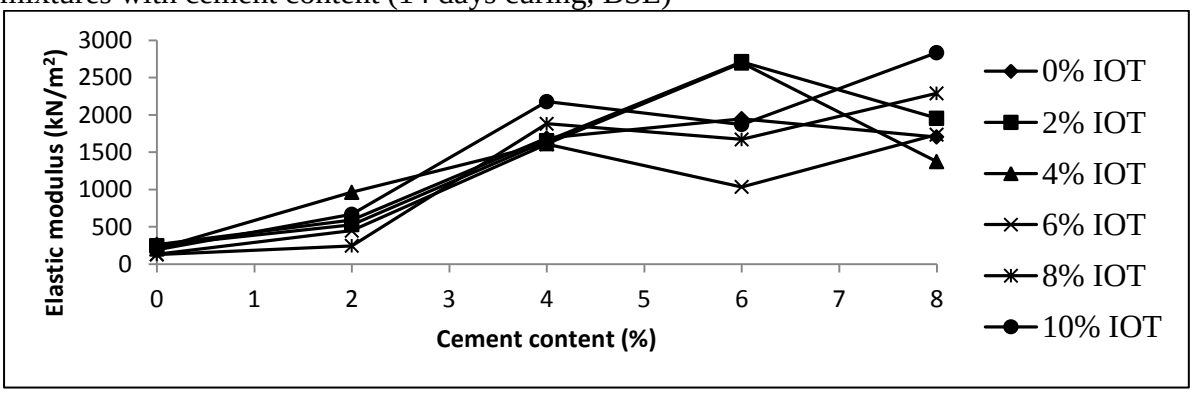


Figure 4.91: Variation of modulus elasticity of lateritic soil – iron ore tailings mixtures with cement content (28 days curing, BSL)

At WAS compaction energy, increases in elastic modulus with increased cement contents were also observed. The mean elastic modulus of 174.41 kN/m2 recorded for the natural soil increased to 1923.08 kN/m^2 at 6 % cement / 0 % IOT, 332. 4 kN/ m^2 at 0 %

cement / 8 % IOT to 2113.63 kN/ m^2 at 6 % cement / 8 % IOT at 7 days curing time (see Figure 4.92).

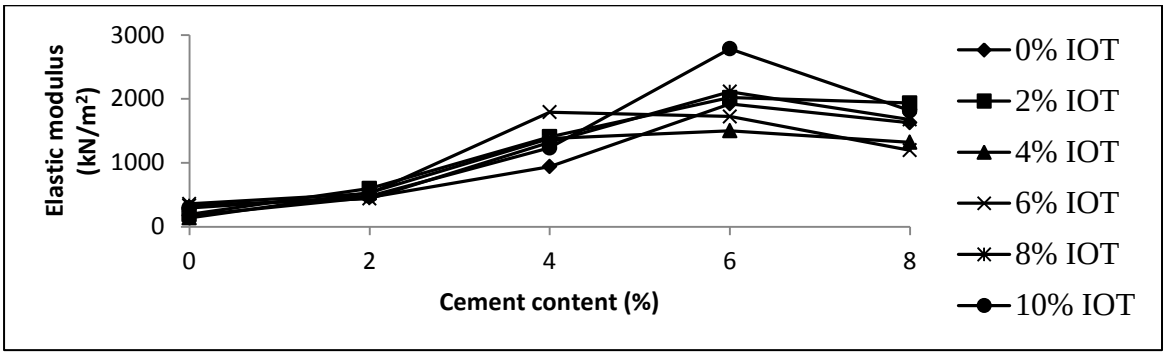


Figure 4.92: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (7 days curing, WAS)

Similar results were obtained for the various cement / IOT treatments. Samples cured for 14 and 28 days also showed trend similar to those of 7 days curing as shown in Figures 4.93 and 4.94.

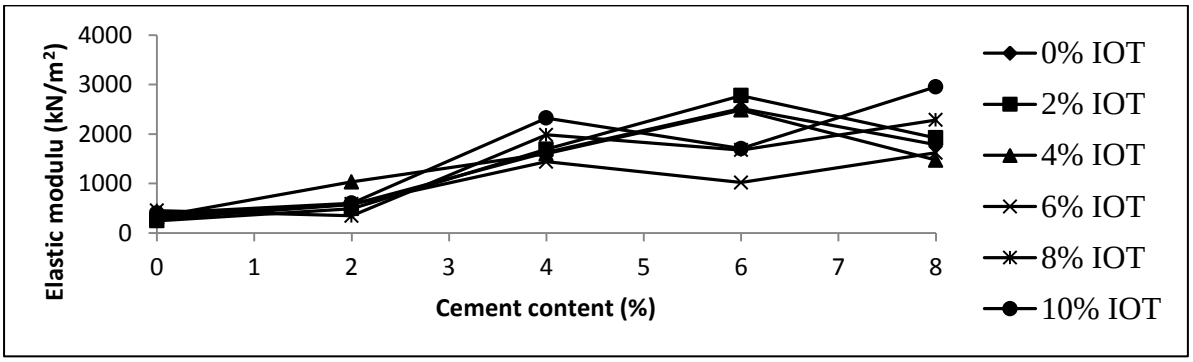


Figure 4.93: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (14 days curing, WAS)

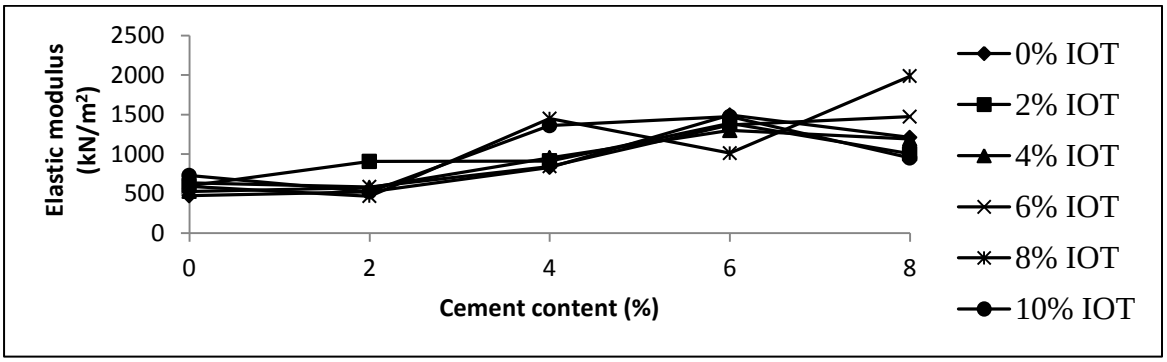


Figure 4.94: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (28 days curing, WAS)

The elastic modulus values obtained at BSH compaction energy showed trend similar to WAS and BSL compactions however, higher values were recorded (see Figures 4.95 – 4.97). Detailed test results are shown in tables A82 – A90 in the appendix A.

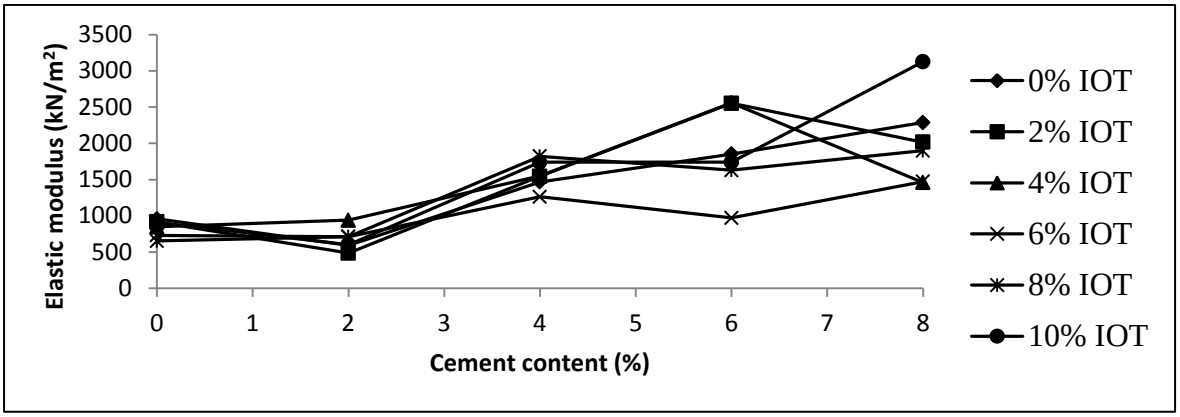


Figure 4.95: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (7 days curing, BSH)

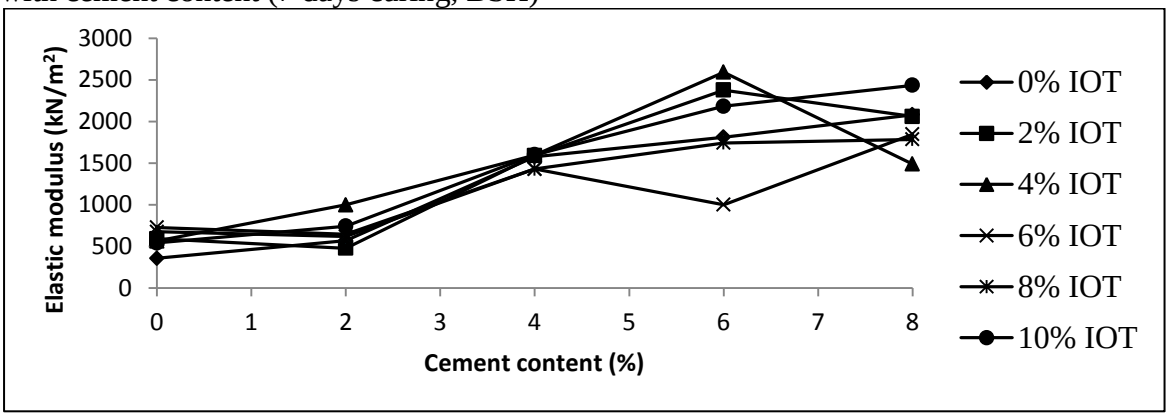


Figure 4.96: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (14 days curing, BSH)

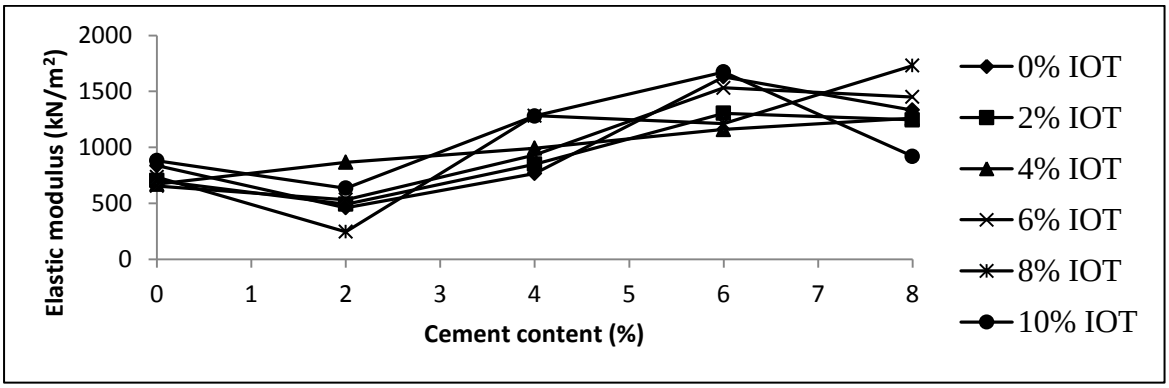


Figure 4.97: Variation of modulus of elasticity of lateritic soil – iron ore tailings mixtures with cement content (28 days curing, BSH)

The increase in the elastic modulus might not be unconnected to the hydration of cement to form cementitious compounds such as calcium silicate hydrates (CSH), calcium aluminates hydrates (CAH) and hydrated lime. The hydrated lime released in the system thus, reacted with the pozollanic IOT to form secondary cementitious material.

The effect of compaction energy on the elastic modulus showed that elastic modulus increases with increase in compactive effort. The elastic modulus values recorded at 4 % cement / 8 % IOT for BSL, WAS and BSH compaction energies cured for 7 days were 367.47 kN/m^2, 1319.1 kN/m^2 and 1812.13 kN/m^2 respectively while 1305.81 kN/m^2, 2584.46 kN/m^2 and 2654.45 kN/m^2 were recorded at 6 % cement / 6 % IOT for BSL, WAS and BSH compaction energies respectively (see Figure 4.98). Similar results were obtained for various soil – cement – IOT blend.

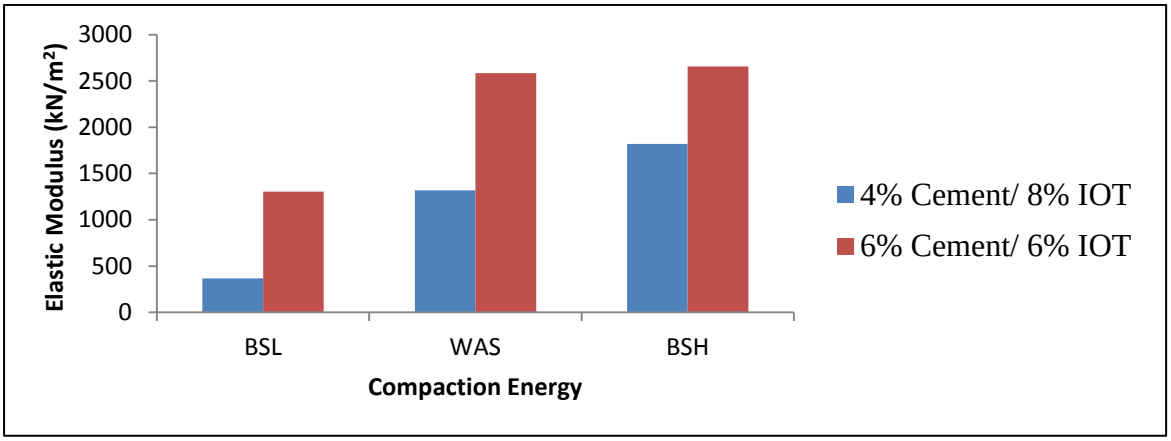


Figure 4.98: Variation of elastic modulus of lateritic soil – cement – iron ore tailings mixtures with compaction energy

The effect of curing time on the elastic modulus does not indicate a definate trend. The values increased and decreased at no constant rate as shown in Figures 4.99 – 4.101.

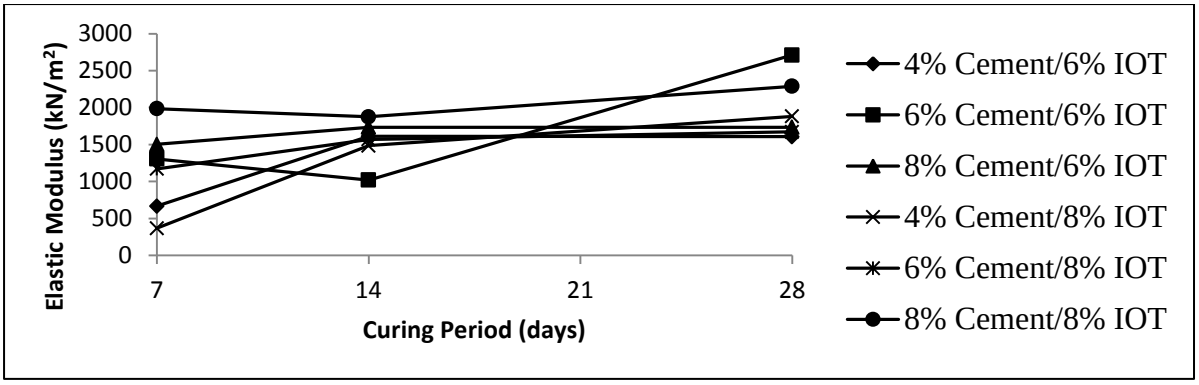


Figure 4.99: Variation of elastic modulus of lateritic soil –cement mixtures with curing period for varying iron ore tailings content (BSL compaction)

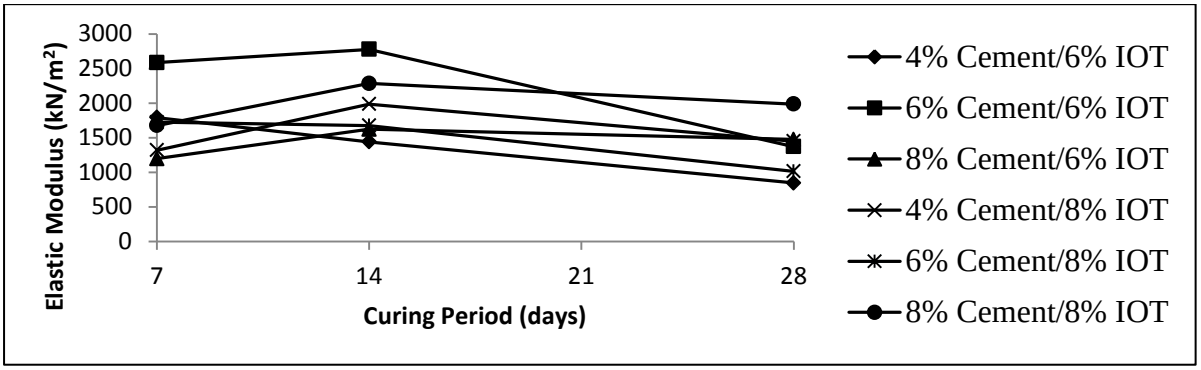


Figure 4.100: Variation of elastic modulus of lateritic soil –cement mixtures with curing period for varying iron ore tailings content (WAS compaction)

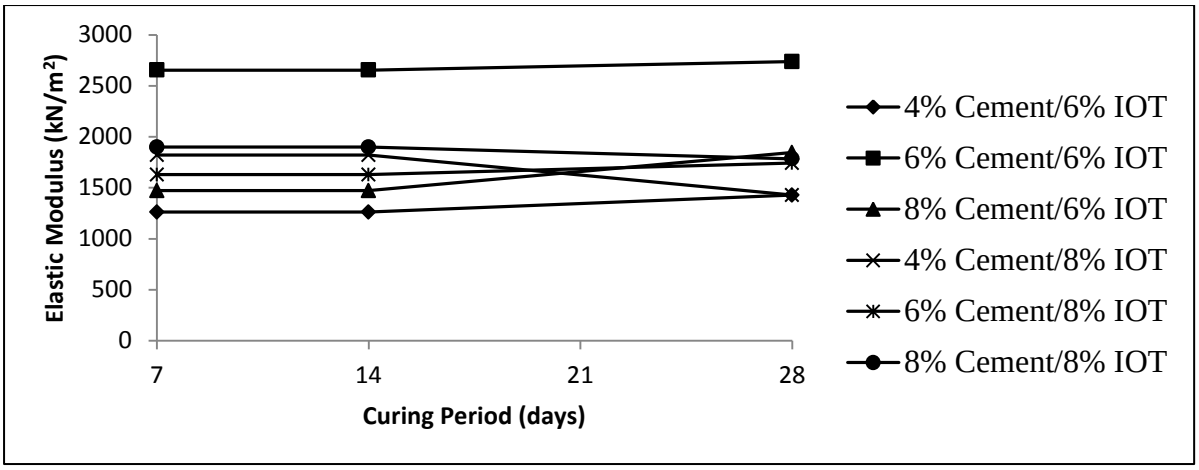


Figure 4.101: Variation of elastic modulus of lateritic soil –cement mixtures with curing period for varying iron ore tailings content (BSH compaction)

This might be as a result of complex reactions that took place within the soil – cement – IOT mixtures during the curing periods. Similar trend were recorded for the various soil – cement – IOT treatment. The practical significance of these test results is that the lateritic soil

when treated with cement / IOT blend will be able to withstand axial load when used as a pavement material.

4.6 California Bearing Ratio

The California bearing ratio is a penetration test for evaluation of mechanical strength of road sub-grades and base courses. The results obtained by these tests are used with the empirical curves to determine the thickness of pavement and its component layers. It is an important parameter used to indicate the strength and bearing capacity for base and sub-base in pavement structure.

4.6.1 Unsoaked condition

Figures 4.102 – 4.104 show the variation of CBR (unsoaked) values of lateritic soil-cement mixtures with iron ore tailings content for the three energy levels considered. The results showed an increase in CBR values with increase in specific cement contents for varied IOT contents from 0 % IOT to the range of 6 – 8 % IOT where it peaked and dropped thereafter.

At BSL compaction energy level, within the range of 0 – 8 % cement content admixed with the range of 6 – 8 % IOT peak CBR values of 20.48 %, 35.25 %, 71.33 %, 97.34 % and 93.35 % respectively were recorded. For WAS compaction energy, soil treated with additives within the same range as above, has these peak CBR values of 25.35 %, 37.34 %, 75.15 % 98.07 % and 95.71 % respectively. Similarly, for BSH compaction energy peak CBR values of 25.74 %, 44.73 %, 78.31 %, 102.78 % and 107.85 % for 0 %, 2 %, 4 %, 6 % and 8 % cement content respectively admixed with the range of 6 – 8 % IOT. These resultant peak CBR values revealed that there was improvement in the CBR values with increase in cement content for varied IOT contents. The increase resulted from the hydration of cement to form cementitious compounds like calcium silicate hydrates (CSH), calcium aluminates hydrates

(CAH) and hydrated lime. The first two hydrates developed cementitious linkages between these hydration products and soil particles regardless of the type of soil (Ola, 1983). The hydrated lime released however, reacted with pozzolanic iron ore tailing to form secondary cementitious material. Detailed test results are given in Tables A38 – 40 in the Appendix A.

Similarly, CBR values increase with increase in IOT contents for specific cement contents. This is noticed from the increase in CBR value from 10 % at 0 % IOT to 20.48 % at 6 % IOT, 25.74 % recorded at 0 % IOT to 35.25 % at 6% IOT both admixed with 2 % cement, 50.26 % at 0 % IOT to 71.33 % at 6 % IOT at 4 % cement each, 74.67 % at 0 % IOT to 97.34 % at 6 % IOT both at 6 % cement contents and 79.21 % at 0 % IOT to 93.35 % at 8 % IOT both admixed at 8 % cement content at BSL compaction (see Figure 4.102). Similar results were also observed at WAS and BSH compaction levels. These improvements resulted from the secondary cementitious materials formed from the reaction between the lime librated from the hydration reaction of cement and the pozzolanic IOT. This reaction also contributed to inter particle bonding (Mustapha, 2006).

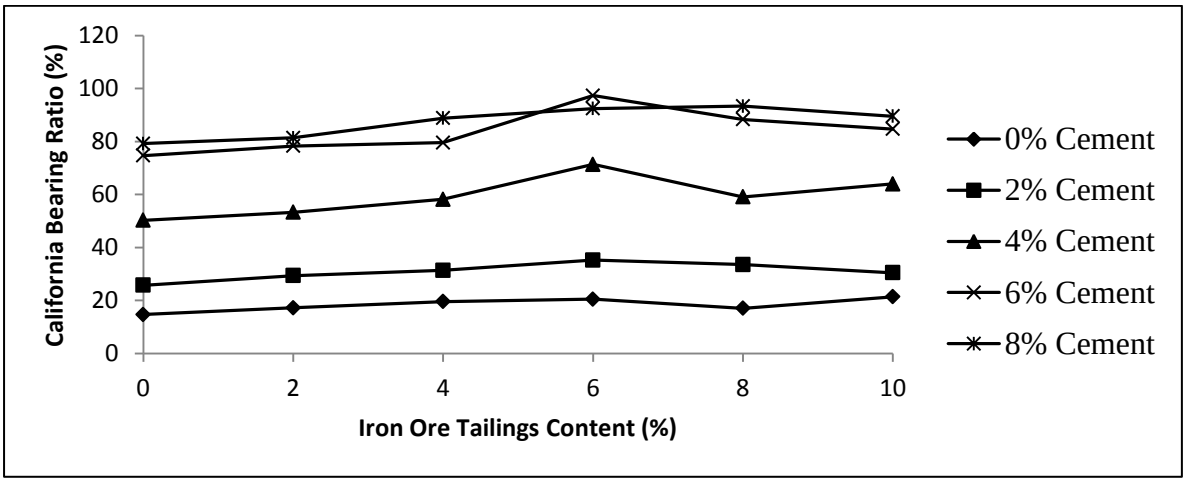


Figure 4.102: Variation of California bearing ratio (unsoaked condition) of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

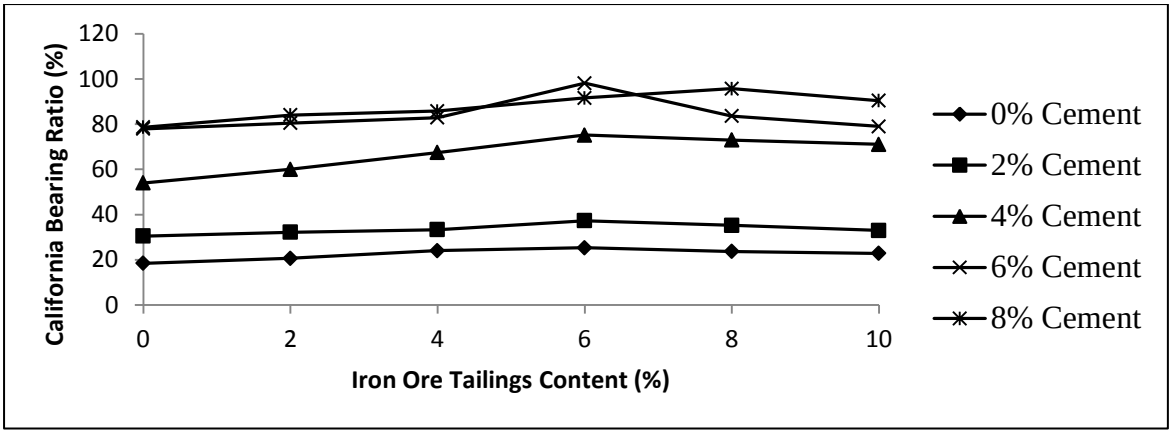


Figure 4.103: Variation of California bearing ratio (unsoaked condition) of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

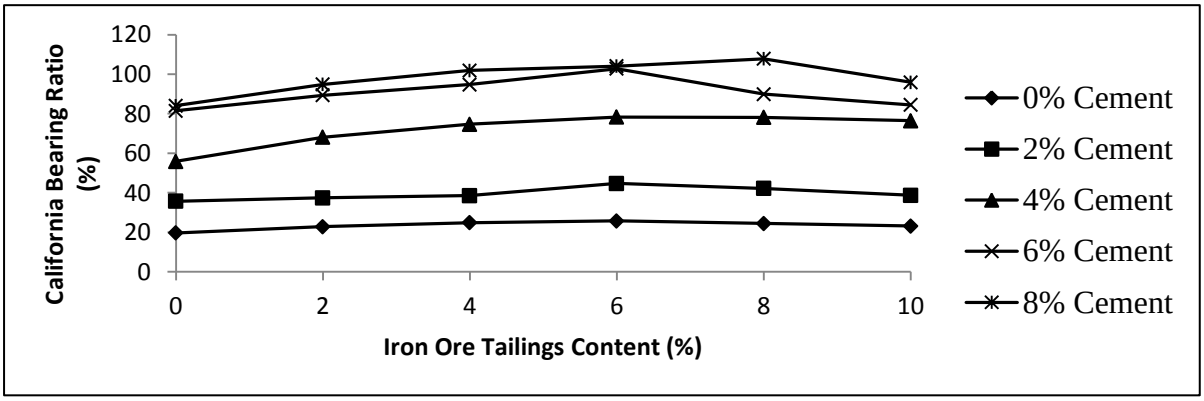


Figure 4.104: Variation of California bearing ratio (unsoaked condition) of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction)

Increase in CBR values with higher compactive effort was also observed in the order BSL, WAS,and BSH compaction with peak CBR values of 100 % for BSL compaction and 100 % for WAS compaction both at 6 % IOT/ 6 % cement while 110 % was the peak CBR value recorded for BSH compaction at 8 % IOT/ 8 % cement. This trend is consistent with Osinubi (2001), Mustapha (2006), Yisa (2013), Yohanna (2015) as well as Etim (2015). The reason for this trend is the increase in dry density in the same order BSL – WAS – BSH compaction energy levels.

The Nigerian General Specifications (1997) recommends that a CBR value of 180 % should be attained in the laboratory for cement stabilization. However, an unsoaked CBR

value of 80 % is required for bases and soaked value of 30 % for sub-bases both when compacted at optimum moisture and at 100 % West African Standard compaction (Gidigasu and Dogbey 1980; Gidigasu, 1982; Osinubi, 2001). Based on the above criterion, suffice to state that the optimally treated soil; 6 % cement - 6 % iron ore tailings which has CBR values of 100, 100 and 100 % for BSL, WAS and BSH energy respectively met the requirement for base course material. On the other hand 2 and 4% cement contents admixed with the range of 4 – 8 % IOT will be adequate for lateritic soil to be used as sub base material, 6 and 8 % cement contents when admixed with 4 – 10 % IOT met the requirement for base course material at BSL compaction energy level. At WAS and BSH compaction energies, 6 and 8 % cement contents when admixed within the range of 2 – 8 % IOT met the requirement for base course material. Detailed test results are given in Tables A38 – 40 in the Appendix A.

The two – way analysis of variance (ANOVA) test on the unsoaked CBR result for BSL,WAS and BSH compaction (see Table 4.19) shows that the effects of cement and iron ore tailings on lateritic soil were statistically significant (F_{CAL} = 394.42, 483.02, 438.21 > F_{CRIT} = 2.87) for cement and (F_{CAL} = 8.56, 9.76, 9.36 > F_{CRIT} = 2.71) for iron ore tailings respectively.

Table 4.19: Two-way analysis of variance for California bearing ratio (unsoaked condition) of lateritic soil-cement-iron ore tailing mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Unsoaked	Cement	4	394.42	1.03E-18	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	8.56	0.000183	2.71	$F_{CAL} > F_{CRIT,}$ significant
WAS	Unsoaked	Cement	4	483.02	1.39E-19	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	9.76	7.70E-05	2.71	$F_{CAL} > F_{CRIT,}$ significant
BSH	Unsoaked	Cement	4	438.21	3.64E-19	2.87	$F_{CAL} > F_{CRIT,}$ significant
		IOT	5	9.36	0.000102	2.71	$F_{CAL} > F_{CRIT,}$ significant

Detailed test results are given in Tables A73 – 75 in the Appendix A.

4.6.2 Soaked condition

The variation of California bearing ratio (24 hours soaking) of lateritic soil- cement mixtures with iron ore tailings content is shown in Figures 4.105 – 4.107. For BSL, WAS and BSH compactive efforts CBR values increased with higher additive contents. The values of 80, 80 and 90 % were recorded at optimum blend for the respective energies of BSL, WAS and BSH. It was observed that the CBR values did not decrease very significantly when soaked.

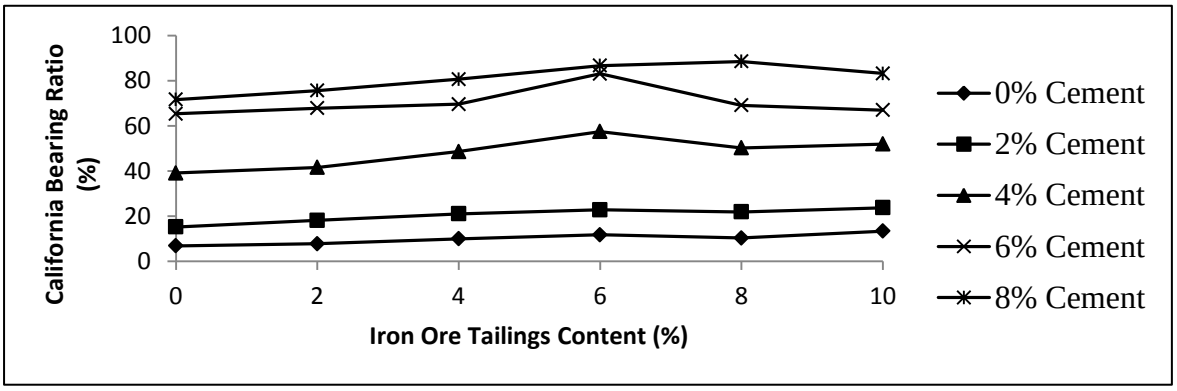


Figure 4.105: Variation of California bearing ratio (24 hours soaking) of lateritic soil – cement mixtures with iron ore tailing content (BSL compaction)

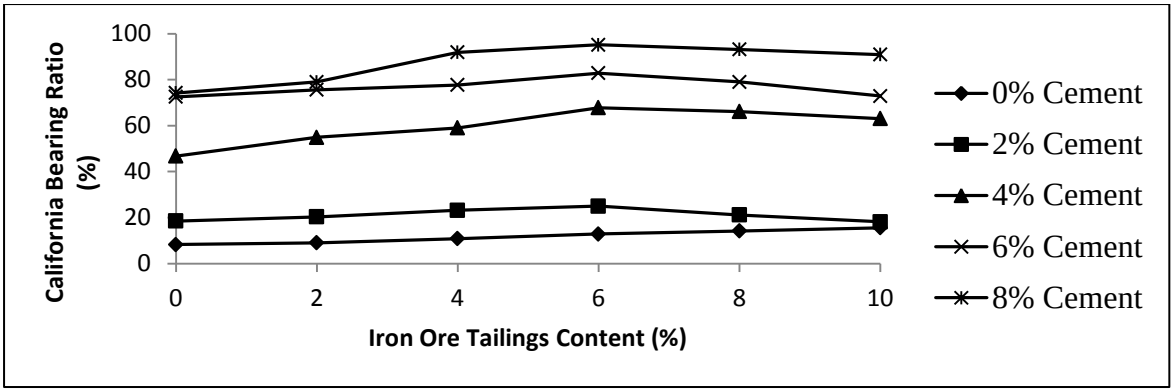


Figure 4.106: Variation of California bearing ratio (24 hours soaking) of lateritic soil – cement mixtures with iron ore tailing content (WAS compaction)

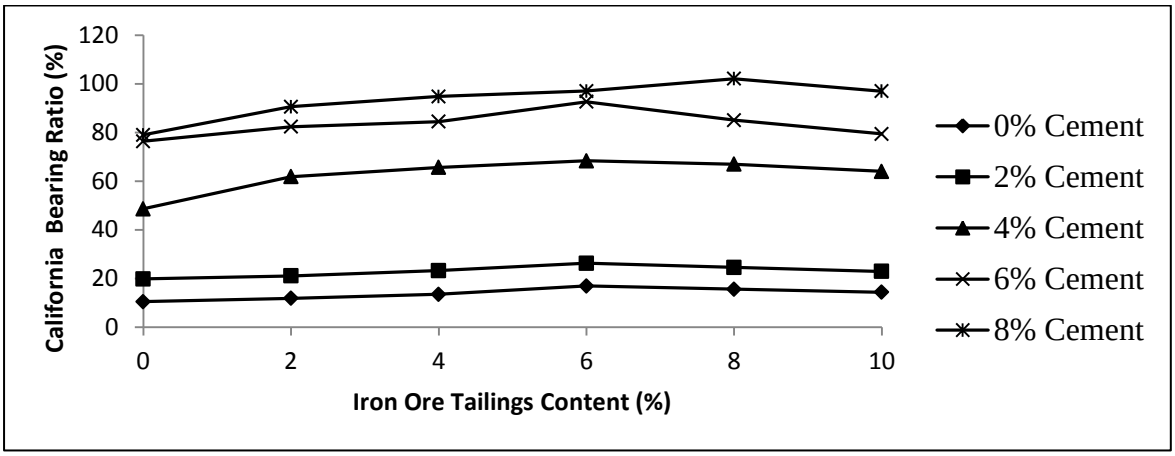


Figure 4.107: Variation of California bearing ratio (24 hours soaking) of lateritic soil – cement mixtures with iron ore tailing content (BSH compaction)

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. However, soil treated with 6 % cement - 6 % iron ore tailings and compacted with the three energy levels considered, met the 80 % requirement for base materials. At both BSL and WAS compaction energy, 6 % cement and 8 % cement admixed within the range of 4 – 10 % IOT met the 80 % criterion for base course material with the peak value of 90 % at 8% cement/ 8 % IOT and 100 % at 8 % cement/ 6 % IOT respectively. Still at BSL and WAS compaction energy, 4 % cement when admixed with 2 – 10 % IOT met the requirement of 30 % for sub-base material. At BSH compaction energy, 6 and 8 % cement contents when treated within the range of 2 – 8 % IOT

met the requirement of 80 % for base course material. Detailed test results are given in Tables A41 – 43 in the Appendix A.

The two – way analysis of variance (ANOVA) test on the soaked CBR result for BSL, WAS and BSH compaction (Table 4.20) shows that the effects of cement and IOT on the lateritic soil were statistically significant for cement (F_{CAL} = 530.33, 459.85, 670.69 > F_{CRIT} = 2.87) and IOT (F_{CAL} = 9.67, 7.40, 9.93 > F_{CRIT} = 2.71).

Table 4.20 Two - way analysis of variance for California bearing ratio (24 hours soaking) of lateritic soil – cement – iron ore tailings mixtures

Property		Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Soaked	Cement	4	530.33	5.510E-20	2.87	$F_{cal} > F_{crit}$, significant
		IOT	5	9.67	8.24E-05	2.71	$F_{cal} > F_{crit}$, significant
WAS	Soaked	Cement	4	459.85	2.26E-19	2.87	$F_{cal} > F_{crit}$, significant
		IOT	5	7.40	0.0004496	2.71	$F_{cal} > F_{crit}$, significant
BSH	Soaked	Cement	4	670.69	5.38E-21	2.87	$F_{cal} > F_{crit}$, significant
		IOT	5	9.93	6.88E-05	2.71	$F_{cal} > F_{crit}$, significant

Detailed test results are given in Tables A76 – 78 in the Appendix A.

4.6.3 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 the analysis include the cement content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter.

The regression Equation (4.4) revealed the extent to which these parameters influence the California bearing ratio of treated soil which is a function of the coefficient of each parameter. The regression Equation (4.4) showed that the CBR of the treated soil is influenced by the cement content,

compactive effort, t percentage fine, plasticity index and iron ore tailing. The coefficient of multiple determination value (R^2) shows a strong relationship between CBR of the treated soil and the parameters with R^2 value of 0.939. The regression equation is shown in Equation 4.4

$$CBR = 30.21 + 9.18C - 0.12IOT + 0.006PF - 1.12PI + 4.6CE \quad (4.4)$$

$R^2 = 0.939$

where:

CBR = California bearing ratio of soaked treated sample

C = Cement content, IOT = Iron ore tailing content, PF = Percentage fine, Pl = Plasticity index,

CE = Compactive effort. Detailed test results are shown in Table 4.21.

Table 4.21 Regression analysIs for California bearing ratio of lateritic soil – cement – iron ore tailings mixtures

Dependent variable	Independent variable	Coefficients	p-value	Adjusted R^2	F
CBR	Intercept	30.2062853	0.234101278	0.938516659	2.31994E-50
	Cement content	9.188986004	6.38083E-14		
	Iron ore tailings content	-0.10712952	0.899022152		
	Percentage fine	0.006055985	0.972449051		
	Plasticity index	-1.107454554	0.205014048		
	Compactive effort	4.6	1.05041E-05		

4.7 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 lateritic soil-cement mixtures with iron ore tailings content is shown in Figures 4.108 – 4.110. For BSL, WAS and BSH compactions the resistance to loss in strength increased from 46.77, 40.96 and 36.99 % for the natural soils to peak values of 87.28, 92.41 and 92.48 % at 6 % cement - 6 % iron ore tailing, 8 % cement - 8 % iron ore tailing and 6 % cement - 6 % iron ore tailing treatments, respectively. The peak resistance to loss in strength values fell within the acceptable 80 % earlier mentioned for all the energy levels considered. Detailed test results are given in Tables A44 – 46 in the Appendix A.

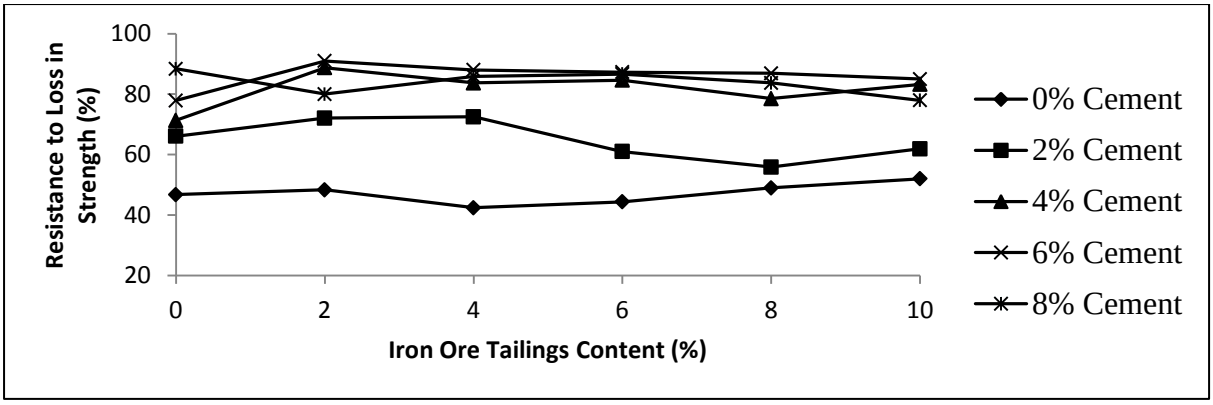


Figure 4.108: Variation of resistance to loss in strength of lateritic soil – cement mixtures with iron ore tailings content (BSL compaction)

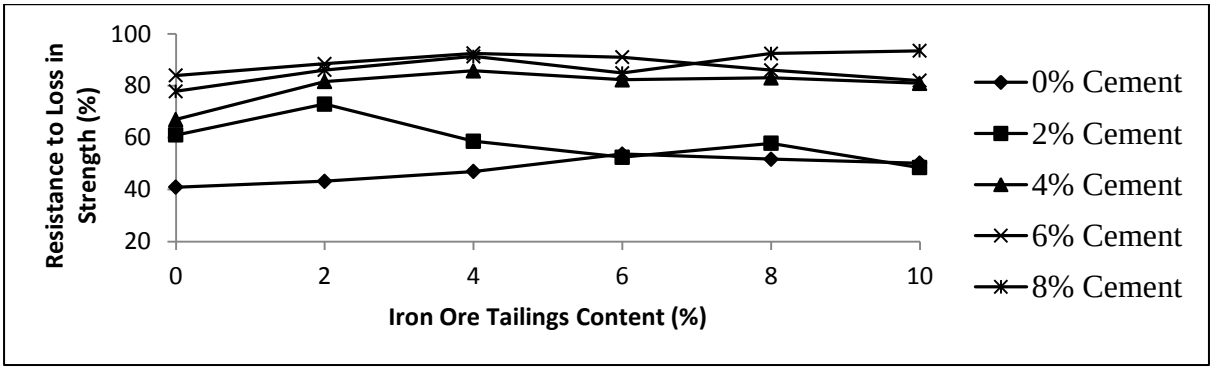


Figure 4.109: Variation of resistance to loss in strength of lateritic soil – cement mixtures with iron ore tailings content (WAS compaction)

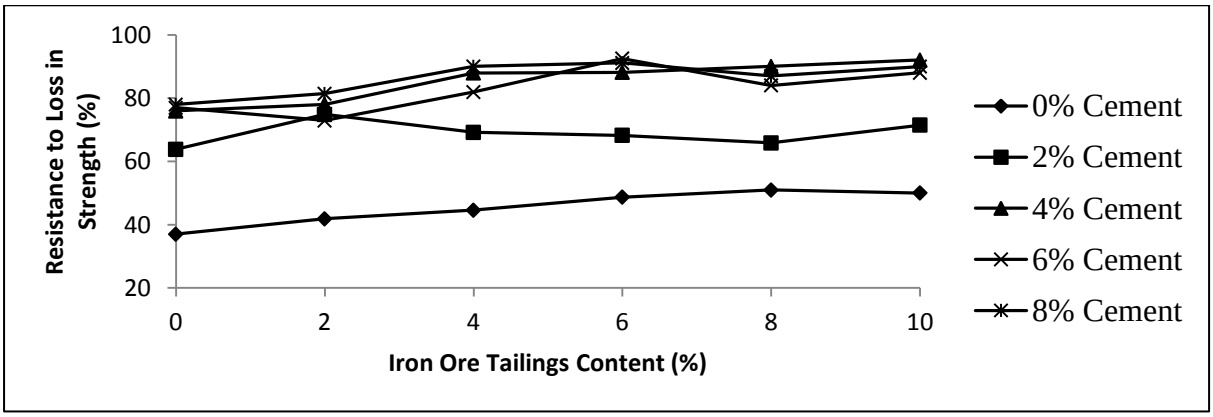


Figure 4.110 Variation of resistance to loss in strength of lateritic soil – cement mixtures with iron ore tailings content (BSH compaction)

The two – way analysis of variance (ANOVA) test on the durability assessment result for BSL and WAS compaction (Table 4.22) shows that the effects of cement on lateritic soil were statistically significant, while that of iron ore tailing is not statistically significant; for

cement (F_{CAL} = 64.22, 58.13 > F_{CRIT} = 2.87) and iron ore tailing (F_{CAL} = 0.989, 1.636 < F_{CRIT} = 2.71). However, BSH compaction shows that both cement and iron ore tailing has significant effect on the lateritic soil.

Table 4.22: Two-way analysis of variance for resistance to loss in strength of lateritic soil – cement – iron ore tailings mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	P-value	F_{CRIT}	Remark
BSL	Cement	4	64.22	3.98E-11	2.87	$F_{cal} > F_{crit}$, Significant
	IOT	5	0.989	0.448768	2.71	$F_{cal} < F_{crit}$, Not Significant
WAS	Cement	4	58.13	9.92E-11	2.87	$F_{cal} > F_{crit}$, Significant
	IOT	5	1.636	0.196279	2.71	$F_{cal} < F_{crit}$, Not Significant
BSH	Cement	4	122.82	8.89E-14	2.87	$F_{cal} > F_{crit}$, Significant
	IOT	5	7.637	0.000372	2.71	$F_{cal} > F_{crit}$, Significant

Detailed test results are given in Tables A79 – 81 in the Appendix A.

4.7.1 Regression analysis for durability

The regression analysis results showed that the resistance to loss in strength (RLS) was influenced by the cement 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 equation revealed the extent to which these parameters influence the resistance to loss in strength which is a function of the coefficient of each parameter. The coefficient of multiple determination value (R^2) shows a strong relationship between resistance to loss in strength and the parameters with R^2 value of 0.866

The regression equation is shown in Equation 4.5

$$RLS = 4498.3 + 218.8C - 30.40IOT - 25.91PF - 111.71PI + 230.9CE \quad (4.5)$$

$R^2 = 0.866$

where:

RSL = Resistance to loss in strength

C = Cement content, IOT = Iron ore tailing content, PF = Percentage fine, Pl = Plasticity index, CE = Compactive effort. Detailed test results are shown in Table 4.23

Table 4.23: Regression analysis for Resistance to loss in strength (RLS) of lateritic soil – cement – iron ore tailings mixtures

Dependent variable	Independent variable	Coefficients	p-value	Adjusted R^2	F
Resistance to Loss in Strength (RLS)	Intercept	4498.254674	0.003398764	0.865520723	3.91722E-36
	Cement content	218.7975312	0.000513151		
	Iron ore tailings content	-30.40235268	0.543387035		
	Percentage fine	-25.90640635	0.014243251		
	Plasticity index	-111.7089055	0.032326333		
	Compactive effort	230.8931667	0.000147784		

4.8 Microanalysis of Specimens

4.8.1 Scanning electron microscopy

In fine grained soil, it is extremely difficult to suggest a suitable type of model to take care of particulate arrangement and their particles linkages. Because of the colloidal nature of

the particles involved in clayey soils, it becomes exceedingly difficult to observe the mode of deposition of their particle and to determine the pore structure by means of any direct visual technique. However, these limitations are to some extent overcome by means of some techniques like Scanning Electron Microscopy (SEM). Microstructural 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. Materials evaluation using scanning electron microscopy (SEM) include grain size, surface roughness, porosity, particle size distribution, material homogeneity, inter metallic distribution and diffusion.

4.8.1.1 Micrograph of specimens for 7 days curing period

Scanning electron microscope (SEM) equipment was employed to investigate the morphology of the stabilized soil. Plate I – IV indicates the SEM results for the natural and optimally treated lateritic soil – cement mixtures with iron ore tailings after 7 days curing time.

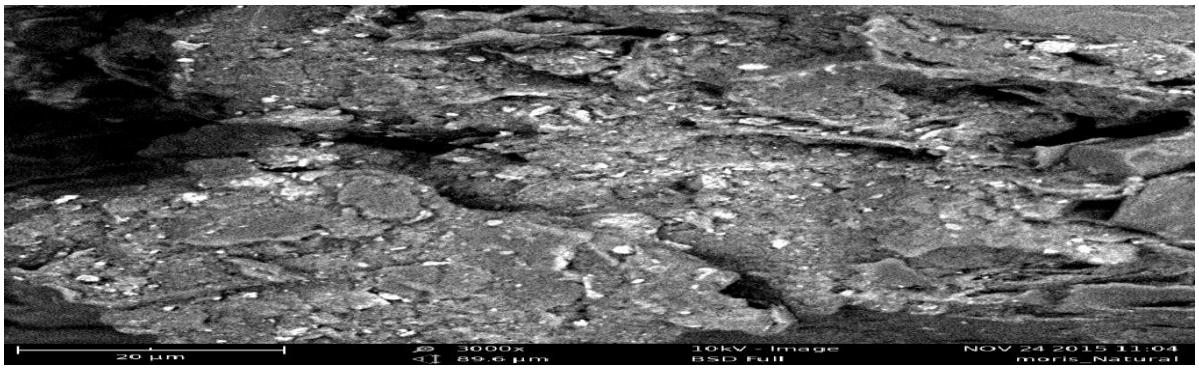


Plate I: Micrograph of natural lateritic soil after 7 days curing period at 20µm (3000X)



Plate II: Micrograph of lateritic soil optimally stabilized with 6 %cement - 6 % iron ore tailings blend after 7 days curing period at 20µm (3000X)

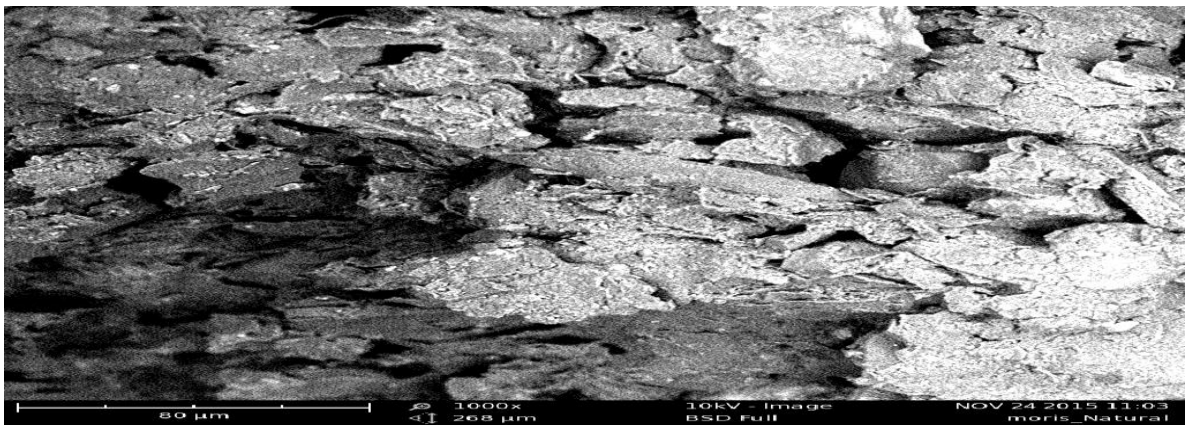


Plate III: Micrograph of natural lateritic soil after 7 days curing period at 80µm (3000X)

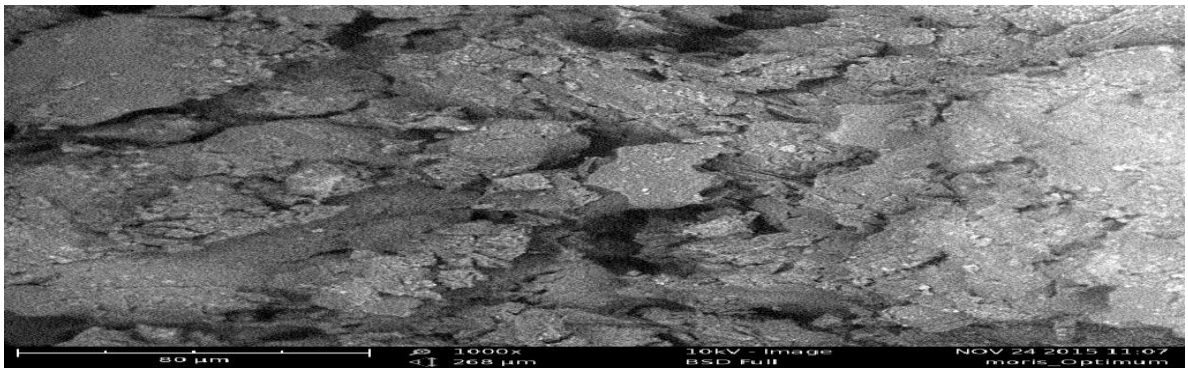


Plate IV: Micrograph of lateritic soil optimally stabilized with 6 % cement - 6 % iron ore tailings blend after 7 days curing period at 80µm (3000X)

The micrographs of the natural lateritic soil indicates a scaly-like surface morphology with inter-grain porosity induced by drying and microstructure alteration. This result is

similar to those of Romero and Simms (2008) and Zhang *et al.* (2005). It could also be due to the fact that no significant pozzolanic and ionic reaction might have taken place during the curing period. Similar behaviour was observed by Azige (2012), Yisa (2013) as well as Ishola (2014). However, from the image of the optimally treated lateritic soil, after 7 days of curing, samples were aggregated. Moreover, new compounds were formed. The aggregation of the soil particle may be due to cation exchange, flocculation-agglomeration, pozzolanic reaction, and carbonation that took place during the curing period. 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) as well as Deneele *et al.* (2010).

4.8.1.2 Micrograph of specimens cured for 28 days

The micrographs of specimen of the natural and stabilized lateritic soil cured for 28 days are shown in Plates V – VIII. The image for the untreated 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 lateritic soil after 28 days curing period shows a more aggregated structure. This shows that the clay particles and the flocs, were grown within the pore. The stabilization reaction in the soil - cement - 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 cement and iron ore tailings (see Plate I - IV).This finding is consistent with those reported by Okonkwo (2009) and Negi *et al.* (2013).

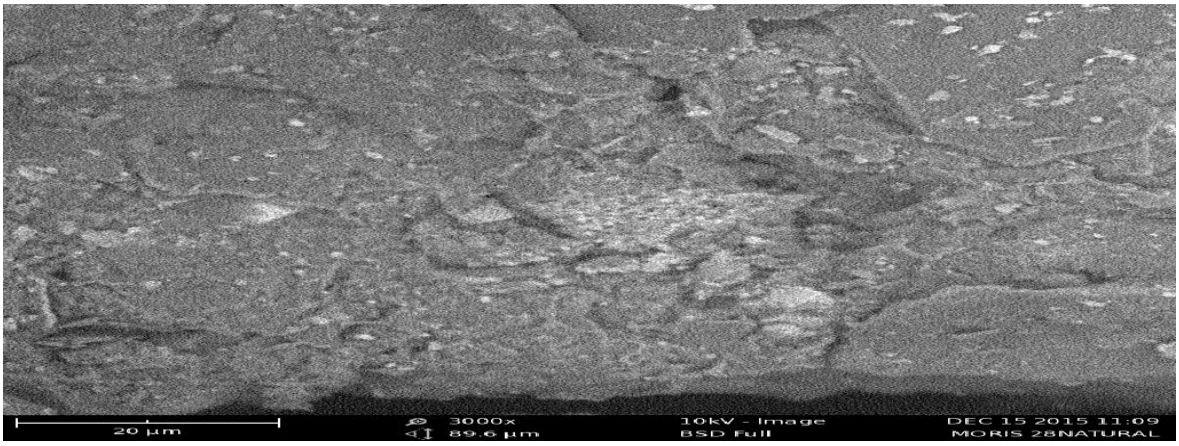


Plate V: Micrograph of natural lateritic soil after 28 days curing period at 20µm (3000X)

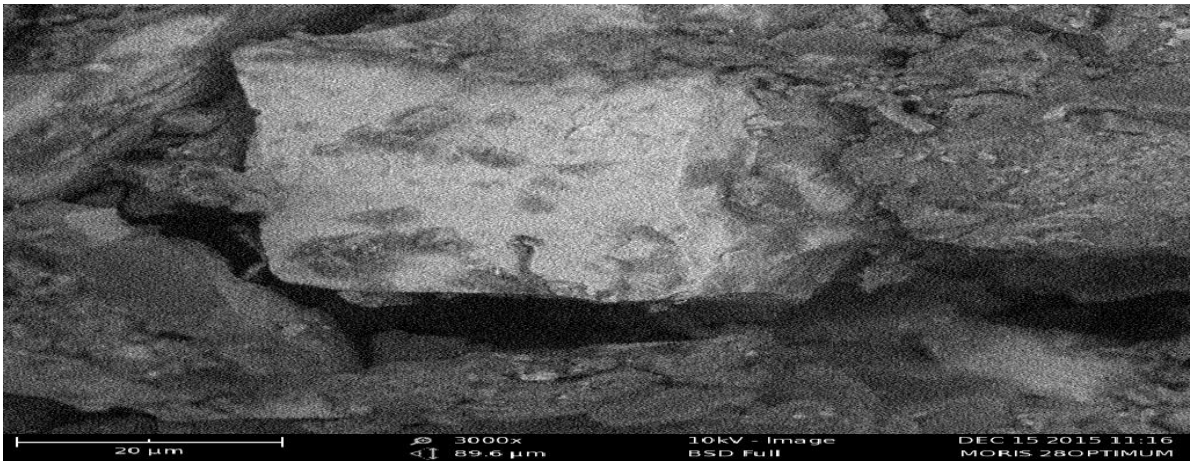


Plate VI: Micrograph of laterritic soil optimally stabilized with 6 % cement - 6 % iron ore tailings blend after 28 days curing period at 20µm (3000X)

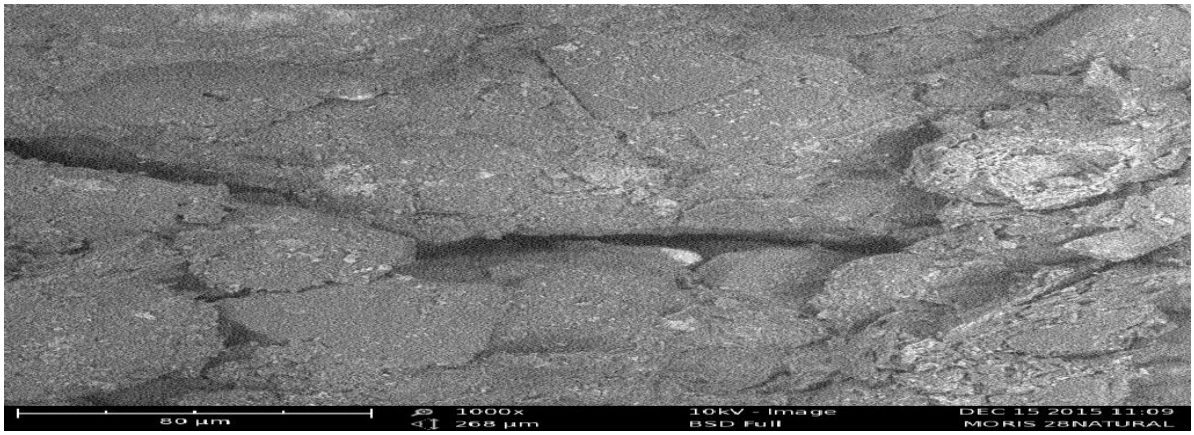


Plate VII: Micrograph of natural lateritic soil after 28 days curing period at 80µm (3000X)

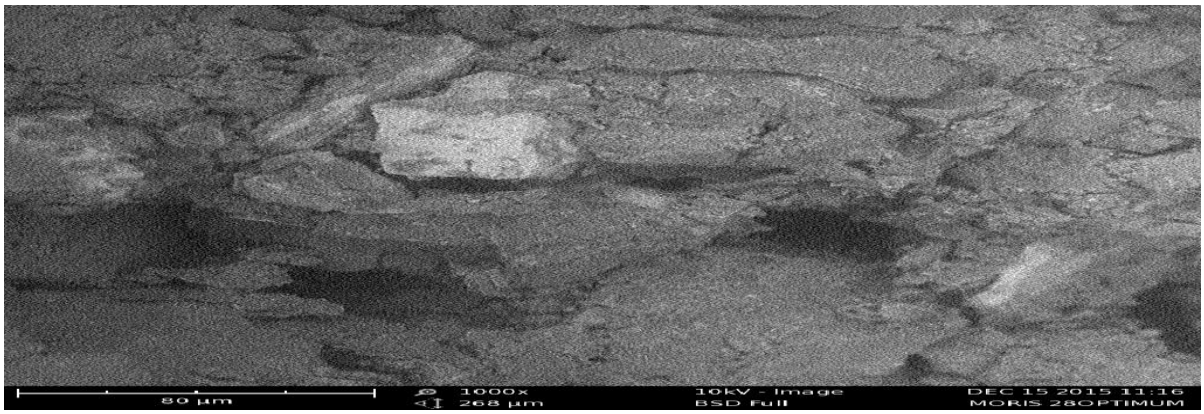


Plate VIII: Micrograph of stabilized lateritic soil optimally blend at 6 % cement 6% iron ore tailings after 28 days curing period at 80µm (3000X)

4.8.2 Fibremetric analysis

The fibremetric 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 fibre and pore size distribution histogram. The fibre metric application can be used on fibres ranging from 40 µm to 100 nm. It can be used for a wide range of applications, like investigation of filtration materials, diaper paddings, fibre research, and fibre 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 behaviour, micro and macro scale interactions, and so on (Romero and Simms, 2008).

The PHENOMWORLD desktop screen shot obtained from fibre and pore image measurement (fibremetric analysis) of the natural and optimally treated lateritic soil is shown in plate IX– XII. The red patches/spots indicate data points from which the fibremetric analysis was achieved.

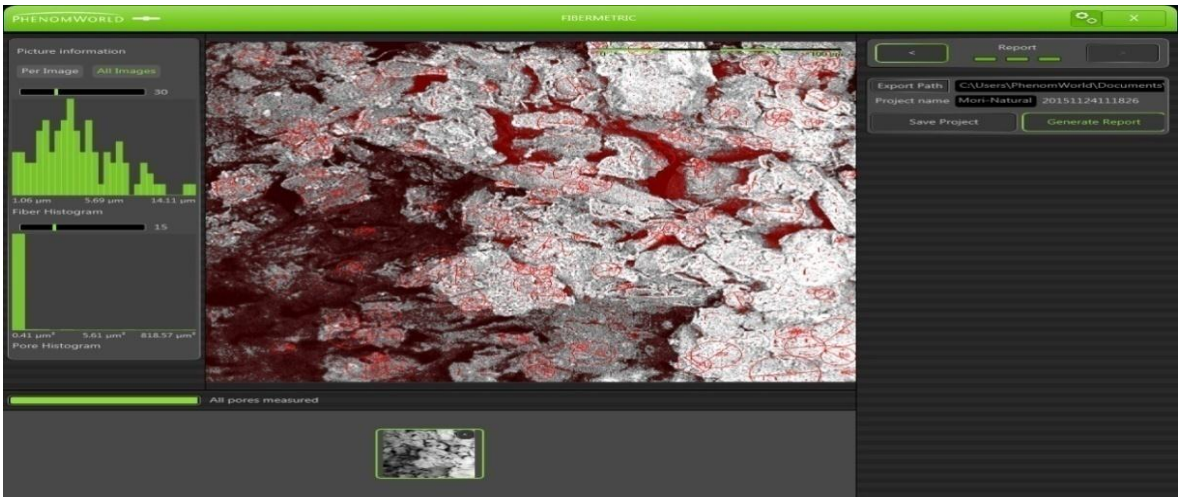


Plate IX: Fibre and pore image measurements of natural lateritic soil cured for 7 days



Plate X: Fibre and pore image measurements of optimally stabilized lateritic soil treated with 6 % cement - 6 % iron ore tailings blend after 7 days curing period

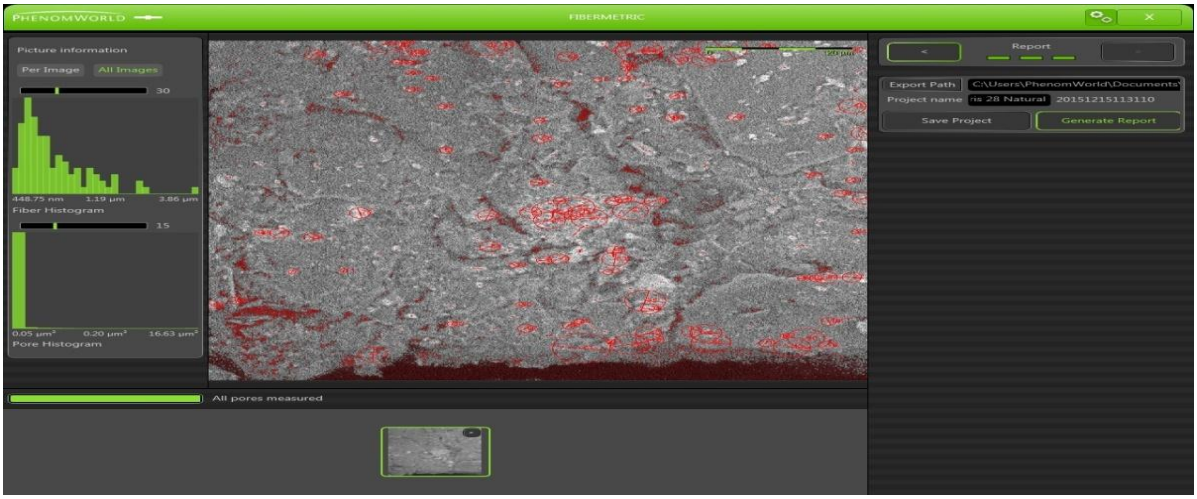


Plate XI: Fibre and pore image measurements of natural lateritic soil cured for 28 days

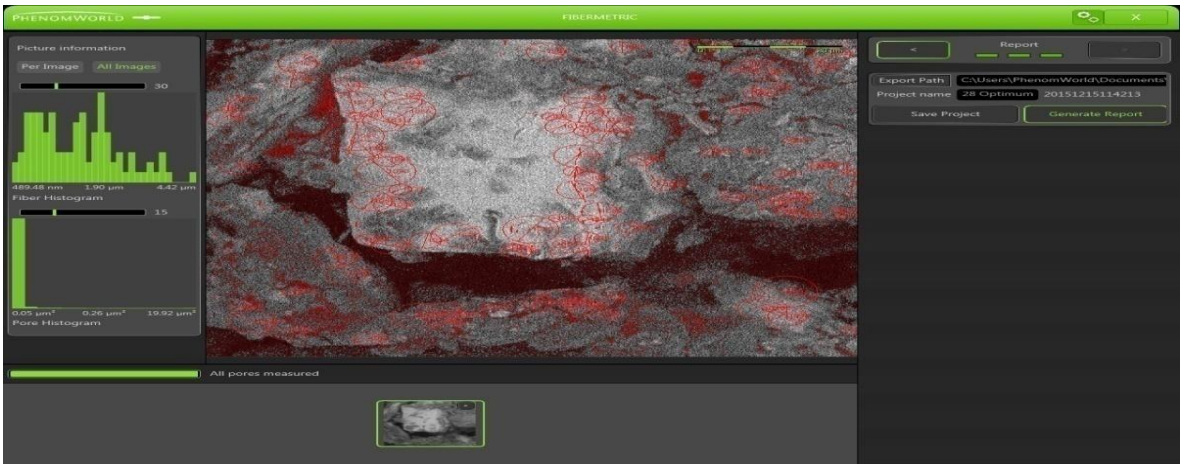


Plate XII: Fibre and pore image measurements of lateritic soil optimally stabilized with 6 % cement - 6 % iron ore tailings blend after 28 days curing period

4.8.2.1 Fibre distribution of specimens cured for 7 days

Plates XIII – XVI shows the distribution of the fabrics of the natural and the stabilized lateritic soil at optimum blend cured for 7 days determined using SEM. The results indicate that the soil fibre/sizes distributed over 1.06 µm for the natural soil and 448.75 nm for the stabilized soil. The distribution of the soil fibre could be attributed to the flocculation of the iron ore tailings as well as cation exchange reaction which lead to the formation of calcium silicate.

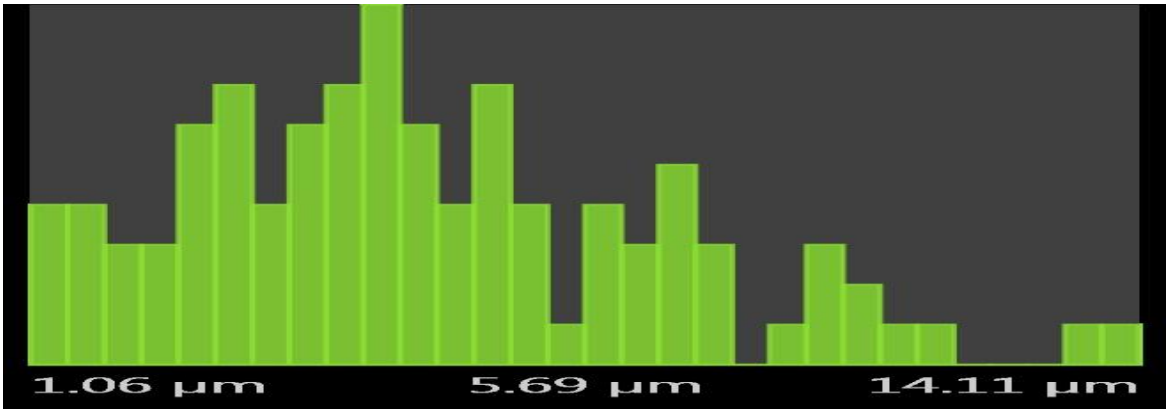


Plate XIII: Fibre distribution of natural lateritic soil after 7 days curing period

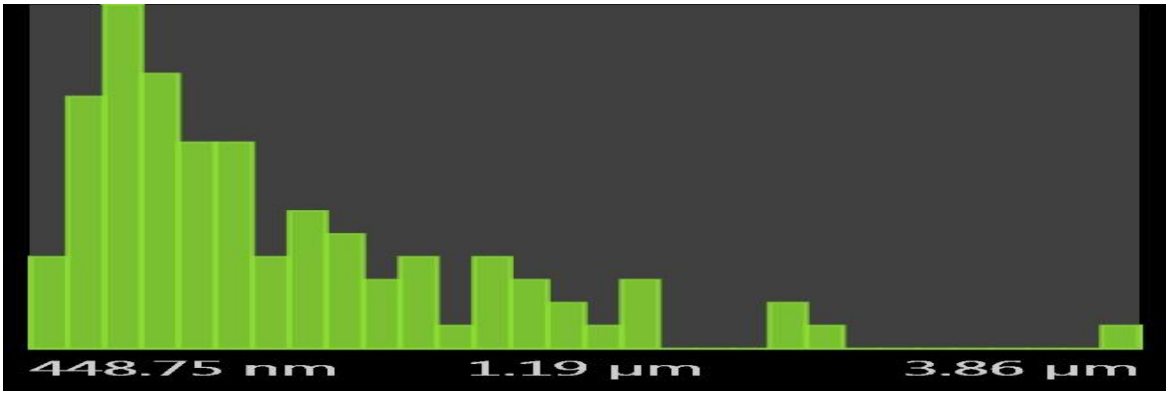


Plate XIV: Fibre distribution of lateritic soil optimally stabilized with 6 % cement - 6 % iron ore tailings blend after 7 days curing period

4.8.2.2 Fibre distribution of specimens cured for 28 days

Fibre analysis for specimens cured for 28 days was similar to those of specimens cured for 7 days as shown in Plates XV - XVI. The results showed soil fiber/sizes distribution of 1.16 µm for the natural soil and 489.48 nm for the stabilized soil after 28 days curing period. The pozzolanic and cation exchange reactions cause the soil particles to aggregate due to the formation of calcium silicate as well as other compounds may be responsible for the distribution in the soil fibre length.

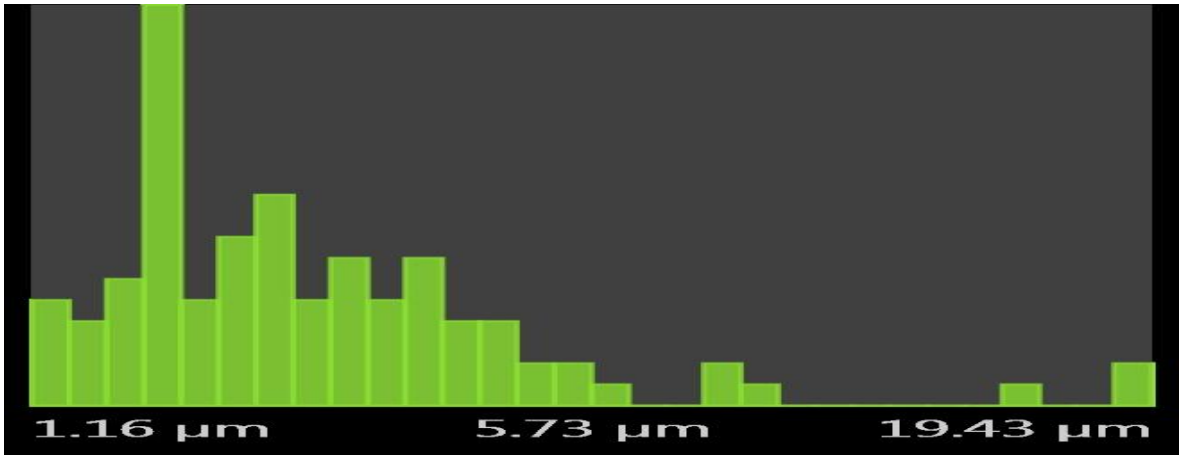


Plate XV: Fibre distribution of natural lateritic soil after 28 days curing period

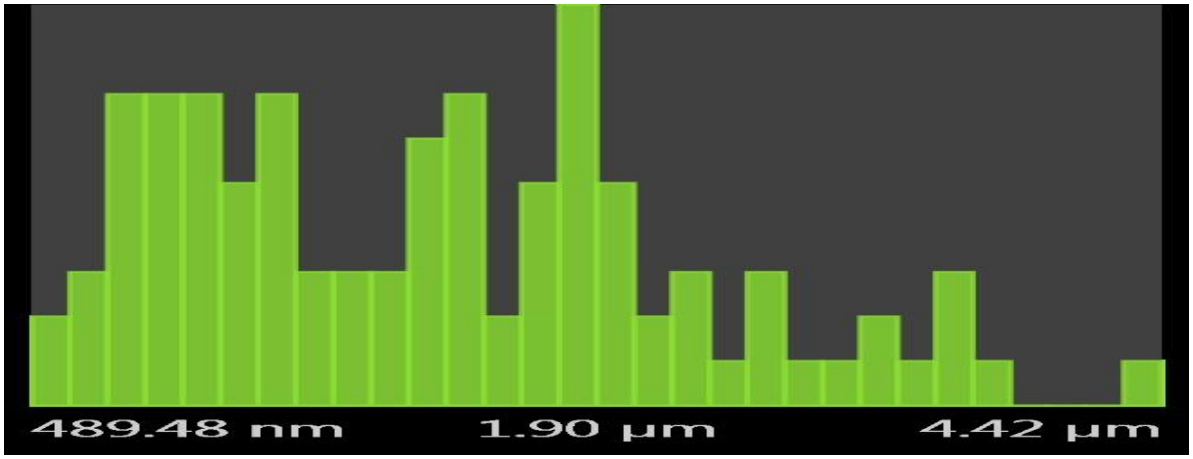


Plate XVI: Fibre distribution of lateritic soil optimally stabilized with 6 % cement – 6 % iron ore tailings after 28 days curing period

4.8.3.1 Pore distribution of specimens cured for 7 days

Plates XVII – XX shows the variation of surface area of pores of the natural and optimally stabilized lateritic soil with 6 % cement - 6% iron ore tailings after 7 days curing period. The result suggest that the surface area of pores within soil-cement-IOT mixtures considered were distributed over an area of 5.61 μm^2 for the natural soil and 3.58 μm^2 for the optimally stabilized soil. The distribution in pores spaces could be as a result of the formation of calcium silicates hydrates that covered the soil grains and filling the inter-aggregate porosity. This finding is similar to that reported by Deneele *et al.* (2010). From the

micro-structural point of view, the cement-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 (1984); Delage *et al.* (1996), Al-Rawas and McGown (1999) as well as Mitchell and Soga (2005).



Plate XVII: Pore distribution of natural lateritic soil after 7 days curing period

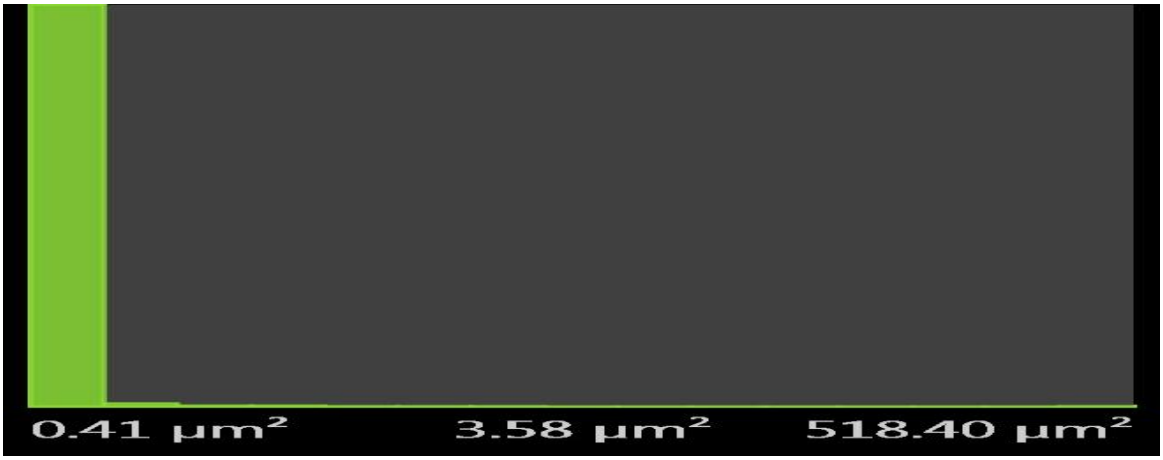


Plate XVIII: Pore distribution of lateritic soil optimally stabilized with 6 % cement – 6 % iron ore tailings after 7 days curing period

4.8.3.2 Pore distribution of specimens cured for 28 days

After 28 days curing period, the pore analysis shows similar trend like that of seven days. However, there was no significant difference between the pore sizes of the natural and optimally stabilized lateritic soil which may not be unconnected with the complete dryness of the sample caused by hydration and pozzolanic reaction. The results are shown in Plates XIX - XX.



Plate XIX: Pore distribution of natural lateritic soil after 28 days curing period



Plate XX: Pore distribution of lateritic soil optimally stabilized with 6 % cement – 6 % iron ore tailings after 28 days curing period

4.9 Leaching Potential of Iron to the Environment

4.9.1 Effect of iron ore tailings on pH of lateritic soil - cement mixtures

The variation of pH of lateritic soil – cement mixtures with iron ore tailings content is shown in Figure 4.111

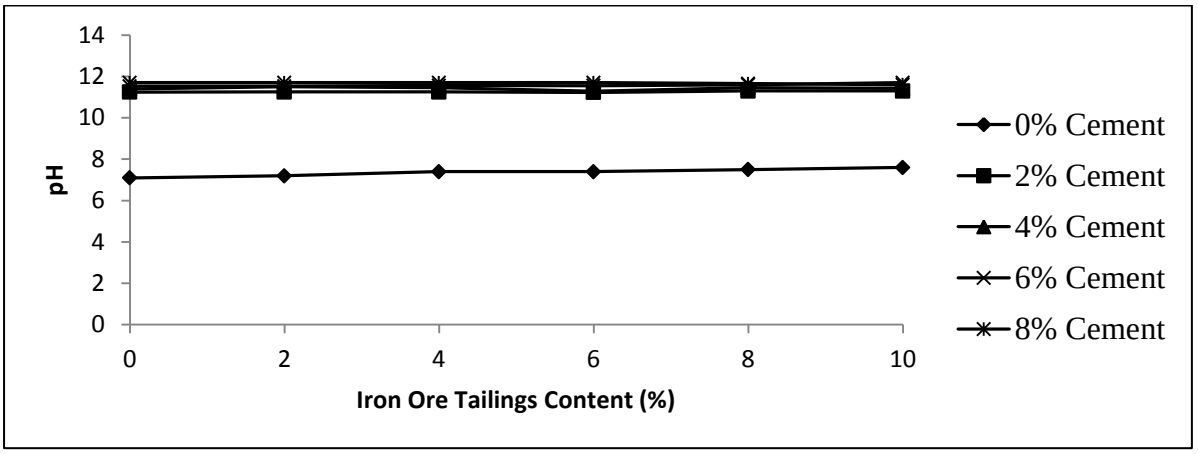


Figure 4.111: Variation of pH of lateritic soil-cement mixtures with iron ore tailings content

The pH of the lateritic soil – cement – IOT mixtures studied increased from a value of 7.1 for the natural soil to 7.6 for 0 % cement – 10 % IOT treatment. Similar trend of increase was observed for 2 % cement – 0 IOT %, 4 % cement – 0 % IOT and 6 % cement -0 % IOT blend from 11.24, 11.4 and 11.53 to 11.3, 11.42 and 11.7 at 2% Cement – 10 % IOT, 4 % cement – 10 % IOT and 6 % cement – 10 % IOT blend respectively. According to Osinubi *et al.* (2010) 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 led to increase in the alkalinity values. Amadi (2010b) also suggested 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 10.40 which caused the increase in pH of the acidic soil. The acid neutralization property may have arisen from the high CEC of IOT (18.9 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 decreased from a value of 11.7 at 8 % cement - 0 % IOT to 11.5 for 8 % cement – 10 % IOT treatment. The decrease is attributed to decrease in the CEC of soil-lime-IOT mixture at higher cement and IOT content. Similar findings were reported by Huang and Petrovic (1994), Katz *et al.* (1996), Liu and Lal, (2012 a, b). Soil 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 11.55 for the optimum blend at 6 % cement – 6 % IOT is above the permissible range of 6.5 – 8.5 for drinking water recommended by APDA (1989), WHO (2006) and NIS (2007).

The effect of cement content on the pH of lateritic soil-cement mixtures with iron ore tailing content is shown in Figure 4.112. It was observed that the pH increases with increase in the cement content. The increase in pH could be as a result of increase in free lime present in the soil with higher cement treatment that resulted in the higher alkalinity (i.e., pH) of the stabilzed soil. This agrees with the findings of Ijimdiya and Osinubi, (2011) who worked on attenuative capacity of compacted black cotton soil treated with bagasse ash. Although the pH increased with increasing cement content, no significant variation was recorded between the various stepped concentrations of 2, 4, 6 and 8% cement content as shown in Figure 4.112. This implies that the IOT has more pronounced effect on the pH that cement.

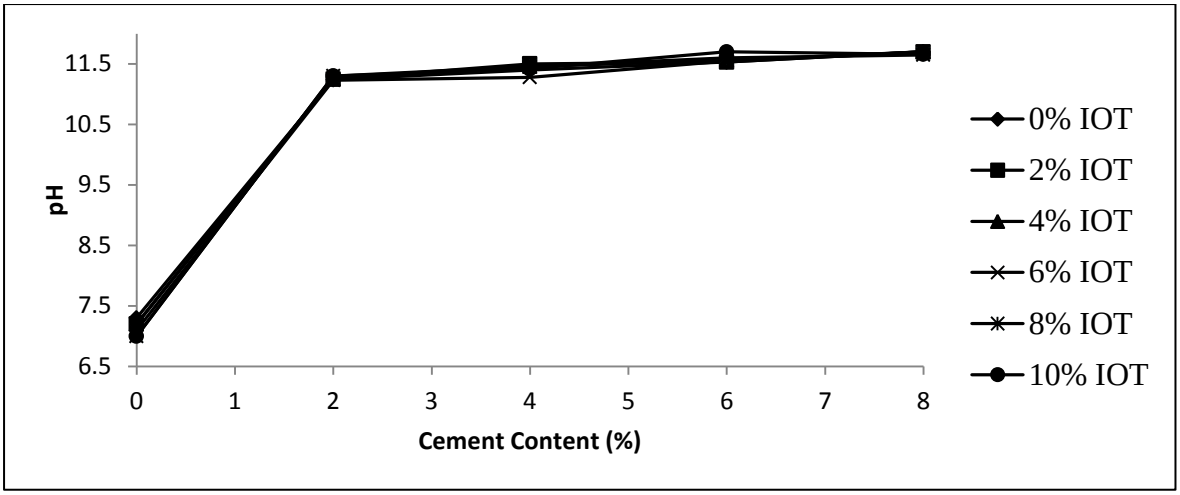


Figure 4.112: Variation of pH of lateritic soil - cement mixtures with iron ore tailings content.

4.9.2 Batch equilibrium

Results of chemical analyses using Atomic Absorption Spectrophotometry (AAS) were used to obtain desorption isotherms for Iron (Fe^{2+}) at various cement - iron ore tailing contents as shown in Figure 4.113.

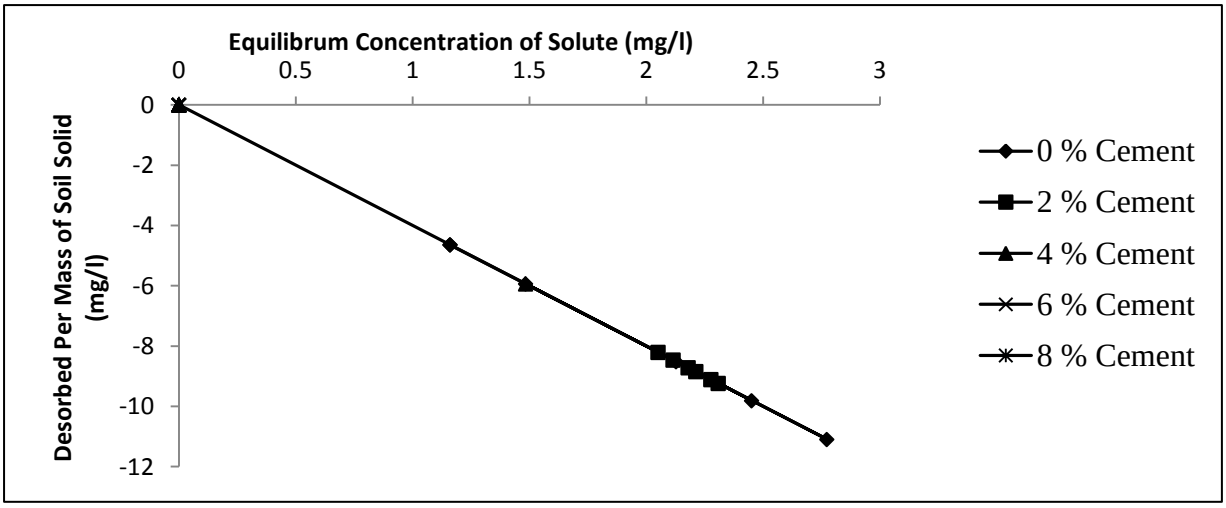


Figure 4.113: Variation of desorption isotherms for Iron (Fe^{2+}) at various cement-Iron ore tailings content.

It was observed that the desorbed values increased with higher IOT content in the range of 1.161mg/l for the natural soil to a peak value of 2.452 mg/l at 0% cement – 10 % IOT blend. The increase could be attributed to increase in the Fe^{2+} concentration with increase in

IOT which has a desorbed value of 5.355 mg/l. This trend of increase in the desorbed values may not be unconnected with the increasing pH of the solution (Ijimdiya and Osinubi, 2011). The increase in the desorption capacity of the soil-cement-IOT mixtures with higher IOT content is thought to be as a result of the high pH value which made the surfaces to become more negatively charged. An increase in pH created a condition for the establishment of attractive electrostatics forces that enhanced the desorption of cation species (Shackelford, 1993; Osinubi and Amadi, 2003). The desorbed values of Fe^{2+} ion obtained are within the range reported by other researches (Aremu *et al.*, 2010; Ikotun *et al.*, 2012). However, at higher cement content treatment: 6 % cement/ 0 % IOT up to 8 % cement/ 10 % IOT, no Fe^{2+} ion were detected in the soil – cement IOT mixture. The desorbed value for the optimum blend at 6 % cement – 6 % IOT therefore, falls within the permissible value of not more than 0.3mg/l Iron(Fe^{2+}) concentration for drinking water recommended by WHO (2006) and NIS (2007).

A Linear equation of the line (i.e. for 0% cement) from Figure 4.113

$$y = -4x \qquad (4.8)$$

With R^2 =1 shows a perfect correlation between desorbed per mass of soil solid and equilibrium concentration of solute. Similar results were observed for all variation in the cement content. Comparatively, for all cement-IOT-soil mixtures results for the isotherms gave a linear relationship between desorbed per mass of soil solid and the equilibrium concentration of solute. Detailed test results are shown in Tables A49 in the Appendix.

4.9.3 Effect of iron ore tailing on desorption isotherm for Iron (Fe^{2+})

The desorption trend observed with higher cement contents in the soil -cement - iron ore tailing mixtures showed remarkable decrease in desorption values of Iron(Fe^{2+}) into the environment. The presence of IOT in the mixture increased the pH value which optimized the conditions that led to immobilization of the cationic ions. Consequently, ionic species became

fixed in the substrate by the combination of desorption and precipitation mechanisms. This agrees with past researches (Ijimdiya and Osinubi, 2011). This implies that more Fe^{2+} was absorbed by the soil– cement mixture. Thus the absorption of Iron (Fe^{2+}) away from the environment occurred (Shackelford, 1993; Osinubi and Amadi, 2003).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The aim of the investigation was to evaluate the effect of iron ore tailings, as an admixture, in cement stabilization of lateritic soil. In an effort to achieve the above aim and improve the suitability of soil for engineering use, the air-dried samples were treated with ordinary Portland cement (OPC) – iron ore tailings (IOT) in stepped concentration of 0, 2, 4, 6, and 8 % by dry weight of the soil for OPC, while 0, 2, 4, 6, 8, and 10 % by dry weight of soil for IOT for all parameters considered. The preliminary index properties tests conducted on the natural lateritic soil showed that the soil is fine-grained, with a natural moisture content of 19.4 %. The soil is reddish brown in colour. It classified as A-7-6(14) and CL according to the American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification System (USCS) respectively. The natural soil has liquid limit of 44.7 %, plastic limit of 22.5 %, plasticity index of 22.2 %, linear shrinkage of 8.1 %, and specific gravity of 2.52. These values indicate that the soil is of moderate plasticity with about 67.9 % of the soil particles passing the No. 200 sieve. Cation exchange capacity values decreased with higher cement and IOT contents.

The Atterberg limits results indicate that the liquid limit of the soil decreased from 44.7 to 37.4 % when treated with 0% cement / up to 10 % IOT. The plastic limit increased from 22.5 to 23.4 % when treated with 0 % cement / up to 10 % IOT. The plasticity index decreased with higher cement and IOT contents.

The maximum dry density (MDD) values increased with higher compaction energy and IOT content. The natural soil recorded MDD values of 1.61, 1.67 and 1.77 Mg/m^3 for BSL, WAS and BSH compactions, respectively, increased to 1.68, 1.75 and 1.87 Mg/m^3 at 0

% cement /10 % IOT treatment. The same trend of increase in MDD was observed for all the cement contents considered. OMC values on the other hand, decreased with higher compactive effort and IOT content. For the natural soil OMC values of 22.5, 21 and 15.3 % for BSL, WAS and BSH compactions, respectively, decreased to 21.3, 18.4 and 12.5 % at 0 % cement /10 % IOT treatment. The same trend of decrease in OMC was observed for all the cement contents considered.

The unconfined compressive strength (UCS) values for BSL, WAS and BSH compactive efforts recorded for the natural soil at 7 days curing period were 263.98, 565.37 and 875.46 kN/m^2, respectively. For the same curing period the UCS values of the lateritic soil treated with 6 % cement – 6 % IOT content increased to peak values of 3783.64, 3860.97 and 3993.14 kN/m^2 for BSL, WAS and BSH compaction, respectively. For the same cement / IOT treatment, peak UCS values generally increased with higher curing period. Peak UCS values of 4105.28, 4286.5 and 4392.21 kN/m2 were recorded at 28 days curing period for BSL, WAS and BSH compaction, respectively.

Based on the UCS criterion of 1720 kN/m^2 the requirement for road base material for lightly trafficked roads after 7 days curing period were met by specimens treated with a minimum of 4 % cement / 2 % IOT blend compacted with the three energies considered in the study. However, samples treated with 2 % cement / 8 % IOT were adequate after 28 days of curing for WAS and BSH compactions with both having UCS values of 1778.93 kN/m^2 and 1813.11 kN/m^2.

The unsoaked CBR values for the natural soil compacted with BSL, WAS and BSH energy efforts increased from 10 %, 14 % and 17 % to 100 %, 100 % and 100 % at 6 % OPC/6% IOT treatment, respectively. The specimens compacted with BSL, WAS, BSH energies and soaked for 24 hours recorded CBR values of 80 %, 80 % and 100 % respectively, which showed about 0 – 20 % decrease from the unsoaked CBR values. The

recorded soaked CBR values meet the 30% recommended for sub-base material by the Nigerian General Specifications.

Durability measured by resistance to loss in strength of the soil increased from 47, 41 and 37 % for the natural soil to 87, 91 and 92% for BSL, WAS and BSH compaction at 6 % OPC / 6 % IOT treatment, respectively. These results suggest that the soil treated with 6 % OPC / 6 % IOT and compacted with the three energy levels considered can be used for sub-base material in road construction based on the limiting value of 80 % resistance to loss in strength even though the specimens were subjected to a harsher 7 days soaking condition as compared with the conventional 4 days soaking period.

Microanalysis conducted using scanning electron microscope showed that treated specimens were aggregated and a change in the fabric orientation of the soil particle occurred. Fibre metric analysis conducted showed a reduction in pore volumes and pore area of the modified soil. These results suggest an improvement in the strength and workability of the stabilized soil.

Batch equilibrium test conducted to determine the leaching potential of iron into the environment results showed that the desorbed values of iron and pH for the specimens optimally treated with 6 % OPC / 6 % IOT blend falls within the permissible value recommended by the World Health Organisation (WHO) and the Nigeria Industrial Standard (NIS).

Based on the Nigerian General Specifications requirements specimens optimally treated with 6 % OPC / 6 % IOT blend met the value of not more than 35 % passing sieve No.200 (0.075 mm aperture) and 30 % maximum plasticity index value for use as subgrade material. Also, the improved geotechnical properties of the optimally treated lateritic soil – cement with iron ore tailings mixture satisfy the combined strength indices evaluation criteria (i.e. CBR, 7 day UCS as well as durability) for use as base materials for road construction.

The statistical analysis of test results using a two-way analysis of variance showed that cement and iron ore tailings treatment of lateritic soil had significant effects on the properties of the treated soil.

5.2 Recommendation

Based on the strength and durability results of the study carried out it is recommended that lateritic soil treated with 4 % cement by weight of dry soil admixed with 6 % IOT content when compacted with a minimum BSL compactive effort could be used as a sub-base material in the construction of medium trafficked roads.

Also, it is recommended that further research into the use of cement - iron ore tailings blend with coarse grain soil should be carried out.

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APPENDICES

APPENDIX A

Table A1: Natural Moisture Content of Lateritic Soil

Natural Moisture Content for the Laterite Soil			
Container No	N_{112}	P_{C4}	B_{21}
Mass of Container M1	8.6	8.3	9.4
Mass of Container + Wet Soil M2	39.8	40.2	38.5
Mass of Container + Dry Soil M3	34.7	35	33.8
Mass of Dry Soil (M3-M1)=Ws	26.1	26.7	24.4
Mass of Wet Soil (M2- M1)	31.2	31.9	29.1
Ww = (M2-M1)-(M3-M1)	5.1	5.2	4.7
Moisture Content = W = Ww/Ws	19.54	19.48	19.26
Average W	19.43		

Table A2: Specific Gravity of Cement

Flask No.	1	2	3
Mass of Bottle M1	37.3	43.4	46.9
Mass of Bottle + Soil M2	42.2	46.8	52
Mass of Bottle + Soil + Water M3	90.1	95.2	100.1
Mass of Bottle + Water M4	86.8	92.9	96.6
M4 - M1	49.5	49.5	49.7
M3 – M2	47.9	48.4	48.1
M2 – M1	4.9	3.4	5.1
(M4 - M1) - (M3 - M2)	1.6	1.1	1.6
Gs = (M2-M1) / ((M4-M1)-(M3-M2))	3.0625	3.09091	3.1875
Average Specific Gravity, Gs	3.11		

Table A3: Specific Gravity of Iron Ore Tailings

Flask No.	A	K	KE
Mass of Bottle M1	23.7	20.6	25.5
Mass of Bottle + Soil M2	27.4	24.8	28.5
Mass of Bottle + Soil + Water M3	51.2	48.3	52.4
Mass of Bottle + Water M4	48.6	45.4	50.3
M4 - M1	24.9	24.8	24.8
M3 – M2	23.8	23.5	23.9
M2 – M1	3.7	4.2	3
(M4 - M1) - (M3 - M2)	1.1	1.3	0.9
Gs = (M2-M1) / ((M4-M1)-(M3-M2))	3.36364	3.23077	3.33333
Average Specific Gravity, Gs	3.31		

Table A4: Specific Gravity Values for Soil-Cement –Iron Ore Tailings Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	2.52	2.56	2.67	2.69	2.7
2	2.54	2.61	2.68	2.72	2.73
4	2.62	2.65	2.71	2.73	2.75
6	2.66	2.7	2.72	2.76	2.77
8	2.67	2.71	2.75	2.77	2.78
10	2.72	2.74	2.76	2.78	2.81

Table A5: Cation Exchange Capacity (Cmol/kg) Test Results for Soil–Cement Iron Ore Tailings Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	39.6	26.4	13.4	11.1	13.6
2	33.7	20	8.5	11.4	11.7
4	21.1	10.5	11.7	11.9	12.5
6	31.4	9.5	19.3	11.1	13
8	22.6	14.3	9.7	11.4	12
10	27.5	11.6	11	12	13

Table A6: Wet Sieve Analysis Test Results for Soil – Cement – Iron Ore Tailings Mixtures

0% Cement											
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	98.6	4.76	98.45	4.76	98.85	4.76	99.05	4.76	98.3	4.76	98.7
2.36	95	2.36	91.05	2.36	92.15	2.36	91.25	2.36	97	2.36	97.95
2	92.15	2	87.95	2	90.1	2	88.05	2	96.2	2	97.1
0.6	90.4	0.6	85.9	0.6	88.9	0.6	85.4	0.6	95.3	0.6	96.45
0.425	86	0.425	81.35	0.425	86.2	0.425	81	0.425	91.5	0.425	93.05
0.3	82.9	0.3	79.35	0.3	84.45	0.3	78.85	0.3	90.4	0.3	91.3
0.212	78.35	0.212	75.9	0.212	81.2	0.212	76	0.212	86.5	0.212	87.4
0.15	74.3	0.15	72.95	0.15	75.4	0.15	72.6	0.15	83.65	0.15	85.15
0.075	67.95	0.075	67.15	0.075	70.05	0.075	65.55	0.075	75.25	0.075	76.6
0.010277	22.38158	0.010696	19.79221	0.009779	22.64198	0.010502	18.42771	0.009634	22.38323	0.009829	20.55814
0.009075	9.118421	0.009331	6.185065	0.008641	10.10802	0.009342	3.204819	0.008659	8.793413	0.009087	3.953488
0.007735	5.802632	0.007775	4.535714	0.007257	8.08642	0.00781	1.201807	0.007823	0.799401		
0.005581	4.144737	0.005553	3.711039	0.005187	7.277778						
0.003985	3.315789	0.004021	1.649351	0.003746	5.660494						

2 % Cement											
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	99.05	4.76	98.44	4.76	98.75	4.76	99.2	4.76	98.95	4.76	98.9
2.36	91.8	2.36	86.74	2.36	90.15	2.36	86.35	2.36	89.8	2.36	90.2
2	90.55	2	85.34	2	88	2	84.55	2	87.65	2	87.6
0.6	83.9	0.6	82.29	0.6	82.6	0.6	81	0.6	83	0.6	83.35
0.425	79.3	0.425	77.14	0.425	78.9	0.425	77.5	0.425	80.15	0.425	80.1
0.3	75	0.3	73.24	0.3	74.8	0.3	72.75	0.3	76.4	0.3	75.55
0.212	71.4	0.212	68.64	0.212	71.05	0.212	70.2	0.212	74.1	0.212	70.35
0.15	65.75	0.15	65.49	0.15	66.45	0.15	63.6	0.15	68.9	0.15	66.7
0.075	65.75	0.075	65.44	0.075	66.3	0.075	63.5	0.075	65.25	0.075	64.15
0.010352	21.33333	0.01036	20.91346	0.010367	19.27273	0.010051	19.85294	0.009775	20.60234	0.00947	21.25862
0.008359	13.94872	0.008438	12.54808	0.007996	14.45455	0.008483	9.529412	0.00758	15.84795	0.007258	17.32184
0.007085	11.48718	0.007057	10.875	0.006867	11.24242	0.007313	5.558824	0.006527	12.67836	0.006979	7.086207
0.00547	4.923077	0.005219	7.528846	0.005355	4.015152	0.005431	1.588235	0.004898	8.716374	0.005243	2.362069
0.003983	2.461538	0.00373	6.692308					0.003725	3.169591		

4% Cement											
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	99.25	4.76	98.75	4.76	98.85	4.76	98.45	4.76	99.05
2.36	88.45	2.36	86.6	2.36	85.55	2.36	88.95	2.36	86.3	2.36	88.2
2	86.6	2	84.7	2	83.15	2	87.05	2	84	2	85.55
0.6	80.35	0.6	79.4	0.6	78.45	0.6	80.45	0.6	79.4	0.6	79.25
0.425	76.95	0.425	75.2	0.425	74.9	0.425	77.2	0.425	72.25	0.425	75.5
0.3	72.4	0.3	71.9	0.3	70.85	0.3	74.4	0.3	65.35	0.3	70.7
0.212	69.65	0.212	67.25	0.212	65.7	0.212	70.35	0.212	62.2	0.212	63.85
0.15	67.35	0.15	63.55	0.15	62.6	0.15	65.55	0.15	58.1	0.15	60.75
0.075	63.75	0.075	61.95	0.075	60	0.075	58.6	0.075	58	0.075	58.45
0.010144	19.98503	0.010275	19.14286	0.010345	18.22515	0.010156	18.97674	0.009745	20.42857	0.009884	19.60227
0.008562	9.592814	0.008336	11.16667	0.008062	12.67836	0.008338	10.27907	0.007557	15.71429	0.007747	14.11364
0.007304	6.39521	0.007204	7.178571	0.006986	8.716374	0.006887	9.488372	0.006341	14.14286	0.007042	7.056818
0.005377	3.197605	0.005255	4.785714	0.005103	6.339181	0.005035	7.116279	0.004938	7.857143	0.005189	3.920455
0.003839	2.398204	0.003863	1.595238	0.003683	4.754386	0.003636	5.534884			0.003811	0.784091

6% Cement											
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	99.4	4.76	98.7	4.76	99.35	4.76	98.95	4.76	98.4	4.76	97.9
2.36	88.75	2.36	87.55	2.36	85.55	2.36	89.9	2.36	91.75	2.36	87.2
2	86.9	2	85.85	2	84.05	2	88.2	2	90.95	2	86.1
0.6	84.5	0.6	83.3	0.6	80.8	0.6	83.65	0.6	87.75	0.6	83.95
0.425	80.15	0.425	78.4	0.425	73.2	0.425	75.6	0.425	81.25	0.425	77.5
0.3	77.55	0.3	75.55	0.3	69.2	0.3	72.05	0.3	76.15	0.3	73.9
0.212	73.65	0.212	71.7	0.212	62.85	0.212	66	0.212	72.1	0.212	70.55
0.15	70.15	0.15	66.55	0.15	58.8	0.15	61.1	0.15	67	0.15	64.8
0.075	63.6	0.075	59.4	0.075	52.05	0.075	53.15	0.075	58.1	0.075	56.4
0.014022	20.69231	0.019659	20.55814	0.018929	22.09249	0.027496	20.38636	0.019708	19.56215	0.021049	16.00843
0.011322	13.52959	0.015771	13.83721	0.014093	19.72543	0.02102	16.46591	0.014603	17.21469	0.016203	10.93258
0.008411	10.34615	0.011792	10.27907	0.010597	16.56936	0.016199	11.36932	0.010777	14.86723	0.012126	7.02809
0.007027	8.754438	0.00872	7.116279	0.007706	14.99133	0.012065	7.840909	0.007976	12.12853	0.009023	3.123596
0.005024	7.95858	0.00742	3.953488	0.006545	12.62428	0.008717	6.272727	0.006633	10.9548	0.007438	2.342697
0.003591	7.162722	0.005298	3.162791	0.004686	11.83526	0.007265	4.704545	0.004911	7.824859	0.005309	1.561798
		0.003782	2.372093	0.003354	11.04624	0.00524	3.136364	0.00351	7.042373	0.003789	0.780899
						0.003741	2.352273				

8% Cement											
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	99.3	4.76	98.75	4.76	98.75	4.76	98.7	4.76	99.05	4.76	98.9
2.36	86.6	2.36	89.5	2.36	85.5	2.36	86.05	2.36	85.15	2.36	86.25
2	84.95	2	86.8	2	81.85	2	83.2	2	81.25	2	83.3
0.6	77.7	0.6	81.9	0.6	76.7	0.6	76.8	0.6	74.9	0.6	75.6
0.425	74.1	0.425	74.2	0.425	71.9	0.425	73.95	0.425	70.7	0.425	70.45
0.3	71.2	0.3	70.45	0.3	65.35	0.3	69.25	0.3	66.05	0.3	66.65
0.212	67.05	0.212	67.3	0.212	62	0.212	65.35	0.212	58.7	0.212	62.45
0.15	62.8	0.15	63.05	0.15	59.35	0.15	56.1	0.15	53.55	0.15	56.75
0.075	61.25	0.075	56.85	0.075	54.75	0.075	50.9	0.075	48.8	0.075	50.65
0.020749	18.26471	0.021193	16.56936	0.020765	17.28571	0.021553	14.86723	0.021786	14.05618	0.029395	15.52486
0.015756	14.29412	0.016032	12.62428	0.015324	14.92857	0.016052	11.73729	0.016397	10.15169	0.021075	14.74862
0.011719	11.11765	0.011895	9.468208	0.011413	11.78571	0.012029	7.824859	0.012126	7.02809	0.016077	10.09116
0.00877	7.147059	0.008788	6.312139	0.008552	7.857143	0.008781	5.477401	0.009023	3.123596	0.011762	7.762431
0.007535	3.176471	0.007325	4.734104	0.007356	3.928571	0.007529	1.564972	0.007509	1.561798	0.008497	6.209945
0.00538	2.382353	0.005334	2.367052	0.005353	1.571429					0.007082	4.657459
0.00384	1.588235	0.003843	0.789017							0.005157	2.328729

Table A7: Dry Sieve Test Results for Soil – Cement – Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

	0% Cement						2% Cement					
BS SIEVE SIZE	0% IOT % Passing	2% IOT % Passing	4% IOT % Passing	6% IOT % Passing	8% IOT % Passing	10% IOT % Passing	0% IOT % Passing	2% IOT % Passing	4% IOT % Passing	6% IOT % Passing	8% IOT % Passing	10% IOT % Passing
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	65.65	63.6	62.7	63.75	64.8	68.8	69.75	72.15	73.3	70.8	70.25	67.15
2	61.5	59.2	58	60.35	59.65	64.45	62.1	65.45	66.15	63.7	62.85	60.4
0.6	53.25	44.9	46.65	48.3	50.1	49.25	45.25	49.6	49.6	46.55	45.1	46.2
0.425	37.05	28.2	26.5	28.55	31.7	28.6	23.65	26.35	28.15	26.4	25.8	24.55
0.3	27	20.9	18.3	19.85	22.55	22	17.55	20	21.25	18.6	17.55	18.4
0.212	19.7	12.9	13.7	10.2	17.35	16.25	12.45	11.25	14.1	13.45	13.4	13.35
0.15	10.8	7.05	6.45	4.55	8.55	8.05	7.45	7	9.05	7.4	7.9	7.6
0.075	7.6	4.4	5.4	3.7	2.3	1.7	2.3	1.5	2.05	2.25	1.8	1.35

BS SIEVE SIZE	4% Cement						6% Cement					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	64.7	65.9	66.85	68.85	66.9	69.2	66.8	66.25	73.2	72.15	73.2	71.85
2	58.5	57.75	59.5	62.35	59.8	62.85	60.75	60.55	67.05	65.45	66.45	66.2
0.6	41.25	42.25	45.35	47.5	48.4	41.1	44.6	45.45	52.65	52.7	51.15	46.15
0.42	20.85	21.35	25.25	26.8	26.8	22.8	20.85	26.65	29.35	31.05	28.9	26.4
0.3	14.15	15.3	16.3	18.75	19.9	17.4	14.6	18.3	20.45	23.7	23.75	20.55
0.21	10.15	10.25	11.85	12.5	14.2	12.8	11.5	14.9	13.3	16.05	18.9	13.3
0.15	6.85	5.95	8.65	8.25	9.4	7.7	6.4	8.3	8.15	11.85	11.8	8.6
0.07	2.45	1.15	1.35	1.15	1.35	2.1	1.75	2.45	1.75	2.25	1.95	1.55

BS SIEVE SIZE	8% Cement					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100
2.36	69.85	69.1	70.65	70.65	71.55	71.3
2	65.15	64.85	64.45	65.95	65.35	66.1
0.6	51.25	43.65	44.2	44.75	44.75	45.05
0.425	32.65	30.95	26.05	30.85	27.7	32.9
0.3	24.35	16.65	17.15	16.05	17.8	19
0.212	17.2	8.3	9.4	6.45	11	10.9
0.15	7.15	4.95	3.1	3.2	5.8	4.85
0.075	2.35	2.25	1.15	1.35	2.5	2.4

Table A8: Dry Sieve Test Results for Soil-Cement– Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

	0% Cement						2% Cement					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	82.65	80.1	83.3	84.8	80.45	86	70	68.75	71.2	68.25	70.8	68.5
2	77	73.35	78	79.25	75	81.45	62.35	61.15	64.5	60.2	63.3	61.65
0.6	64.75	59.05	64.2	65.45	62.65	64.75	45.5	45.9	47.95	43.05	45.55	47.3
0.425	42.85	38.85	40.45	43.3	41.6	42	23.45	23.95	26.75	24	26.75	25.65
0.3	32.8	29.55	29.8	33	30.45	32.85	17.35	17.6	19.85	18.6	18.5	19.5
0.212	23.7	21.55	22.4	21.25	23.65	24.1	12.25	12	13.9	13.45	14.35	14.45
0.15	14.8	13.9	13.3	12.95	11.95	13.75	7.25	7.75	8.85	9.05	8.85	8.7
0.075	6.95	5.55	3.7	2.5	2.05	1.85	4.05	2.25	1.85	3.9	2.75	2.25
	4% Cement						6% Cement					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	66.6	67.5	67.75	69.9	69	70.2	70.6	68	73.2	75.4	75.6	74.65
2	58.2	59.3	60.4	63.4	61.9	62.35	64.35	62.75	67.05	68.7	69.25	68.7
0.6	39.3	43.8	44.95	48.1	46.75	40.6	47.65	44.95	52.65	53.5	53.95	51
0.425	18.9	23	25.65	27.95	27.75	22.3	23.9	24.65	29.35	31.85	31.7	29.15
0.3	12.2	16.85	16.75	19.9	21	16.9	15.45	16.3	20.45	23.05	23.9	20.95
0.212	8.2	11.8	12.3	13.65	15.3	12.3	12.35	12.9	13.3	15.4	19.05	14.6
0.15	4.9	7.5	9.1	9.4	10.5	7.2	6.05	6.3	8.15	10.95	11.8	9.9
0.075	1.25	2.7	1.8	2.25	2.45	1.6	1.4	0.45	1.75	0.85	1.95	1.65

BS SIEVE SIZE	8% Cement					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100
2.36	73.85	70.95	72.15	73.25	73.85	74.9
2	67.5	63.9	65.1	67.9	67.65	68.3
0.6	53.6	42.7	44.85	46.7	45.4	46.25
0.425	33.55	30	26.7	30.8	26.85	31.5
0.3	23.3	15.7	17.8	16	16.95	17.6
0.212	16.15	7.35	10.05	6.4	10.15	9.95
0.15	6.4	4	3.75	3.15	4.95	3.9
0.075	1.6	1.3	1.8	1.3	1.65	1.45

Table A9: Dry Sieve Test Results for Soil-Cement– Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

	0% Cement						2% Cement					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	86.65	81.85	84.75	84.35	77.8	82.1	71.15	71.25	74.85	67.9	71.2	71.3
2	81.35	76.5	79.15	78.8	72.35	77.65	63.5	64.6	68.8	59.85	64.7	64.45
0.6	68.7	63.75	66.55	65	60.5	64.45	47.55	49.35	52.25	44.65	49.95	50.1
0.42	46.15	42	44.55	43.85	40.45	44.5	25.5	27.4	31.05	25.6	28.75	29.5
0.3	38.5	35.2	37.7	36.2	34.35	37.6	19.4	21.05	24.65	20.2	22	23.85
0.21	30.25	27.2	30.3	28.55	27.55	31	14.3	15.45	18.7	15.05	17.85	18.9
0.15	21.8	19.55	21.55	20.25	20	23.85	9.3	11.2	13.65	10.65	12.35	13.15
0.07	11.1	7.8	10	9.8	10.1	11.95	3.7	5.7	6.65	5.5	6.25	6.7
	4% Cement						6% Cement					
BS SIEVE SIZE	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100	100	100	100	100	100	100
2.36	65.65	69	68.15	70.05	69.55	74.3	73.35	72.4	72.1	72.55	73.2	71.25
2	57.25	61.1	61.3	64.3	62.65	66.45	67.1	67.25	66.6	66.7	67.3	65.7
0.6	42.5	45.65	46.55	49.95	48.6	49.5	51.65	51.85	47.7	53.2	53.5	48.6
0.425	22.1	24.85	28	31.05	29.65	31.25	29.9	31.55	27.75	31.95	32.55	30.4
0.3	16.85	18.7	21.2	24.8	24.75	25.85	21.45	23.2	20.5	23.55	25.15	22.95
0.212	12.85	13.65	16.75	18.55	20.25	20.25	18.35	19.8	16.95	19.5	21.2	18.05
0.15	9.55	9.35	13.55	14.3	15.45	15.15	12.05	13.2	11.8	15.05	14.35	13.35
0.075	5.9	4.55	6.25	7.15	7.4	7.85	7.4	7.35	8.4	4.95	4.5	5.1

BS SIEVE SIZE	8% Cement					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	100	100	100	100	100	100
2.36	74.7	71.8	72.7	73.65	74.95	75.55
2	68.05	64.75	65.85	68.3	68.75	68.95
0.6	53.6	43.05	45.6	47.1	46.5	46.9
0.425	33.4	28.65	27.45	31.2	27.45	31.5
0.3	21.65	14.35	18.55	16.4	17.55	17.15
0.212	14.5	6	10.8	6.8	10.75	9.5
0.15	4.75	2.65	4.5	3.55	5.55	3.45
0.075	0.65	0.35	2.1	1.45	1.2	0.35

Table A10: Liquid Limit Test Results for Soil–Cement – Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	44.7	43.4	42.7	41.3	40.5
2	43.3	42	41.3	40.2	38.3
4	43.1	40.8	40.7	38.9	36.2
6	41	39.4	38.5	34.7	33
8	38.8	38.2	36.5	32.8	32.3
10	37.4	36.1	35.4	32.2	31.8

Table A11: Plastic Limit (%) Test Results for Soil–Cement – Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	22.5	22.8	23.3	24.3	24.2
2	22.9	23.3	23.5	24.6	24.3
4	23.4	23.6	23.8	24.8	25.2
6	23.6	23.8	24.4	25.1	25.4
8	23.5	23.7	24.2	25.3	25.5
10	23.4	23.6	23.9	25	25.6

Table A12: Plasticity Index (%) Test Results for Soil–Cement – Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	22.2	20.6	19.4	17	16.3
2	20.4	18.7	17.8	15.6	14
4	19.7	17.2	16.9	14.1	11
6	17.4	15.6	14.1	9.6	7.6
8	15.3	14.5	12.3	7.5	6.8
10	14	12.5	11.5	7.2	6.2

Table A13: Linear Shrinkage (%) Test Results for Soil–Cement – Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	7.81	5.47	3.9	3.52	2.73
2	7.03	5.47	3.9	3.28	2.58
4	7.03	5.47	3.9	3.13	2.42
6	6.25	5.47	3.9	3.13	2.34
8	5.47	4.6	3.9	3.13	2.34
10	4.69	4.3	3.52	3.13	1.95

Table A14: Maximum Dry Density (kN/m^3) Test Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	1.61	1.63	1.66	1.67	1.69
2	1.63	1.65	1.67	1.68	1.69
4	1.64	1.67	1.69	1.7	1.7
6	1.66	1.68	1.7	1.71	1.72
8	1.67	1.68	1.7	1.73	1.74
10	1.68	1.69	1.72	1.75	1.77

Table A15: Maximum Dry Density (kN/m^3) Test Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	1.67	1.69	1.7	1.73	1.75
2	1.68	1.7	1.72	1.74	1.76
4	1.7	1.72	1.74	1.76	1.76
6	1.72	1.73	1.76	1.77	1.78
8	1.74	1.75	1.76	1.79	1.8
10	1.75	1.76	1.77	1.79	1.81

Table A16: Maximum Dry Density (kN/m^3) Test Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	1.77	1.8	1.81	1.84	1.85
2	1.79	1.82	1.83	1.85	1.86
4	1.8	1.82	1.84	1.86	1.87
6	1.83	1.85	1.86	1.88	1.88
8	1.84	1.85	1.87	1.88	1.9
10	1.87	1.88	1.89	1.9	1.91

Table A17: Optimum Moisture Content (%) Tests Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	22.5	22.3	22.1	22	21.8
2	22.3	22.2	21.8	21.5	21.5
4	22.1	22	21.5	21.3	21.2
6	22	21.5	21.3	21.2	21.2
8	21.5	21.3	21.2	21.1	21.1
10	21.3	21.2	21.1	21	21

Table A18: Optimum Moisture Content (%) Tests Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (WAS Compaction).

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	21	20.6	20.1	19.4	19
2	20.5	19.5	19.2	19	18.5
4	20	19	18.5	18.3	18
6	19.6	18.5	18	17.8	17.6
8	19	18	17.6	17.3	17.1
10	18.4	18	17.4	17.2	17

Table A19: Optimum Moisture Content (%) Test Results for Soil–Cement– Iron Ore Tailings (IOT) Mixtures (BSH Compaction).

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	15.3	14.8	14.6	13.7	13.5
2	14.9	13.5	13.4	13	12.7
4	14	13.1	12.5	12.5	12.4
6	13.6	12.5	12.3	12.2	12.2
8	13.4	12.4	12.2	12	12
10	12.5	12.3	12.1	12	12

Table A20: Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	263.98	507.4	1396.28	1780.35	2005.46
2	299.19	731.06	1716.42	2892.72	3185.94
4	307.28	843.27	1890.13	3309.47	3470.72
6	310.38	996.14	2590.38	3783.64	3578.84
8	305.6	660.78	2073.39	3280.38	3398.81
10	300.16	523.86	2082.94	3164.38	3322.49

Table A21: Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	565.37	814.5	1747.16	2158.2	2281.8
2	615.37	1023.3	2398.1	3247.04	3447.34
4	634.97	1244.43	2809.46	3502.56	3688.68
6	752	1390.15	3304.94	3860.97	3678.42
8	768.92	1395.99	3102.05	3673.96	3671.41
10	706.32	1270.58	3111.89	3501.14	3654.74

Table A22: Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	875.46	1083.2	2049.18	2261.19	2391.11
2	988.46	1315.99	2635.26	3617.64	3732.67
4	991.76	1344.72	2702.49	3643.73	3903.74
6	1007.57	1408.22	3504.6	3993.14	3803.23
8	979.25	1374.58	3262.16	3728.03	3736.81
10	975.21	1350.6	3232.14	3759.47	3773.63

Table A23: Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	278.41	717.81	1778.03	2075.96	2204.31
2	316.05	872.92	1876.34	3086.33	3385.13
4	396.84	929.64	1994.87	3544.67	3670.96
6	427.01	1123.96	2678.7	3897.71	3764.26
8	327.02	958.26	2567.91	3638.9	3564.49
10	319.71	715.77	2269.28	3584	3571.89

Table A24: Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	597.93	1030.79	2155.98	2355.72	2487.16
2	725.79	1249.75	2402.01	3548.24	3658.93
4	783.16	1462.2	3022.13	3771	3896.85
6	795.93	1577.77	3623.85	3922.86	3908.83
8	819.71	1630.09	3314.05	3892.38	3877.5
10	809.31	1614.58	3332.87	3774.9	3884.65

Table A25: Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	906.53	1285.96	2232.53	2451.86	2504.63
2	1062.71	1524.11	2853.77	3834.8	3936.51
4	1145.09	1534.58	2908.46	3841.57	4022.6
6	1188.13	1633.28	3658.05	4041.17	4039.7
8	1189.44	1683.11	3481.42	3925.41	3967.94
10	1154.34	1662.24	3433.61	3988.23	4073.9

Table A26: Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	312.37	813.42	1887.43	2276.93	2526.32
2	406.72	959.3	2207.2	3168.65	3508.58
4	437.99	977.84	2222.94	3644.67	3793.61
6	456.2	1157.39	2733.79	4105.28	3868.15
8	449.52	1006.49	2654.98	3941.26	3666.75
10	443.28	988.1	2350.61	3612.06	3678.99

Table A27: Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	605.45	1131.11	2254.82	2479.05	2901.66
2	909.71	1328.45	2708.11	3595.84	3773
4	948.77	1585.82	3121.35	3874.09	3999.33
6	979.07	1611.05	3916.14	4286.5	4104.66
8	986.08	1778.93	3402.61	3991.03	4134.55
10	939.53	1708.21	3417.57	3892.23	4170.73

Table A28: Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	934.7	1467.61	2303.07	2607.37	2975.57
2	1238.4	1726.62	2961.31	3934.69	4028.68
4	1316.32	1816.16	3207.68	3938.63	4224.14
6	1319.58	1873.5	3982.72	4392.21	4220.43
8	1258.77	1813.11	3579.36	4032.66	4254.36
10	1268.75	1892.37	3544.2	4083.65	4212.99

Table A29: Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	130.21	474.26	1268.44	1619.5	1947.68
2	152.86	629.29	1664.84	2808.15	2707.88
4	168.34	673.76	1670.33	3119.1	3153.51
6	189.37	685.8	1758.3	3402.04	3261.24
8	160.2	535.3	2016.27	3162.33	2984.47
10	166.3	443.24	1972.38	3046.77	2783.83

Table A30: Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	244.91	628.91	1444.92	1977.26	1935.58
2	313.62	911.12	1960.61	3138.3	3147.54
4	368.13	857.08	2590.85	3487.29	3557.5
6	427.26	827.4	2981.37	3569.55	3634.34
8	423.68	942.49	2750.81	3346.5	3583.35
10	406.11	782.69	2698.11	3094.44	3629.47

Table A31: Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	335.35	820.32	1695.92	1887.53	1952.53
2	444.66	1140.79	2226.14	2795.1	2792.31
4	510.88	1061.59	2558.36	3147.76	3620.58
6	578.11	1114.2	2815.11	3737.14	3681.58
8	606.41	1107.58	3132.88	3297.18	3450.6
10	576.98	1187.58	3161.15	3509.06	3664.2

Table A32: Deviator Stress (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

7 DAYS						
AXIAL STRAIN E = ΔL/L0	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS
	Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0	0
0.197368421	50.27	73.77	90.69	306.06	328.01	336.01
0.394736842	71.25	97.96	134.04	252.29	352.15	543.15
0.592105263	86.21	124.43	173.32	302.48	408.08	552.15
0.789473684	103.78	146.66	213.89	439.95	578.69	708.08
0.986842105	123.94	169.97	217.45	617.09	889.21	978.69
1.184210526	139.89	190.84	230.37	769.96	1142.93	1178.21
1.381578947	161.65	208.68	248.37	948.65	1231.29	1337.93
1.578947368	177.46	234.66	354.31	1062.08	1606.88	1531.29
1.776315789	195.55	254.68	440.83	1195.53	2036.98	1796.88
1.973684211	207.43	283.38	542.17	1307.98	2189.78	2126.98
2.171052632	221.59	326.55	696.32	1437.45	2699.85	2389.78
2.368421053	235.11	378.26	795.15	1833.3	3101.77	2699.85
2.763157895	243.43	428.9	899.38	2157.39	3376.12	3101.77
3.157894737	253.7	437.26		2505.55	3411.48	3376.12
3.552631579	257.64	482.9		2979.73	3452.8	3416.48
3.947368421	265.13	536.75		3423.75	3566.48	3552.8
4.342105263		581.58		3569.33	3645.45	3559.48
4.736842105				3690.88	3675.17	3645.45
5.131578947				3706.69	3698.84	3725.17
5.526315789				3777.69	3710.43	3727.91
5.921052632					3730.43	3850.61
6.315789474					3740.43	3894.95
6.710526316					3745.43	3953.61
7.105263158					3810.43	

Table A33: Deviator Stress (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

14 DAYS						
AXIAL STRAIN E = ΔL/L0	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS
	Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0	0
0.197368421	67.22	93.69	120.46	234.62	314.62	334.62
0.394736842	94.99	138.04	164.75	325.43	418.43	525.43
0.592105263	123.54	173.32	195.54	479.93	467.93	679.93
0.789473684	146.66	212.89	248.37	613.65	846.65	913.65
0.986842105	169.97	243.45	314.27	828.72	1128.72	1128.72
1.184210526	190.84	300.39	388.74	963.41	1258.99	1146.04
1.381578947	211.62	348.29	449.69	1086.38	1415.19	1399.88
1.578947368	231.73	387.19	514.79	1188.36	1570.76	1534.57
1.776315789	254.68	425.93	588.4	1369.6	1773.99	1759.88
1.973684211	265.13	495.19	648.57	1472.79	1989.53	1873.03
2.171052632	278.41	498.57	692.69	2039.77	2212.95	2089.73
2.368421053		567.4	810.59	2114.77	2422.73	2762.74
2.763157895		599.88	910.33	2599.39	2682.04	2991.72
3.157894737				3147.4	2978.55	3271.15
3.552631579				3319.96	3186.31	3571.31
3.947368421				3473.85	3336.44	3685.15
4.342105263				3652.01	3515.16	3796.74
4.736842105				3739.14	3583.31	3748.09
5.131578947				3757.58	3643.66	3872.76
5.526315789				3817.97	3745.09	4015.55
5.921052632				3837.65	3928.57	4044.56
6.315789474				3859.73		
6.710526316				3882.95		
7.105263158						

Table A34: Deviator Stress (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

28 DAYS						
AXIAL STRAIN E = ΔL/L0	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS	DEVIATOR STRESS
	Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0	0
0.197368421	84.77	118.98	258.78	334.62	458.06	468.47
0.394736842	129.13	189.99	351.77	525.43	822.29	846.04
0.592105263	173.32	269.6	466.62	679.93	1152.48	1199.88
0.789473684	208.45	351.86	598.75	913.65	1439.95	1534.57
0.986842105	239.02	430.83	725.92	1128.72	1555.12	1659.88
1.184210526	265.05	538.94	826.08	1258.99	1728.73	1873.03
1.381578947	272.79	573.13	906.38	1415.19	1895.74	2089.73
1.578947368	298.59	607.18		1570.76	2100.21	2362.74
1.776315789	315.52			1773.99	2341.9	2691.72
1.973684211				1989.53	2559.22	2971.15
2.171052632				2212.95	2784.4	3271.31
2.368421053				2522.73	3014.47	3605.15
2.763157895				2782.04	3303.67	3834
3.157894737				3034.83	3512.5	3965.63
3.552631579				3246.67	3670.65	4130.56
3.947368421				3538.26	3873.19	4186.65
4.342105263				3767.48	3971.31	4225.04
4.736842105				3994.68	4011.7	4318.33
5.131578947				4054.45	4037.49	
5.526315789				4105.16	4147.39	
5.921052632					4214.18	

Table A35: Elastic Modulus (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

7 Days Modulus of Elasticity = Stress/Strain					
Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0
254.69039	373.74684	459.51877	1044.0473	1155.2411	1702.44
180.48761	248.17046	339.56141	639.1278	892.11229	1375.98
145.60506	210.15163	292.7112	510.84884	689.19619	932.5193
131.45852	185.76474	270.92517	557.27346	733.01338	896.89714
125.59029	172.23811	220.34854	625.32088	901.0687	991.74403
118.12792	161.15135	194.53439	650.18461	965.13914	994.93503
117.00557	151.04356	179.77233	686.63948	891.21903	968.40498
112.39248	148.61815	224.39863	672.64868	1017.6931	969.81665
110.08649	143.37612	248.17046	673.03805	1146.7447	1011.5791
105.09568	143.58143	274.6982	662.70785	1109.4874	1077.6702
102.0639	150.40995	320.73018	662.09679	1243.568	1100.7461
99.266859	159.71153	335.73198	774.06019	1309.6346	1139.9373
88.09798	155.22025	325.48824	780.76915	1221.8351	1122.5439
80.337251	138.46523		793.42301	1080.303	1069.1057
72.520889	135.92865		838.73766	971.89837	961.67671
67.167255	135.97667		867.34985	903.50801	900.04187
	133.94058		822.02745	839.5589	819.7588
			779.18564	775.86898	769.59566
			722.3287	720.79925	725.93034
			683.5811	671.41025	674.57463
				630.02735	650.32456
				592.23397	616.70076
				558.14178	589.16532
				536.28205	
av. =119.37	av. =173.38	av. =283.58	av. =722.27	av.=898.17	av. =959.22

Table A36: Elastic Modulus (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

14 Days Modulus of Elasticity = Stress/Strain					
Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0
340.59188	474.71877	610.3527	1188.7575	1594.0908	1695.4242
240.65014	349.69474	417.37759	824.42944	1060.0294	1331.0961
208.65055	292.7112	330.23828	810.55078	790.28411	1148.3286
185.76474	269.6585	314.60158	777.28439	1072.4177	1157.2844
172.23811	246.69521	318.46108	839.76868	1143.7687	1143.7687
161.15135	253.66417	328.27127	813.5483	1063.1513	967.76344
153.17093	252.09383	325.48823	786.32944	1024.3306	1013.2457
146.76043	245.21995	326.03107	752.62579	994.81276	971.89417
143.37612	239.7842	331.24827	771.03163	998.68882	990.74783
134.33005	250.89744	328.60904	746.21673	1008.0304	949.00241
128.23641	229.64377	319.05579	939.53234	1019.296	962.54006
	239.5673	342.24893	892.90404	1022.9308	1166.4882
	217.09859	329.45204	940.73106	970.64358	1082.7168
			996.67545	943.20868	1035.8654
			934.50949	896.88638	1005.2577
			880.041	845.23097	933.57091
			841.06802	809.55259	874.40094
			789.37499	756.47733	791.26343
			732.24625	710.04753	754.69135
			690.87005	677.68217	726.62264
			655.78744	663.49263	683.08187
av.=183.17	av.=273.96	av.=355.5	av.=838.3	av.=955.48	av.=972.05

Table A37: Elastic Modulus (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

28 Days Modulus of Elasticity = Stress/Strain					
Natural soil BSL	Natural soil WAS	Natural soil BSH	Optimum blend BSL	Optimum blend WAS	Optimum blend BSH
0	0	0	0	0	0
429.50746	602.81748	1311.128	1695.4242	2320.8473	2373.5938
327.13379	481.30029	891.15756	1331.0961	2083.1278	2143.2903
292.7112	455.32853	788.06862	1148.3286	1946.4044	2026.4622
264.04061	445.68557	758.41453	1157.2844	1823.9401	1943.7883
242.20984	436.57576	735.60025	1143.7687	1575.8591	1682.0128
223.82132	455.10336	697.57645	1063.1513	1459.8124	1581.6707
197.44983	414.83794	656.04299	1024.3306	1372.1563	1512.563
189.10816	384.54949		994.81276	1330.1325	1496.399
177.62651			998.68882	1318.4011	1515.3372
			1008.0304	1296.6735	1505.3847
			1019.296	1282.5134	1506.7854
			1065.1531	1272.778	1522.1737
			1006.8341	1195.6154	1387.5432
			961.03094	1112.2916	1255.7837
			913.87746	1033.2196	1162.6754
			896.3582	981.20764	1060.618
			867.65917	914.60402	973.03888
			843.31861	846.91485	911.64719
			790.09867	786.79282	
			742.83815	750.48052	
				711.72796	
av.=260.40	av.=459.52	av.=833.99	av.=1033.57	av.=1305.50	av.=1531.15

Table A38: California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	14.68	25.74	50.26	74.67	79.21
2	17.22	29.34	53.27	78.31	81.39
4	19.58	31.36	58.19	79.58	88.82
6	20.48	35.25	71.33	97.34	92.45
8	17.04	33.53	59.09	88.3	93.35
10	21.4	30.45	63.97	84.7	89.55

Table A39: California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	18.52	30.54	54.02	77.95	78.64
2	20.66	32.22	60	80.48	84.05
4	24.11	33.35	67.45	82.85	85.8
6	25.35	37.34	75.15	98.07	91.6
8	23.69	35.23	72.99	83.56	95.71
10	22.84	32.99	71.06	79	90.4

Table A40: California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	19.72	35.71	55.91	81.52	84.05
2	22.84	37.39	68.16	89.34	94.87
4	24.89	38.6	74.68	94.8	101.87
6	25.74	44.73	78.31	102.78	104.05
8	24.47	42.2	78.16	89.91	107.85
10	23.2	38.72	76.47	84.47	95.89

Table A41: California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	6.89	15.27	39.08	65.29	71.6
2	7.79	18.16	41.6	67.79	75.59
4	9.97	21.03	48.58	69.61	80.66
6	11.78	22.85	57.46	83.02	86.65
8	10.33	21.93	50.21	69.06	88.46
10	13.41	23.75	51.94	66.97	83.2

Table A42: California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	8.3	18.52	46.77	72.51	74.19
2	9.06	20.32	54.92	75.59	79
4	10.88	23.2	59.04	77.68	91.9
6	12.87	25.01	67.82	82.84	95.17
8	14.19	21.16	66.16	79.03	93.17
10	15.59	18.16	63.08	72.87	90.9

Table A43: California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	10.46	19.76	48.58	76.35	79
2	11.78	21.04	61.81	82.36	90.54
4	13.47	23.2	65.62	84.47	94.8
6	16.86	26.21	68.34	92.63	96.98
8	15.59	24.53	66.97	85.02	102.05
10	14.32	22.85	63.97	79.4	96.97

Table A44: Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	46.77	66.07	71.34	77.87	88.36
2	48.36	72.09	88.73	90.99	79.99
4	42.42	72.48	83.73	87.99	85.9
6	44.35	61.02	84.64	87.28	86.64
8	48.98	55.86	78.52	86.9	83.73
10	52.01	61.92	83.26	85.01	77.94

Table A45: Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	40.96	61.01	67.02	83.93	77.82
2	43.21	72.9	81.62	88.45	86.02
4	47	58.62	85.73	92.48	91.29
6	53.68	52.44	82.27	90.99	84.88
8	51.69	57.82	83	85.98	92.41
10	50.18	48.48	80.95	81.97	93.43

Table A46: Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	36.99	63.79	75.96	76.98	77.96
2	41.84	74.84	78.01	72.89	81.4
4	44.61	69.18	87.96	81.94	90
6	48.66	68.22	88.14	92.48	91.14
8	50.98	65.81	89.99	84	86.96
10	49.98	71.44	92.06	87.99	89.94

Table A47: pH Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	7.1	11.24	11.4	11.53	11.7
2	7.2	11.25	11.5	11.53	11.7
4	7.4	11.25	11.46	11.56	11.7
6	7.4	11.23	11.28	11.55	11.7
8	7.5	11.3	11.46	11.6	11.65
10	7.6	11.3	11.42	11.7	11.6

Table A48: Desorption isotherms for Iron (Fe^{2+}) Test Results for Soil – Cement – Iron Ore Tailings (IOT) Mixtures

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	1.161	2.3097	1.484	0	0
2	1.161	2.2129	0	0	0
4	2.774	2.2774	0	0	0
6	1.484	2.0516	0	0	0
8	2.129	2.1161	0	0	0
10	2.452	2.1806	0	0	0

Table A49: Analysis of Variance for Specific Gravity of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	13.14	2.628	0.0077	0% CEMENT	6	15.73	2.62167	0.00610
2% IOT	5	13.28	2.656	0.0064	2% CEMENT	6	15.97	2.66167	0.00462
4% IOT	5	13.46	2.692	0.0030	4% CEMENT	6	16.29	2.715	0.00131
6% IOT	5	13.61	2.722	0.0020	6% CEMENT	6	16.45	2.74167	0.00118
8% IOT	5	13.68	2.736	0.0021	8% CEMENT	6	16.54	2.75667	0.00151
10% IOT	5	13.81	2.762	0.0012					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.064027	5	0.012805333	26.93969144	3.06788E-08	2.71089
CEMENT	0.076653	4	0.019163333	40.31556802	2.64675E-09	2.866081
Error	0.009507	20	0.000475333			
Total	0.150187	29				

Table A50: Analysis of Variance for cation Exchange capacity of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	104.1	20.82	146.372	0% CEMENT	6	175.9	29.3167	49.04567
2% IOT	5	85.3	17.06	104.893	2% CEMENT	6	92.3	15.3833	43.32567
4% IOT	5	67.7	13.54	18.388	4% CEMENT	6	73.6	12.2667	14.69067
6% IOT	5	84.3	16.86	79.903	6% CEMENT	6	68.9	11.4833	0.149667
8% IOT	5	70	14	25.825	8% CEMENT	6	75.8	12.6333	0.498667
10% IOT	5	75.1	15.02	49.202					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	179.1297	5	35.82593333	1.993530353	0.123532503	2.71089
CEMENT	1338.91	4	334.7275	18.6258771	1.60108E-06	2.866081
Error	359.422	20	17.9711			
Total	1877.462	29				

Table A51: Analysis of Variance for Liquid Limit of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	212.6	42.52	2.782	0% CEMENT	6	248.3	41.383	8.0617
2% IOT	5	205.1	41.02	3.577	2% CEMENT	6	239.9	39.983	7.0017
4% IOT	5	199.7	39.94	6.593	4% CEMENT	6	235.1	39.183	8.2257
6% IOT	5	186.6	37.32	11.197	6% CEMENT	6	220.1	36.683	15.5417
8% IOT	5	178.6	35.72	9.117	8% CEMENT	6	212.1	35.35	12.675
10% IOT	5	172.9	34.58	6.082					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	245.349	5	49.0699	80.5834	1.48576E-12	2.71089
CEMENT	145.213	4	36.3033	59.6179	7.86839E-11	2.866081
Error	12.178	20	0.60893			
Total	402.741	29				

Table A52: Analysis of Variance for Plastic Limit of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	117.1	23.42	0.657	0% CEMENT	6	139.3	23.21667	0.181667
2% IOT	5	118.6	23.72	0.502	2% CEMENT	6	140.8	23.46667	0.134667
4% IOT	5	120.8	24.16	0.628	4% CEMENT	6	143.1	23.85	0.171
6% IOT	5	122.3	24.46	0.618	6% CEMENT	6	149.1	24.85	0.131
8% IOT	5	122.2	24.44	0.838	8% CEMENT	6	150.2	25.03333	0.386667
10% IOT	5	121.5	24.3	0.91					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4.4697	5	0.8939	32.1945	6.58E-09	2.71089
CEMENT	16.057	4	4.01417	144.5678	1.86E-14	2.866081
Error	0.555	20	0.02777			
Total	21.082	29				

Table A53: Analysis of Variance for Plasticity Index of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	95.5	19.1	6.05	0% CEMENT	6	109	18.1667	9.9547
2% IOT	5	86.5	17.3	6.4	2% CEMENT	6	99.1	16.5167	8.5897
4% IOT	5	78.9	15.78	11.077	4% CEMENT	6	92	15.3333	10.0987
6% IOT	5	64.3	12.86	16.988	6% CEMENT	6	71	11.8333	18.2507
8% IOT	5	56.4	11.28	15.482	8% CEMENT	6	61.9	10.3167	17.3057
10% IOT	5	51.4	10.28	11.597					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	307.39	5	61.478	90.3692	5.006E-13	2.71089
CEMENT	256.77	4	64.193	94.3591	1.093E-12	2.866081
Error	13.61	20	0.6803			
Total	577.77	29				

Table A54: Analysis of Variance for Linear shrinkage of Soil-Cement –Iron Ore Tailings (IOT) Mixtures

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	23.43	4.686	4.044	0% CEMENT	6	38.28	6.38	1.318
2% IOT	5	22.26	4.452	3.2163	2% CEMENT	6	30.78	5.13	0.286
4% IOT	5	21.95	4.39	3.4612	4% CEMENT	6	23.02	3.837	0.0241
6% IOT	5	21.09	4.218	2.6271	6% CEMENT	6	19.32	3.22	0.0252
8% IOT	5	19.44	3.888	1.4952	8% CEMENT	6	14.36	2.393	0.0702
10% IOT	5	17.59	3.518	1.1486					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4.491	5	0.8982	4.3501	0.00767	2.71089
CEMENT	59.84	4	14.9602	72.453	1.301E-11	2.866081
Error	4.129	20	0.20648			
Total	68.461	29				

Table A55: Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8.26	1.652	0.00102	0% CEMENT	6	9.89	1.6483	0.0007
2% IOT	5	8.32	1.664	0.00058	2% CEMENT	6	10	1.667	0.00051
4% IOT	5	8.4	1.68	0.00065	4% CEMENT	6	10.14	1.69	0.0005
6% IOT	5	8.47	1.694	0.00058	6% CEMENT	6	10.24	1.707	0.0001
8% IOT	5	8.52	1.704	0.00093	8% CEMENT	6	10.31	1.718	0.0010
10% IOT	5	8.61	1.722	0.00147					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.0168	5	0.00336	54.4864	5.768E-11	2.71089
CEMENT	0.0196	4	0.0049	79.8108	5.280E-12	2.86608
Error	0.0012	20	6.17E-05			
Total	0.0377	29				

Table A56: Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8.54	1.708	0.0012	0% CEMENT	6	10.26	1.71	0.0010
2% IOT	5	8.6	1.72	0.001	2% CEMENT	6	10.35	1.725	0.0008
4% IOT	5	8.68	1.736	0.0007	4% CEMENT	6	10.45	1.742	0.00074
6% IOT	5	8.76	1.752	0.0007	6% CEMENT	6	10.58	1.763	0.00063
8% IOT	5	8.84	1.768	0.0007	8% CEMENT	6	10.66	1.777	0.00059
10% IOT	5	8.88	1.776	0.0006					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.0179	5	0.0036	100.859	1.755E-13	2.71089
CEMENT	0.0177	4	0.0044	124.533	7.7944E-14	2.86608
Error	0.0007	20	3.57E-05			
Total	0.0365	29				

Table A57: Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	9.07	1.814	0.00103	0% CEMENT	6	10.9	1.817	0.001347
2% IOT	5	9.15	1.83	0.00075	2% CEMENT	6	11.02	1.837	0.0008
4% IOT	5	9.19	1.838	0.00082	4% CEMENT	6	11.1	1.85	0.0008
6% IOT	5	9.3	1.86	0.00045	6% CEMENT	6	11.21	1.868	0.0005
8% IOT	5	9.34	1.868	0.00057	8% CEMENT	6	11.27	1.878	0.0005
10% IOT	5	9.45	1.89	0.00025					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.019	5	0.0039	84.613	9.35726E-13	2.71089
CEMENT	0.0146	4	0.00364	79.745	5.3215E-12	2.866081
Error	0.0009	20	4.57E-05			
Total	0.0348	29				

Table A58: Analysis of Variance for Optimum Moisture Content Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	110.7	22.14	0.073	0% CEMENT	6	131.7	21.95	0.215
2% IOT	5	109.3	21.86	0.143	2% CEMENT	6	130.5	21.75	0.227
4% IOT	5	108.1	21.62	0.167	4% CEMENT	6	129	21.5	0.148
6% IOT	5	107.2	21.44	0.113	6% CEMENT	6	128.1	21.35	0.131
8% IOT	5	106.2	21.24	0.028	8% CEMENT	6	127.8	21.3	0.088
10% IOT	5	105.6	21.12	0.017					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3.699	5	0.7398	42.7630	5.268E-10	2.71089
CEMENT	1.818	4	0.4545	26.2716	1.027E-07	2.866081
Error	0.346	20	0.0173			
Total	5.863	29				

Table A59: Analysis of Variance for Optimum Moisture Content Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	100.1	20.02	0.682	0% CEMENT	6	118.5	19.75	0.919
2% IOT	5	96.7	19.34	0.553	2% CEMENT	6	113.6	18.933	1.0067
4% IOT	5	93.8	18.76	0.613	4% CEMENT	6	110.8	18.4667	1.06267
6% IOT	5	91.5	18.3	0.64	6% CEMENT	6	109	18.1667	0.810667
8% IOT	5	89	17.8	0.565	8% CEMENT	6	107.2	17.8667	0.622667
10% IOT	5	88	17.6	0.34					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	21.558	5	4.3115	156.5932	2.519E-15	2.71089
CEMENT	13.021	4	3.2553	118.2324	1.281E-13	2.866081
Error	0.5507	20	0.0275			
Total	35.130	29				

Table A60: Analysis of Variance for Optimum Moisture Content Test Results for Soil–Cement –Iron Ore Tailings (IOT) Mixtures (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	71.9	14.38	0.577	0% CEMENT	6	83.7	13.95	1.051
2% IOT	5	67.5	13.5	0.715	2% CEMENT	6	78.6	13.1	0.908
4% IOT	5	64.5	12.9	0.455	4% CEMENT	6	77.1	12.85	0.955
6% IOT	5	62.8	12.56	0.353	6% CEMENT	6	75.4	12.567	0.4507
8% IOT	5	62	12.4	0.34	8% CEMENT	6	74.8	12.467	0.3267
10% IOT	5	60.9	12.18	0.047					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	16.947	5	3.3893	44.8918	3.394E-10	2.71089
CEMENT	8.438	4	2.1095	27.9404	6.156E-08	2.866081
Error	1.51	20	0.0755			
Total	26.895	29				

Table A61: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	5953.47	1190.69	594870.18	0% CEMENT	6	1786.6	297.765	292.0007
2% IOT	5	8825.32	1765.06	1627702.45	2% CEMENT	6	4262.5	710.418	35638.815
4% IOT	5	9820.87	1964.17	2021674.28	4% CEMENT	6	11750	1958.257	161466.489
6% IOT	5	11259.4	2251.88	2392001.92	6% CEMENT	6	18211	3035.157	461427.714
8% IOT	5	9718.97	1943.79	2062535.36	8% CEMENT	6	18962	3160.376	337808.777
10% IOT	5	9393.83	1878.77	2026652.89					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3121015	5	624203.05	6.7041	0.00081	2.71089
CEMENT	41039595	4	10259898.65	110.194	2.508E-13	2.866081
Error	1862154	20	93107.69			
Total	46022764	29				

Table A62: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	7567.03	1513.41	612020.29	0% CEMENT	6	4043	673.825	6580.391
2% IOT	5	10731.2	2146.23	1643157.30	2% CEMENT	6	7138.9	1189.823	52147.583
4% IOT	5	11880.1	2376.02	1872951.37	4% CEMENT	6	16474	2745.602	339159.38
6% IOT	5	12986.5	2597.10	2032193.10	6% CEMENT	6	19944	3323.979	367815.83
8% IOT	5	12612.3	2522.47	1831449.59	8% CEMENT	6	20422	3403.729	310388.46
10% IOT	5	12244.7	2448.93	1856453.95					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4009168	5	801833.58	11.6946	2.21E-05	2.71089
CEMENT	38021612	4	9505403.02	138.634	2.78E-14	2.866081
Error	1371290	20	68564.52			
Total	43402070	29				

Table A63: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8660.13	1732.03	492415.13	0% CEMENT	6	5817.7	969.6185	2254.959
2% IOT	5	12290	2458.00	1616174.08	2% CEMENT	6	7877.3	1312.884	13619.40
4% IOT	5	12586.4	2517.29	1731891.15	4% CEMENT	6	17386	2897.636	287996.07
6% IOT	5	13716.8	2743.35	2015079.14	6% CEMENT	6	21003	3500.531	386333.02
8% IOT	5	13080.8	2616.17	1782603.64	8% CEMENT	6	21341	3556.865	330056.53
10% IOT	5	13091	2618.21	1830171.24					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3310007	5	662001.32	7.39132	0.00045	2.71089
CEMENT	36082044	4	9020511.06	100.7150	5.90E-13	2.866081
Error	1791293	20	89564.66			
Total	41183344	29				

Table A64: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	7054.52	1410.905	742375.07	0% CEMENT	6	2065	344.173	3128.80
2% IOT	5	9536.77	1907.354	1794268.2	2% CEMENT	6	5318.4	886.394	24236.95
4% IOT	5	10537	2107.396	2209061.89	4% CEMENT	6	13165	2194.186	138799.62
6% IOT	5	11891.6	2378.325	2425160.38	6% CEMENT	6	19828	3304.595	431284.54
8% IOT	5	11056.6	2211.315	2279237.23	8% CEMENT	6	20161	3360.175	336617.00
10% IOT	5	10460.7	2092.133	2370653.74					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	2807499	5	561499.7822	6.0284	0.001473	2.71089
CEMENT	45420190	4	11355047.6	121.911	9.56E-14	2.866081
Error	1862836	20	93141.78197			
Total	50090525	29				

Table A65: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8627.6	1725.51	729161.94	0% CEMENT	6	4531.8	755.305	7025.772
2% IOT	5	11585	2316.94	1748734.03	2% CEMENT	6	8565.2	1427.528	57761.013
4% IOT	5	12935	2587.07	1956483.40	4% CEMENT	6	17851	2975.149	333074.331
6% IOT	5	13829	2765.85	2168342.44	6% CEMENT	6	21265	3544.183	356356.688
8% IOT	5	13534	2706.75	1966324.34	8% CEMENT	6	21714	3618.987	316250.843
10% IOT	5	13416	2683.26	1927695.30					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3901236.939	5	780247.39	10.7538	3.98E-05	2.71089
CEMENT	40535859.51	4	10133964.88	139.6723	2.595E-14	2.866081
Error	1451106.305	20	72555.32			
Total	45888202.75	29				

Table A66: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	9381.5	1876.3018	535480.2045	0% CEMENT	6	6646.2	1107.70	11843.08
2% IOT	5	13212	2642.38	1721804.21	2% CEMENT	6	9323.3	1553.88	21557.57
4% IOT	5	13452	2690.4589	1717854.098	4% CEMENT	6	18568	3094.64	283569.58
6% IOT	5	14560	2912.06552	1927544.625	6% CEMENT	6	22083	3680.51	368813.64
8% IOT	5	14247	2849.4644	1731018.022	8% CEMENT	6	22545	3757.54	379207.20
10% IOT	5	14312	2862.4616	1854840.281					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3765814.951	5	753162.9901	9.661259181	8.26186E-05	2.71089
CEMENT	36395025.33	4	9098756.333	116.7150329	1.44918E-13	2.866081
Error	1559140.431	20	77957.02154			
Total	41719980.71	29				

Table A67: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	9381.5	1876.3018	535480.2045	0% CEMENT	6	6646.2	1107.707	11843.08
2% IOT	5	13212	2642.38	1721804.21	2% CEMENT	6	9323.3	1553.877	21557.57
4% IOT	5	13452	2690.4589	1717854.098	4% CEMENT	6	18568	3094.639	283569.58
6% IOT	5	14560	2912.06552	1927544.625	6% CEMENT	6	22083	3680.508	368813.64
8% IOT	5	14247	2849.4644	1731018.022	8% CEMENT	6	22545	3757.544	379207.20
10% IOT	5	14312	2862.4616	1854840.281					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3765814.951	5	753162.9901	9.661	8.261E-05	2.71089
CEMENT	36395025.33	4	9098756.333	116.715	1.45E-13	2.866081
Error	1559140.431	20	77957.02154			
Total	41719980.71	29				

Table A68: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	9372.1	1874.4152	932073.6735	0% CEMENT	6	5368.6	894.767	20858.546
2% IOT	5	12315	2463.0224	1689864.256	2% CEMENT	6	9143.6	1523.928	60585.833
4% IOT	5	13529	2705.8728	1888074.3	4% CEMENT	6	18821	3136.768	343754.47
6% IOT	5	14897	2979.486	2431476.68	6% CEMENT	6	22119	3686.4567	399281.08
8% IOT	5	14293	2858.6388	1969608.448	8% CEMENT	6	23084	3847.321	235245.90
10% IOT	5	14128	2825.6528	2025829.19					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4081783.736	5	816356.7473	13.41759202	8.14867E-06	2.71089
CEMENT	42530860.8	4	10632715.2	174.7586887	2.97215E-15	2.866081
Error	1216845.386	20	60842.26932			
Total	47829489.92	29				

Table A69: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	10288	2057.662	703541.2984	0% CEMENT	6	7336.5	1222.751	20952.50985
2% IOT	5	13890	2777.9391	1602881.049	2% CEMENT	6	10589	1764.893	24568.49517
4% IOT	5	14503	2900.5859	1652383.01	4% CEMENT	6	19578	3263.056	342535.3526
6% IOT	5	15788	3157.68632	2090482.197	6% CEMENT	6	22989	3831.534	387813.3317
8% IOT	5	14938	2987.649	1853822.177	8% CEMENT	6	23916	3986.029	251602.4124
10% IOT	5	15002	3000.393	1791471.118					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3819302.824	5	763860.5647	11.59070006	2.35441E-05	2.71089
CEMENT	37460265.71	4	9365066.428	142.104045	2.19389E-14	2.866081
Error	1318057.685	20	65902.88425			
Total	42597626.22	29				

Table A70: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	5440.1	1088.0182	587036.6493	0% CEMENT	6	967.28	161.212	380.280
2% IOT	5	7963	1592.6018	1431861.744	2% CEMENT	6	3441.7	573.609	10810.7
4% IOT	5	8785	1757.0088	1877578.874	4% CEMENT	6	10351	1725.093	72439.67
6% IOT	5	9296.8	1859.35214	2130362.42	6% CEMENT	6	17158	2859.646	405751.03
8% IOT	5	8858.6	1771.71324	1897512.687	8% CEMENT	6	16839	2806.436	221336.8
10% IOT	5	8412.5	1682.503	1748208.812					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	1932887.383	5	386577.4766	4.770485731	0.004954752	2.71089
CEMENT	37069539.86	4	9267384.965	114.3623993	1.76017E-13	2.866081
Error	1620704.886	20	81035.24429			
Total	40623132.13	29				

Table A71: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	6231.6	1246.3164	608202.2283	0% CEMENT	6	2183.7	363.952	5214.740
2% IOT	5	9471.2	1894.2396	1646932.08	2% CEMENT	6	4949.7	824.947	12499.478
4% IOT	5	10861	2172.16764	2202005.997	4% CEMENT	6	14427	2404.446	338295.562
6% IOT	5	11440	2287.9827	2382872.977	6% CEMENT	6	18613	3102.224	338647.895
8% IOT	5	11047	2209.3668	2066923.166	8% CEMENT	6	19488	3247.962	447113.232
10% IOT	5	10611	2122.1648	2072007.487					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	3748966.877	5	749793.3754	7.651391361	0.00036831	2.71089
CEMENT	41955888.08	4	10488972.02	107.0364617	3.30759E-13	2.866081
Error	1959887.66	20	97994.38299			
Total	47664742.62	29				

Table A72: Analysis of Variance for Unconfined Compressive Strength (kN/m^2) (7 days curing, 7 days soaking) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	6691.7	1338.33052	520255.314	0% CEMENT	6	3052.4	508.73065	10636.13156
2% IOT	5	9399	1879.8007	1099039.287	2% CEMENT	6	6432.1	1072.009	16917.1191
4% IOT	5	10899	2179.83192	1797947.053	4% CEMENT	6	15590	2598.258	320795.0694
6% IOT	5	11926	2385.2259	2143549.56	6% CEMENT	6	18374	3062.294	433790.3635
8% IOT	5	11595	2318.92906	1825066.868	8% CEMENT	6	19162	3193.633	481847.0526
10% IOT	5	12099	2419.7907	2049745.481					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	4327673.652	5	865534.7305	8.688995315	0.000165726	2.71089
CEMENT	35750159.22	4	8937539.806	89.72284851	1.75869E-12	2.866081
Error	1992255.029	20	99612.75143			
Total	42070087.9	29				

Table A73: Analysis of Variance for California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	244.56	48.912	823.00797	0% CEMENT	6	110.4	18.4	6.35984
2% IOT	5	259.53	51.906	820.17023	2% CEMENT	6	185.67	30.945	11.06011
4% IOT	5	277.53	55.506	892.57268	4% CEMENT	6	356.11	59.352	57.17449667
6% IOT	5	316.85	63.37	1173.31385	6% CEMENT	6	473.29	78.882	50.16897667
8% IOT	5	278.42	55.684	950.90048	8% CEMENT	6	529.66	88.277	47.88598667
10% IOT	5	278.24	55.648	830.76582					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	588.30915	5	117.66183	8.559156813	0.000182538	2.71089
CEMENT	21687.98622	4	5421.996555	394.4160885	1.0277E-18	2.866081
Error	274.9379	20	13.746895			
Total	22551.23327	29				

Table A74: Analysis of Variance for California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	259.67	51.934	742.14818	0% CEMENT	6	135.17	22.528	6.293496667
2% IOT	5	277.41	55.482	803.78382	2% CEMENT	6	201.67	33.612	5.669256667
4% IOT	5	304.2	60.84	975.0713	4% CEMENT	6	400.67	66.778	67.23485667
6% IOT	5	323.28	64.656	1008.41768	6% CEMENT	6	491.21	81.868	11.92037667
8% IOT	5	311.18	62.236	976.49708	8% CEMENT	6	546.99	91.165	62.43155
10% IOT	5	299.97	59.994	938.79388					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	544.6149367	5	108.9229873	9.763066064	7.7015E-05	2.71089
CEMENT	21555.71501	4	5388.928753	483.0244627	1.38871E-19	2.866081
Error	223.1327467	20	11.15663733			
Total	22323.4627	29				

Table A75: Analysis of Variance for California Bearing Ratio (%) (Unsoaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	276.91	55.382	791.02347	0% CEMENT	6	140.86	23.477	4.5403
2% IOT	5	312.6	62.52	1000.91595	2% CEMENT	6	237.35	39.558	10.971
4% IOT	5	328.14	65.628	1072.62737	4% CEMENT	6	431.69	71.948	75.7085
6% IOT	5	348.72	69.744	1123.98588	6% CEMENT	6	529.23	88.205	24.381
8% IOT	5	342.59	68.518	1182.61387	8% CEMENT	6	595.47	99.245	73.31
10% IOT	5	325.64	65.128	1093.94167					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	661.8394267	5	132.3678853	9.364012237	0.000101707	2.71089
CEMENT	24777.71667	4	6194.429167	438.2083341	3.63527E-19	2.866081
Error	282.7161733	20	14.13580867			
Total	25722.27227	29				

Table A76: Analysis of Variance for California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	198.13	39.626	836.53403	0% CEMENT	6	60.17	10.028	5.8915
2% IOT	5	210.93	42.186	883.01723	2% CEMENT	6	122.99	20.498	10.2478
4% IOT	5	229.85	45.97	921.76535	4% CEMENT	6	288.87	48.145	46.1272
6% IOT	5	261.76	52.352	1164.85647	6% CEMENT	6	421.74	70.29	41.2601
8% IOT	5	239.99	47.998	1046.02327	8% CEMENT	6	486.16	81.027	42.0307
10% IOT	5	239.27	47.854	849.71213					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	514.7628167	5	102.9525633	9.665807662	8.23589E-05	2.71089
CEMENT	22594.60969	4	5648.652422	530.3295623	5.51032E-20	2.866081
Error	213.0242333	20	10.65121167			
Total	23322.39674	29				

Table A77: Analysis of Variance for California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	220.29	44.058	913.90817	0% CEMENT	6	70.89	11.815	8.36475
2% IOT	5	238.89	47.778	1013.08852	2% CEMENT	6	126.37	21.062	7.12026
4% IOT	5	262.7	52.54	1204.9676	4% CEMENT	6	357.79	59.631	61.9063
6% IOT	5	283.71	56.742	1303.05277	6% CEMENT	6	460.52	76.753	15.5058
8% IOT	5	273.71	54.742	1242.30107	8% CEMENT	6	524.33	87.388	74.24582
10% IOT	5	260.6	52.12	1135.57375					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	542.59188	5	108.518376	7.404303203	0.000449663	2.71089
CEMENT	26958.44507	4	6739.611267	459.84954	2.25788E-19	2.866081
Error	293.1224533	20	14.65612267			
Total	27794.1594	29				

Table A78: Analysis of Variance for California Bearing Ratio (%) (Soaked) Test Results for Soil–Cement–Iron Ore Tailings v Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	234.15	46.83	991.2409	0% CEMENT	6	82.48	13.747	5.633
2% IOT	5	267.53	53.506	1267.03178	2% CEMENT	6	137.59	22.931	5.404
4% IOT	5	281.56	56.312	1323.16987	4% CEMENT	6	375.29	62.548	52.042
6% IOT	5	301.02	60.204	1376.10213	6% CEMENT	6	500.23	83.372	31.148
8% IOT	5	294.16	58.832	1416.58292	8% CEMENT	6	560.34	93.39	63.577
10% IOT	5	277.51	55.502	1281.13167					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	562.4284567	5	112.4856913	9.92853441	6.87766E-05	2.71089
CEMENT	30394.44635	4	7598.611588	670.6904294	5.37878E-21	2.866081
Error	226.5907267	20	11.32953633			
Total	31183.46554	29				

Table A79: Analysis of Variance for Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	350.41	70.082	238.96657	0% CEMENT	6	282.89	47.148	11.758
2% IOT	5	380.16	76.032	295.48142	2% CEMENT	6	389.44	64.907	43.236
4% IOT	5	372.52	74.504	357.58493	4% CEMENT	6	490.22	81.703	36.412
6% IOT	5	363.93	72.786	372.39288	6% CEMENT	6	516.04	86.007	19.677
8% IOT	5	353.99	70.798	296.32732	8% CEMENT	6	502.56	83.76	16.424
10% IOT	5	360.14	72.028	208.13347					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	126.43499	5	25.286998	0.98951488	0.448768247	2.71089
CEMENT	6564.447467	4	1641.111867	64.21895598	3.97506E-11	2.866081
Error	511.0988933	20	25.55494467			
Total	7201.98135	29				

Table A80: Analysis of Variance for Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	330.74	66.148	278.507	0% CEMENT	6	286.72	47.7867	24.773
2% IOT	5	372.2	74.44	339.903	2% CEMENT	6	351.27	58.545	70.25
4% IOT	5	375.12	75.024	434.587	4% CEMENT	6	480.59	80.098	43.7870
6% IOT	5	364.26	72.852	336.643	6% CEMENT	6	523.8	87.3	16.656
8% IOT	5	370.9	74.18	330.704	8% CEMENT	6	525.85	87.6417	35.2548
10% IOT	5	355.01	71.002	415.7678					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	276.83	5	55.36683	1.636217	0.19628	2.71089
CEMENT	7867.7	4	1966.921	58.12705	9.919E-11	2.866081
Error	676.77	20	33.8383			
Total	8821.3	29				

Table A81: Analysis of Variance for Resistance to Loss in Strength (%) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	331.68	66.336	302.17583	0% CEMENT	6	273.06	45.51	29.339
2% IOT	5	348.98	69.796	254.66883	2% CEMENT	6	413.28	68.88	15.588
4% IOT	5	373.69	74.738	349.55162	4% CEMENT	6	512.12	85.35	44.64
6% IOT	5	388.64	77.728	360.31592	6% CEMENT	6	496.28	82.713	50.97
8% IOT	5	377.74	75.548	277.16417	8% CEMENT	6	517.4	86.233	28.87
10% IOT	5	391.41	78.282	316.95092					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	555.86552	5	111.173104	7.636756358	0.00037265	2.71089
CEMENT	7152.15648	4	1788.03912	122.8248437	8.89642E-14	2.866081
Error	291.15268	20	14.557634			
Total	7999.17468	29				

Table A82: Elastic Modulus (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	119.35	321.61	990.76	1281.33	1447.04
2	182.7	517.24	705.42	921.91	1198.99
4	133.44	457.58	1077	1021.8	1428.03
6	122.98	426.59	667.61	1305.81	1502.04
8	107.02	335.53	367.47	1170.76	1986.37
10	87.97	247.08	952.33	1523.04	1322.65

Table A83: Elastic Modulus (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	182.94	422.23	877.95	1284.95	1845.72
2	200.18	595.59	1498.7	1537	2003.23
4	134.4	548.98	1428.49	1257.76	1608.81
6	120.83	533.37	1610.7	1021.22	1735.45
8	91.44	463.27	1485.97	1570.83	1875.82
10	97.99	492.56	1240.86	1611.1	2805.44

Table A84: Elastic Modulus (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSL Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	260.2	590.15	1688.63	1946.96	1703.15
2	245.2	526.62	1651	2710.56	1954.11
4	202.78	963.154	1613.11	2696.51	1373.08
6	130.15	448.78	1607	1033.57	1735.2
8	127.85	244.82	1881.29	1671.39	2289.61
10	190.97	667.58	2177.54	1870.84	2833.11

Table A85: Elastic Modulus (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	174.41	458.83	941.28	1923.08	1626.85
2	191.71	598.6	1406.81	2020.11	1934.88
4	139.1	532.37	1380.43	1501.65	1320.5
6	356.22	520.6	1790.92	1724.43	1196.56
8	332.4	440.69	1319.1	2113.63	1676.21
10	295.7	477.99	1234.48	2784.46	1815.05

Table A86: Elastic Modulus (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	282.41	577.34	1631.23	2517.11	1783.83
2	247.52	491	1691.55	2776.14	1923.3
4	325.55	1032.16	1600.18	2485.54	1472.52
6	335.27	581.38	1439.33	1017.99	1621.2
8	453.21	345.72	1984.52	1675.89	2284.88
10	401.08	601.67	2323.47	1705.74	2952.04

Table A87: Elastic Modulus (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (WAS Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	473.58	524.12	832.69	1493.56	1210.97
2	602.34	906.49	911.99	1389.06	1004.38
4	527.8	577.58	952.59	1298.91	1189.99
6	635.38	585.12	844.05	1369.29	1473.95
8	592.51	468.58	1448.34	1012.94	1985.19
10	728.48	522.74	1360.32	1474.21	951.4

Table A88: Elastic Modulus (kN/m^2) (7 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	957.99	594.57	1467.66	1851.53	2287.3
2	915.78	485	1544.88	2553.01	2015.77
4	849.03	940.59	1552.61	2558	1459.62
6	731.91	710.19	1262.22	971.49	1471.9
8	654.19	712.48	1821.13	1629.59	1899.29
10	910.91	603.01	1740.6	1740.6	3125.21

Table A89: Elastic Modulus (kN/m^2) (14 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron Ore Tailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	355.58	566.66	1576.69	1810.84	2080.9
2	589.69	477.33	1588.39	2376.97	2058.47
4	563.27	998.72	1594.73	2590.81	1489.03
6	727.16	645.99	1428.19	999.29	1845.19
8	676.03	617.2	1428.19	1742.14	1785.22
10	539.77	743.22	1599.68	2181.26	2433.39

Table A90: Elastic Modulus (kN/m^2) (28 days curing) Test Results for Soil–Cement–Iron Ore Tailings (IOT) Mixtures (BSH Compaction)

Iron OreTailings Content (%)	Cement Content (%)				
	0	2	4	6	8
0	836.92	460.47	766.15	1630.03	1332.64
2	703.81	492.36	848.73	1303.87	1245.58
4	670.84	867.08	992.78	1160.18	1260.33
6	654.46	531.66	932.37	1531.16	1450.53
8	734.73	246.34	1282.52	1212.39	1730.68
10	880.94	634.26	1280.4	1673.31	918.8

APPENDIX B

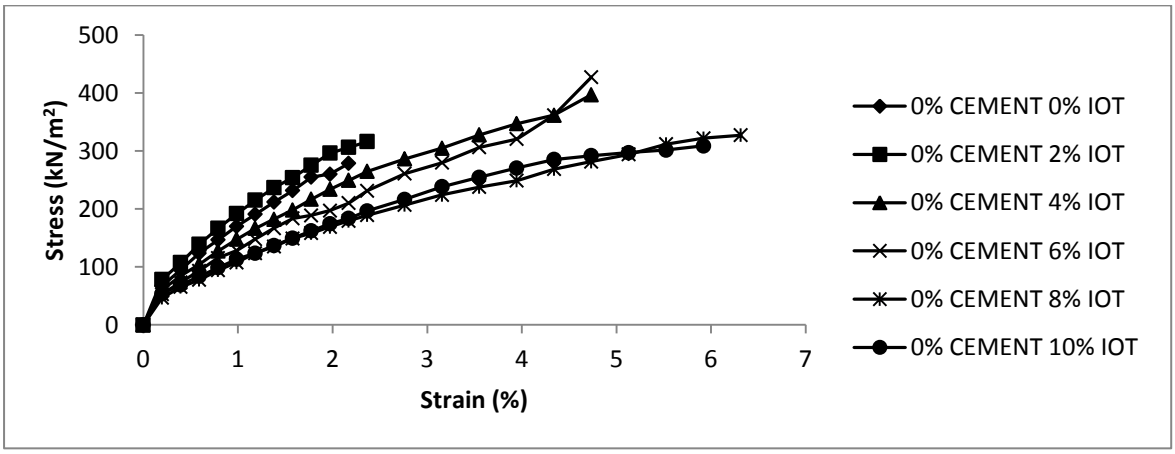


Figure B1: Stress-strain graph for lateritic soil – 0 % cement (14 days curing period) for varying iron ore tailings content (BSL compaction)

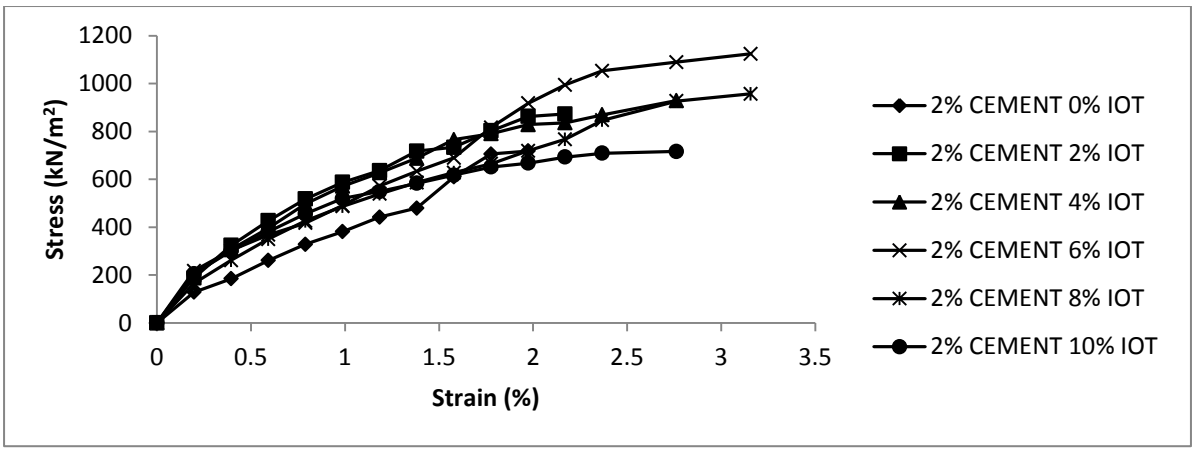


Figure B2: Stress-strain graph for lateritic soil – 2 % cement (14 days curing period) for varying iron ore tailings content (BSL compaction)

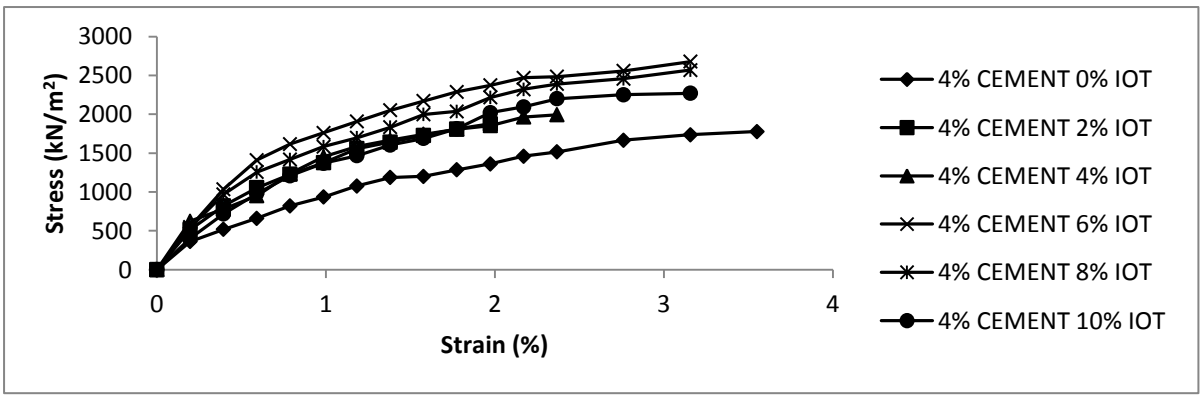


Figure B3 Stress-strain graph for lateritic soil – 4 % cement (14 days curing period) for varying iron ore tailings content (BSL compaction)

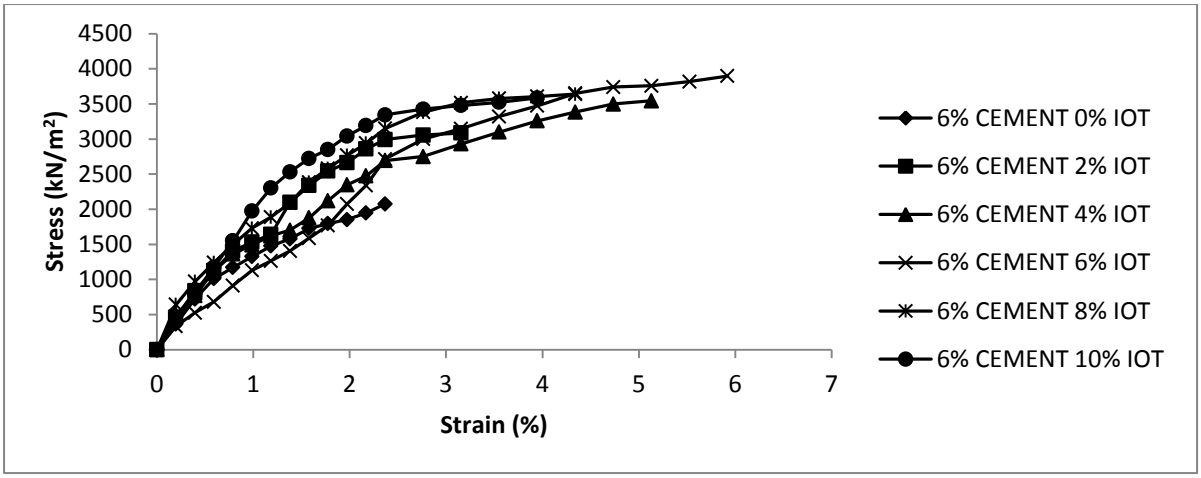


Figure B4: Stress-strain graph for lateritic soil – 6 % cement (14 days curing period) for varying iron ore tailings content (BSL compaction)

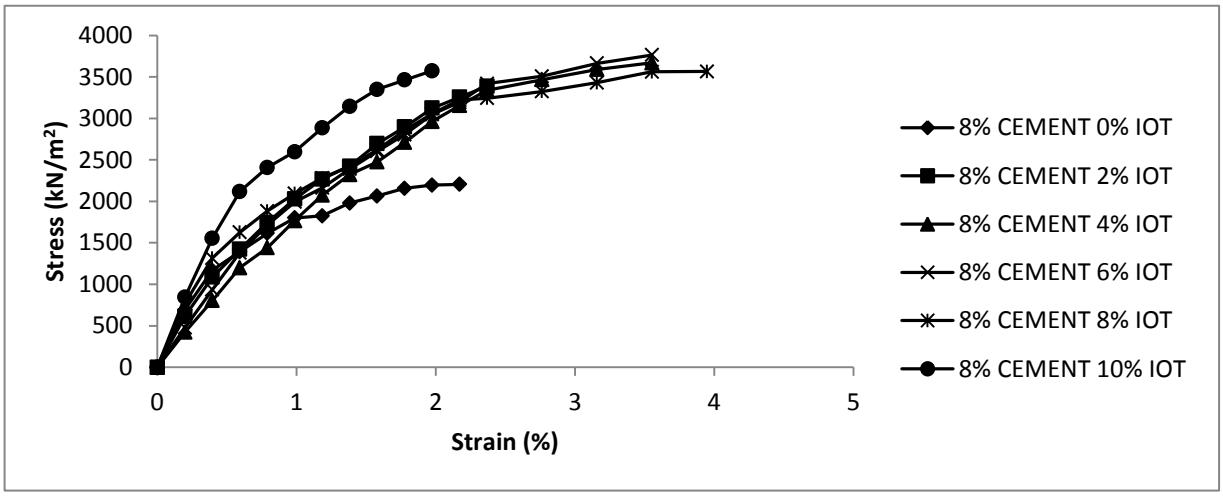


Figure B5: Stress-strain graph for lateritic soil – 8 % cement (14 days curing period) for varying iron ore tailings content (BSL compaction)

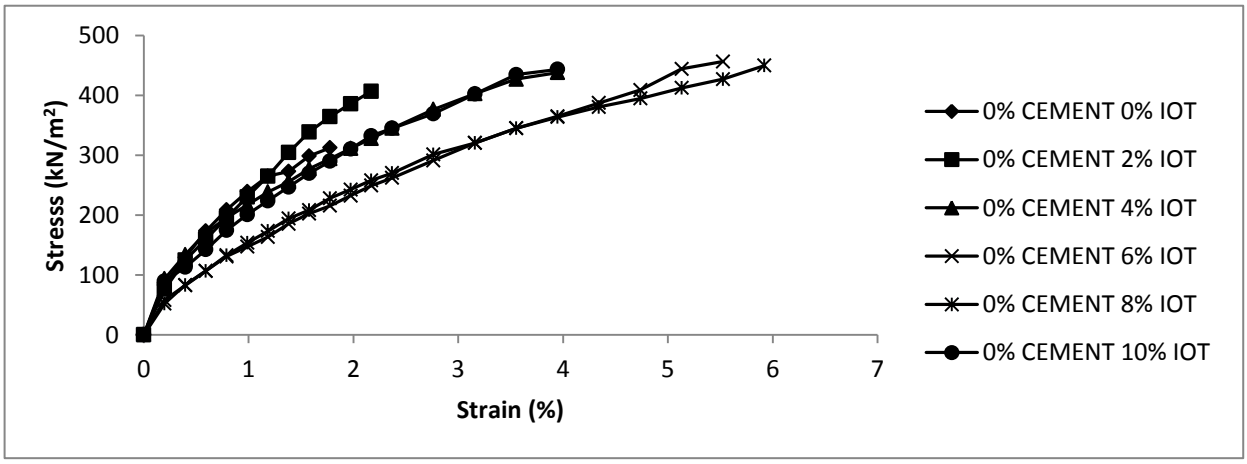


Figure B6: Stress-strain graph for lateritic soil – 0 % cement (28 days curing period) for varying iron ore tailings content (BSL compaction)

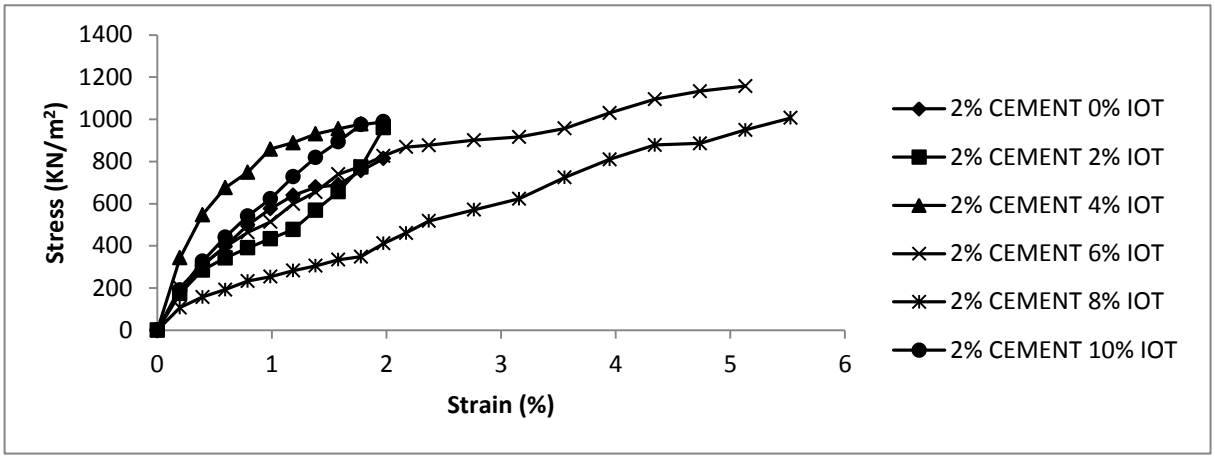


Figure B7: Stress-strain graph for lateritic soil – 2 % cement (28 days curing period) for varying iron ore tailings content (BSL compaction)

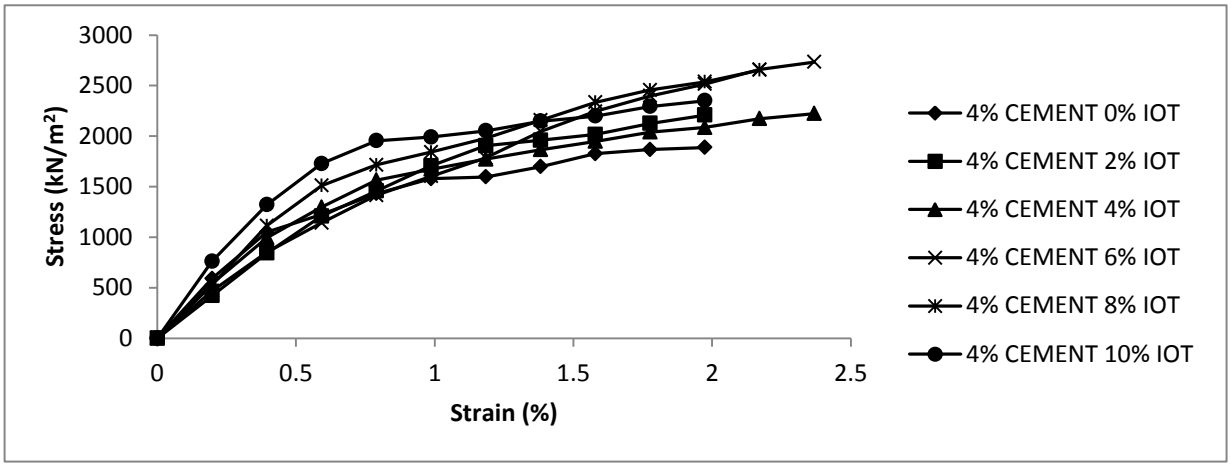


Figure B8: Stress-strain graph for lateritic soil – 4 % cement (28 days curing period) for varying iron ore tailings content (BSL compaction)

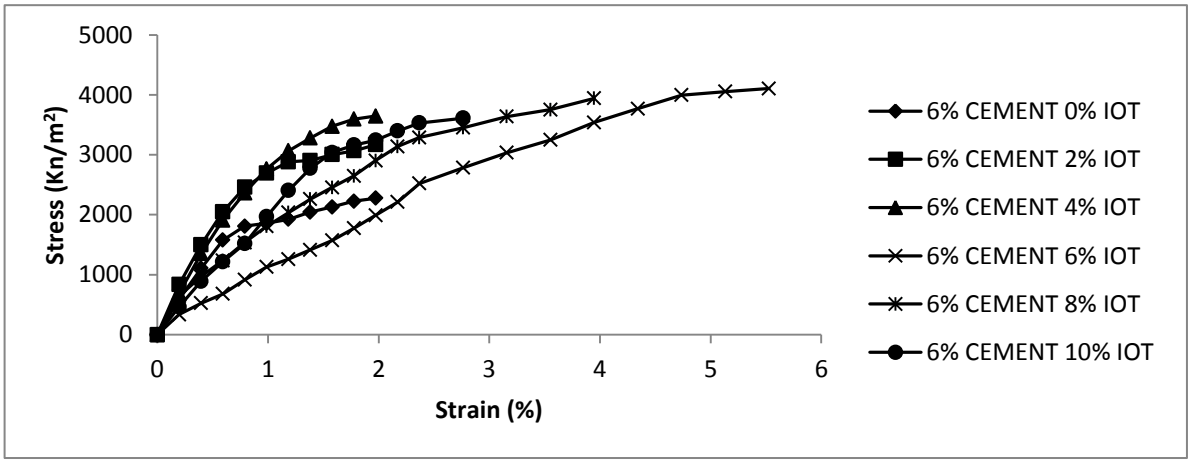


Figure B9: Stress-strain graph for lateritic soil – 6 % cement (28 days curing period) for varying iron ore tailings content (BSL compaction)

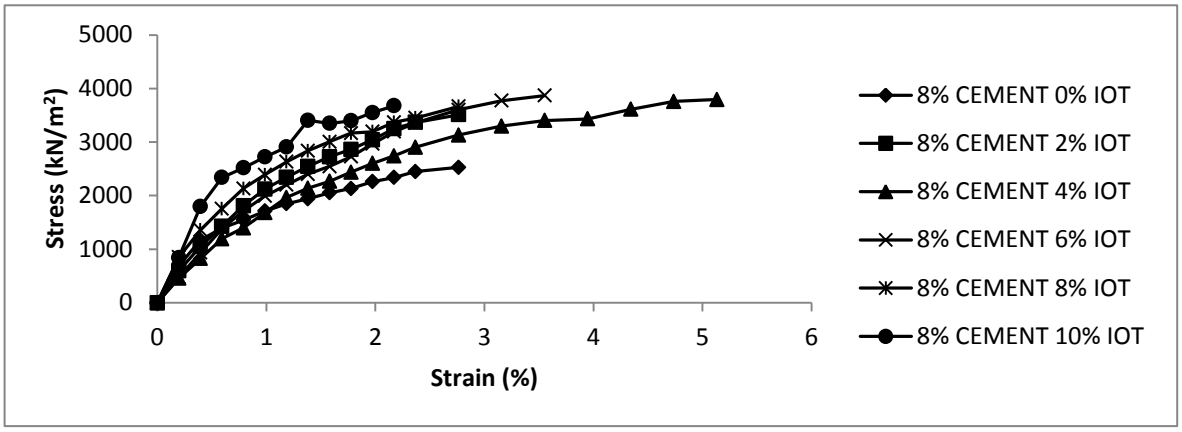


Figure B10: Stress-strain graph for lateritic soil – 8 % cement (28 days curing period) for varying iron ore tailings content (BSL compaction)

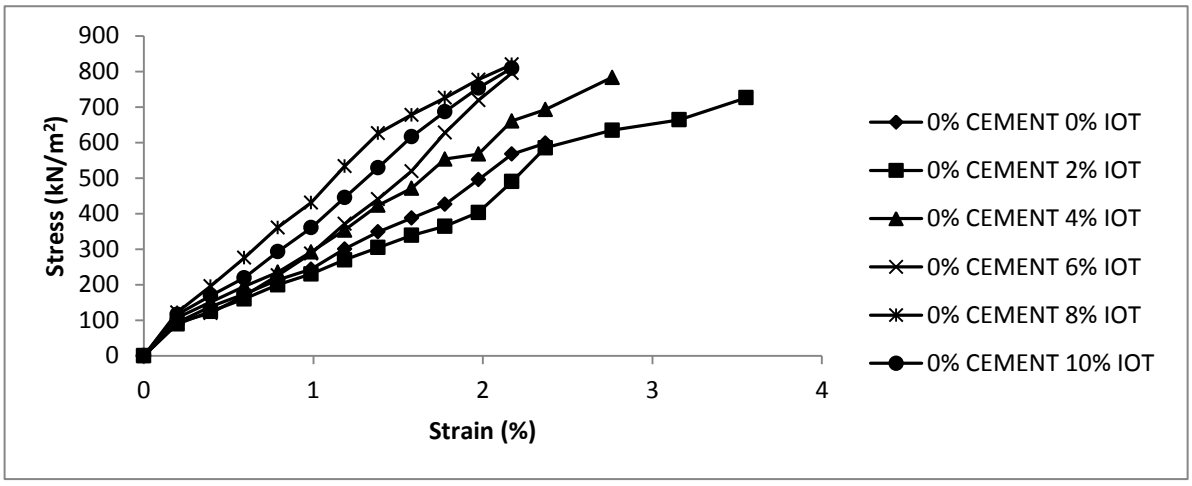


Figure B11: Stress-strain graph for lateritic soil – 0 % cement (14 days curing period) for varying iron ore tailings content (WAS compaction)

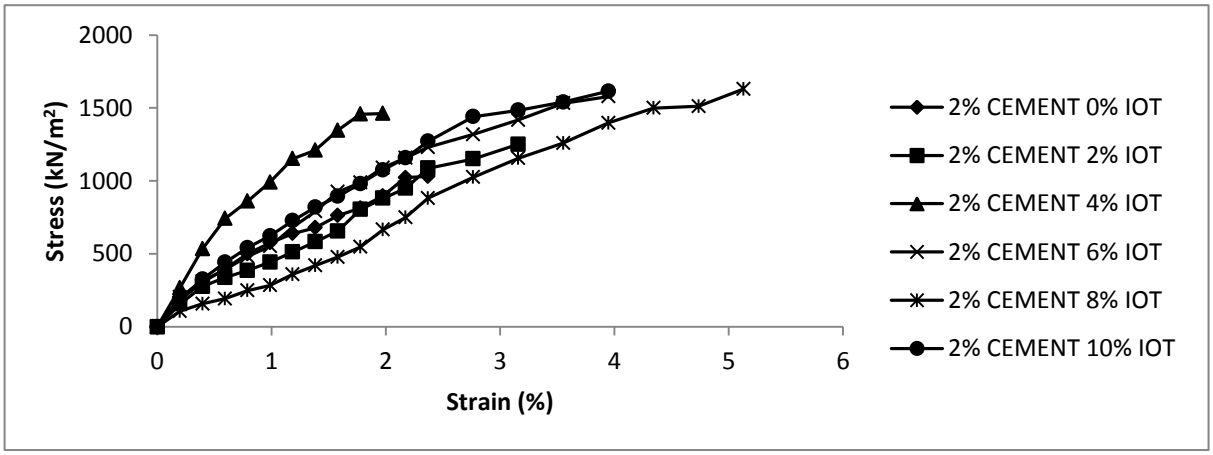


Figure B12: Stress-strain graph for lateritic soil – 2 % cement (14 days curing period) for varying iron ore tailings content (WAS compaction)

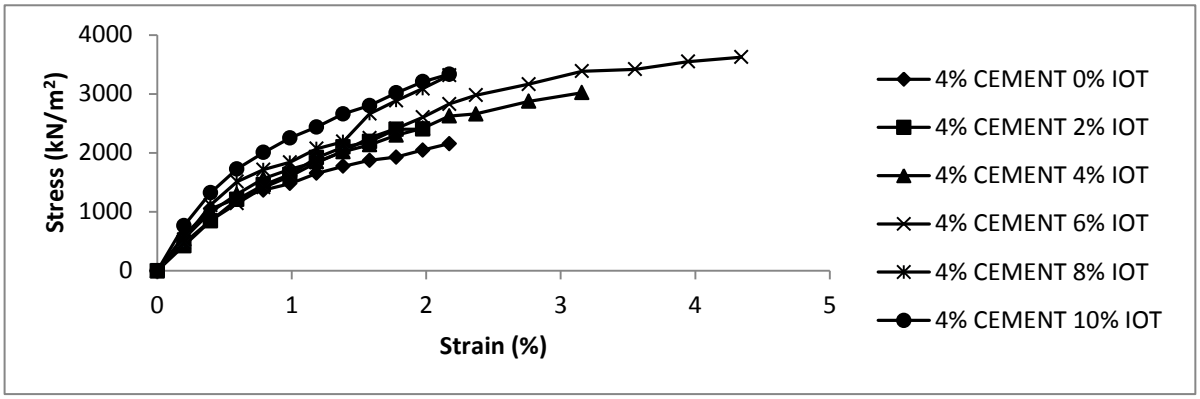


Figure B13: Stress-strain graph for lateritic soil – 4 % cement (14 days curing period) for varying iron ore tailings content (WAS compaction)

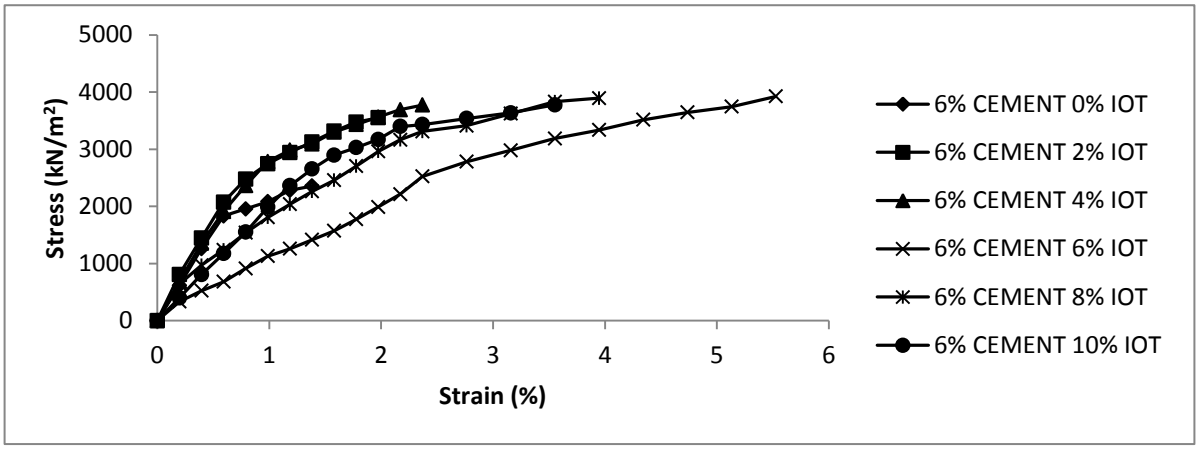


Figure B14: Stress-strain graph for lateritic soil – 6 % cement (14 days curing period) for varying iron ore tailings content (WAS compaction)

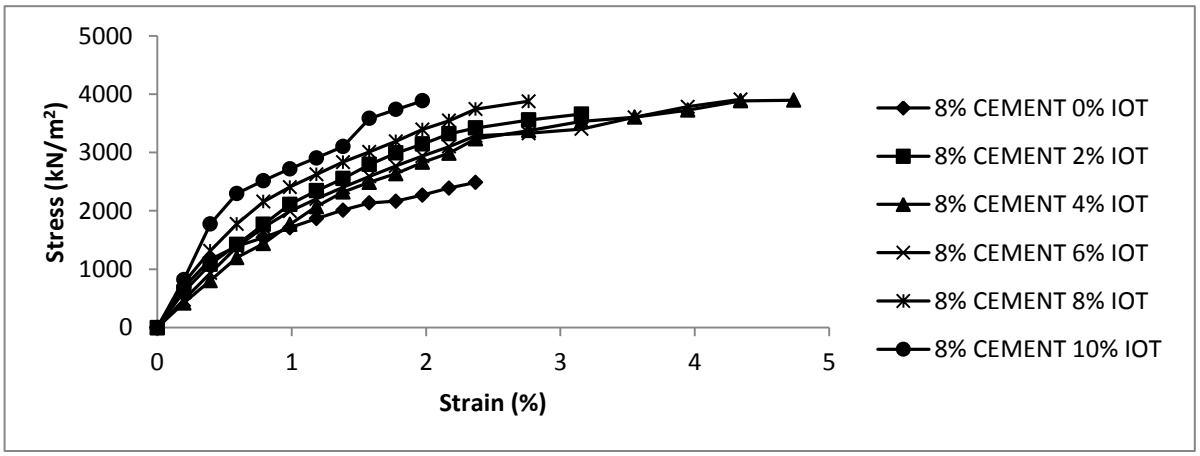


Figure B15: Stress-strain graph for lateritic soil – 8 % cement (14 days curing period) for varying iron ore tailings content (WAS compaction)

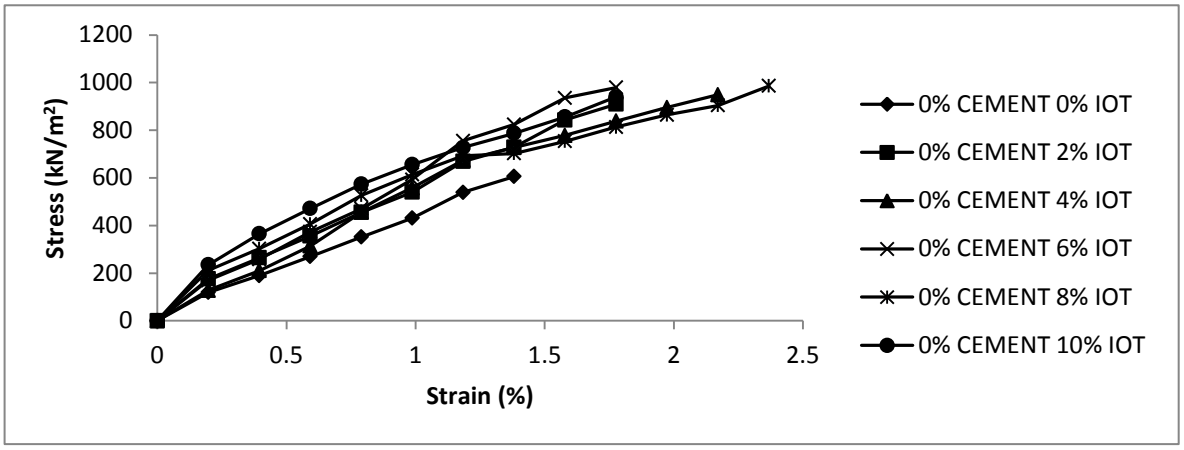


Figure B16: Stress-strain graph for lateritic soil – 0 % cement (28 days curing period) for varying iron ore tailings content (WAS compaction)

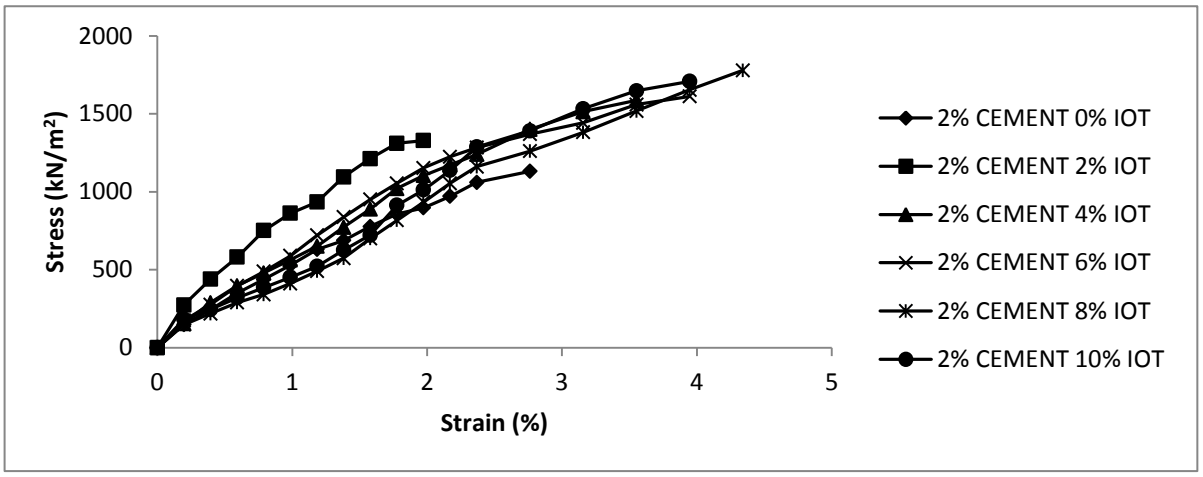


Figure B17: Stress-strain graph for lateritic soil – 2 % cement (28 days curing period) for varying iron ore tailings content (WAS compaction)

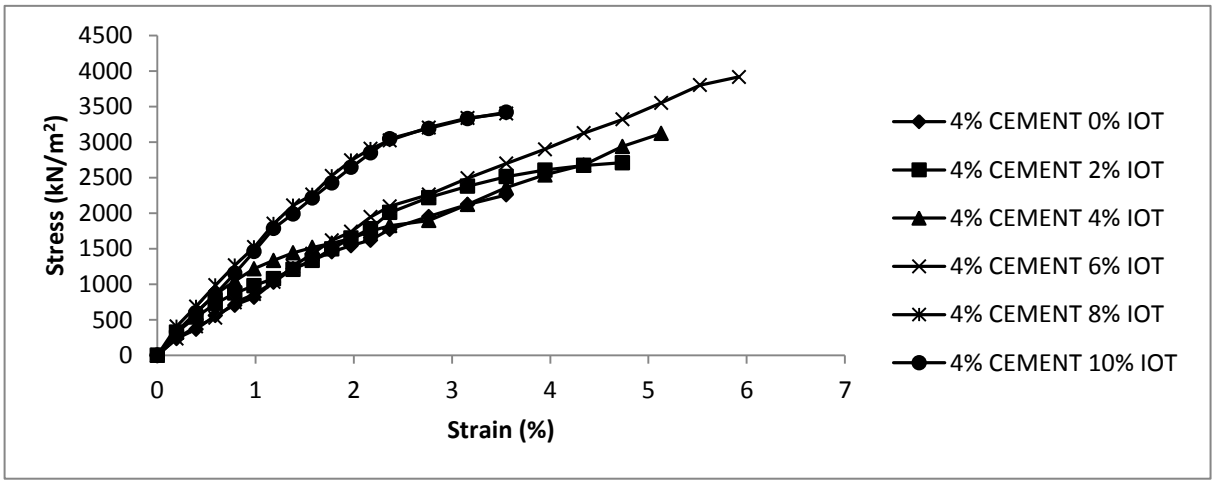


Figure B18: Stress-strain graph for lateritic soil – 4 % cement (28 days curing period) for varying iron ore tailings content (WAS compaction)

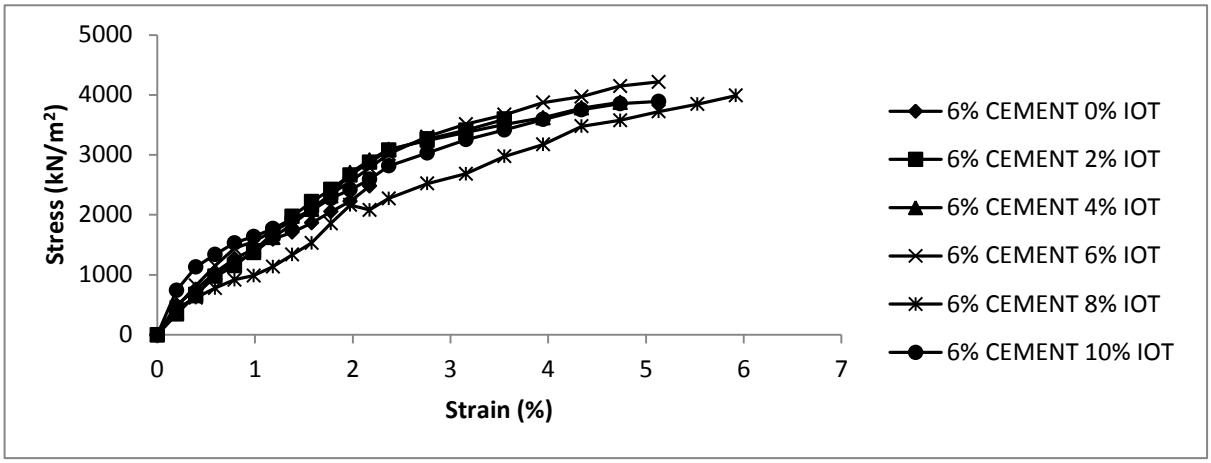


Figure B19: Stress-strain graph for lateritic soil – 6 % cement (28 days curing period) for varying iron ore tailings content (WAS compaction)

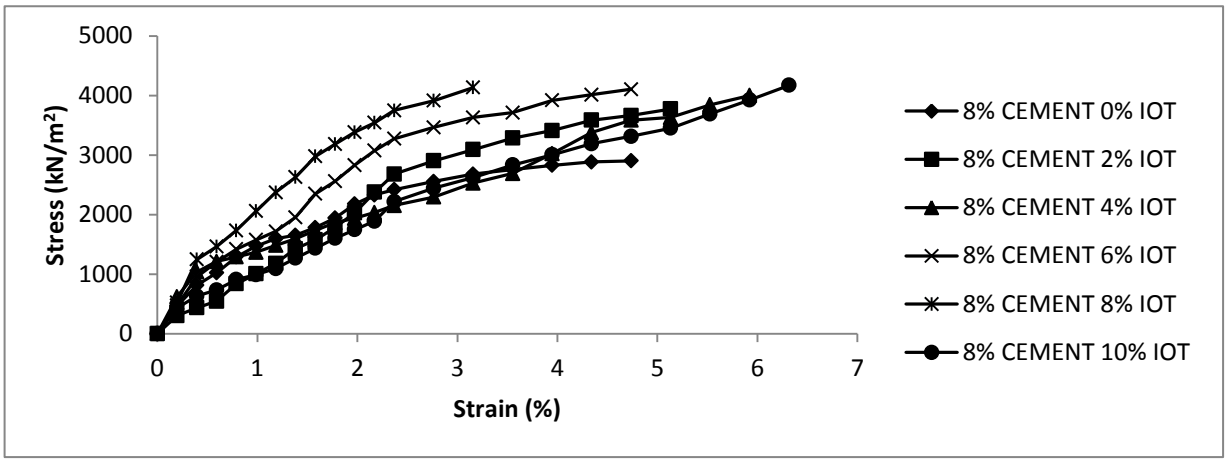


Figure B20: Stress-strain graph for lateritic soil – 8 % cement (28 days curing period) for varying iron ore tailings content (WAS compaction)

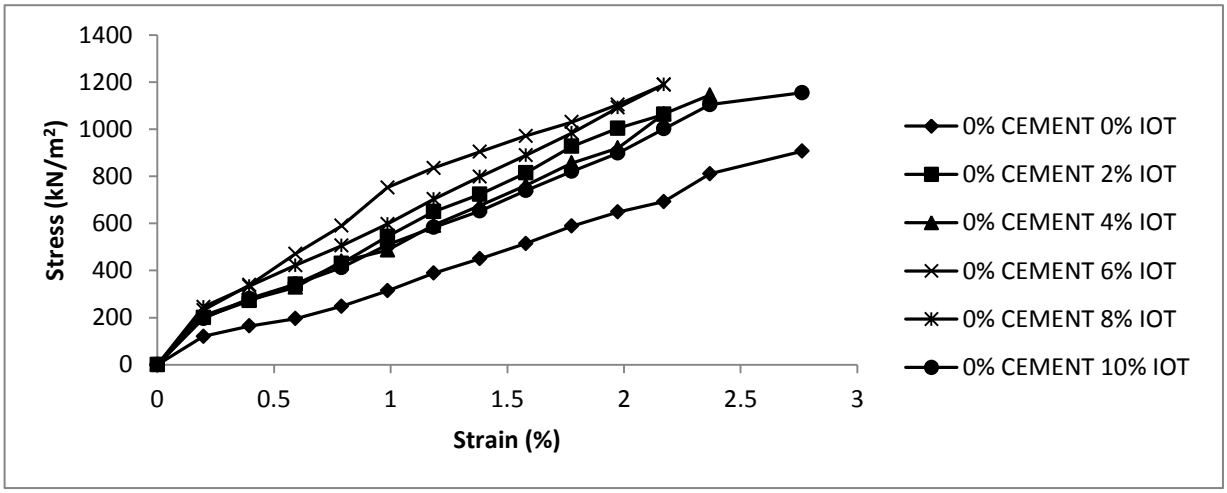


Figure B21: Stress-strain graph for lateritic soil – 0 % cement (14 days curing period) for varying iron ore tailings content (BSH compaction)

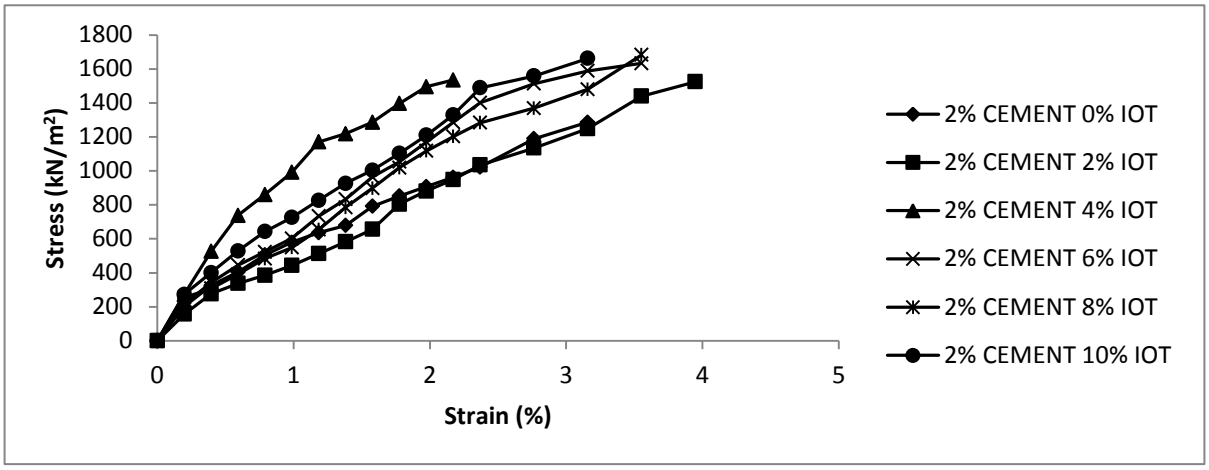


Figure B22: Stress-strain graph for lateritic soil – 2 % cement (14 days curing period) for varying iron ore tailings content (BSH compaction)

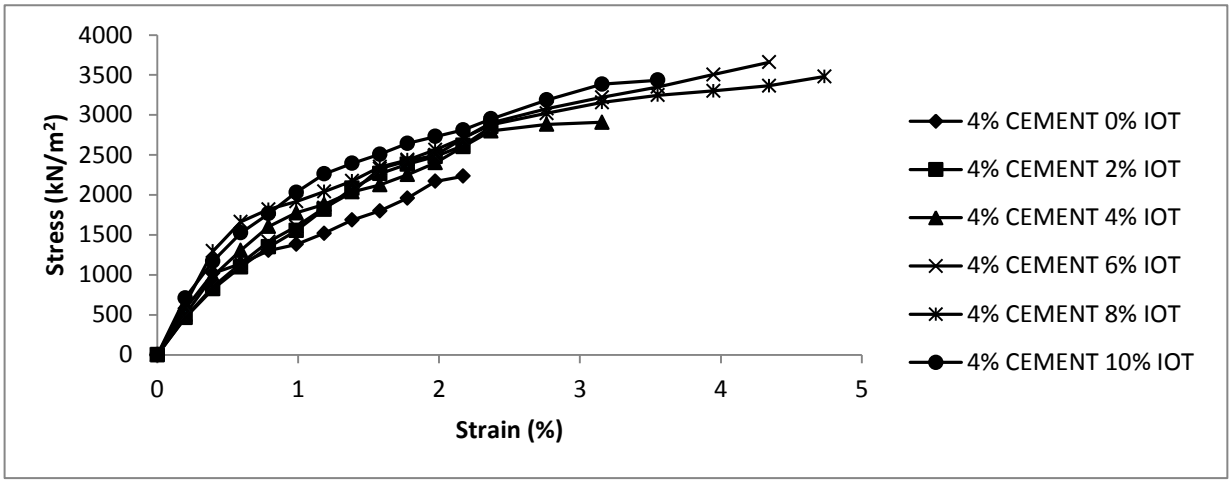


Figure B23: Stress-strain graph for lateritic soil – 4 % cement (14 days curing period) for varying iron ore tailings content (BSH compaction)

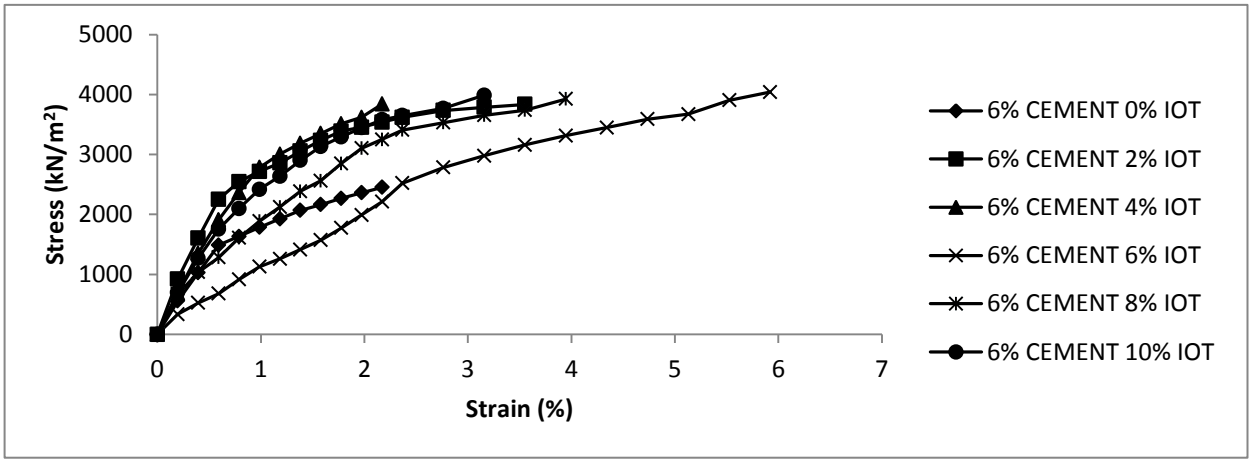


Figure B24: Stress-strain graph for lateritic soil – 6 % cement (14 days curing period) for varying iron ore tailings content (BSH compaction)

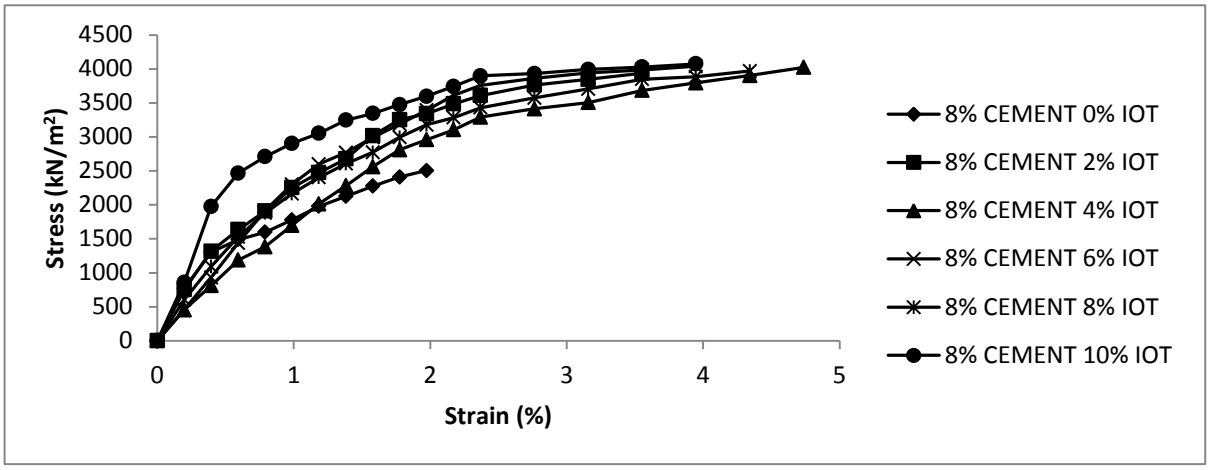


Figure B25: Stress-strain graph for lateritic soil – 8 % cement (14 days curing period) for varying iron ore tailings content (BSH compaction)

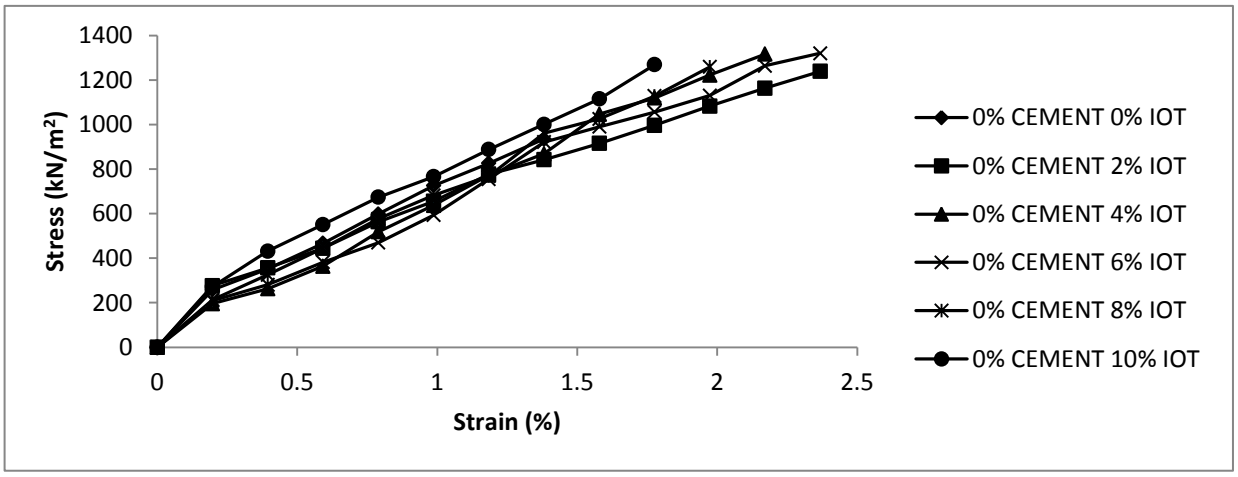


Figure B26: Stress-strain graph for lateritic soil – 0 % cement (28 days curing period) for varying iron ore tailings content (BSH compaction)

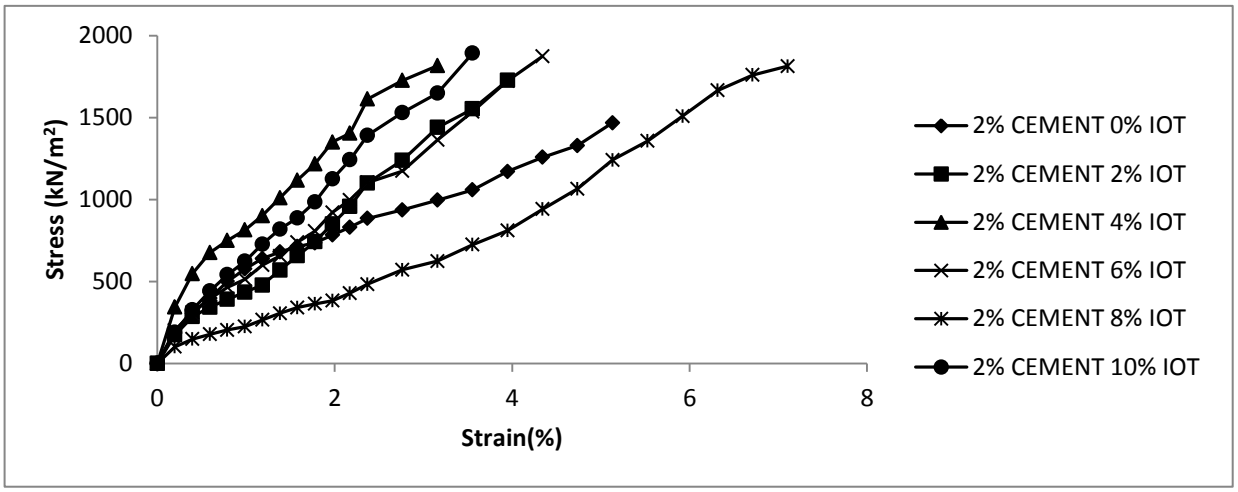


Figure B27: Stress-strain graph for lateritic soil – 2 % cement (28 days curing period) for varying iron ore tailings content (BSH compaction)

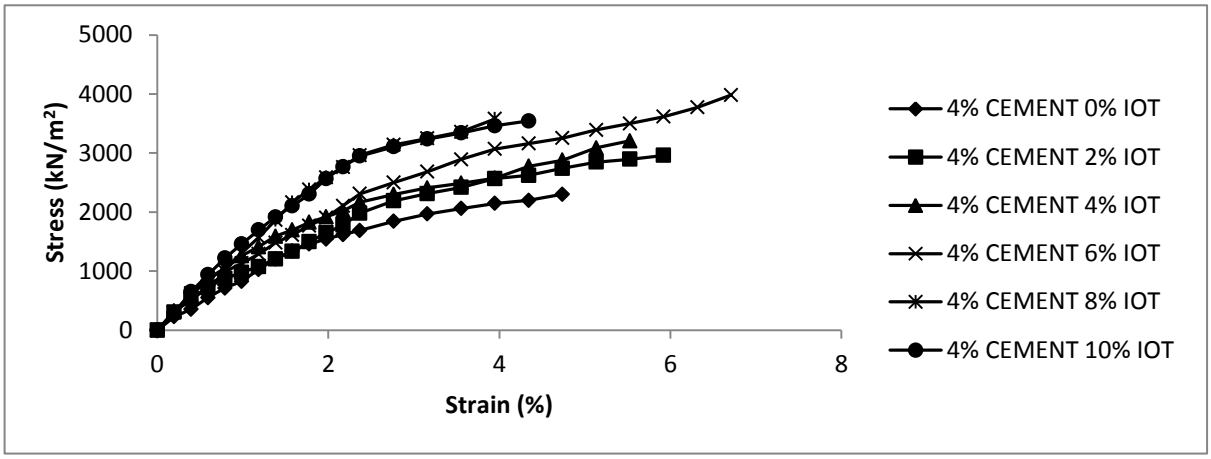


Figure B28: Stress-strain graph for lateritic soil – 4 % cement (28 days curing period) for varying iron ore tailings content (BSH compaction)

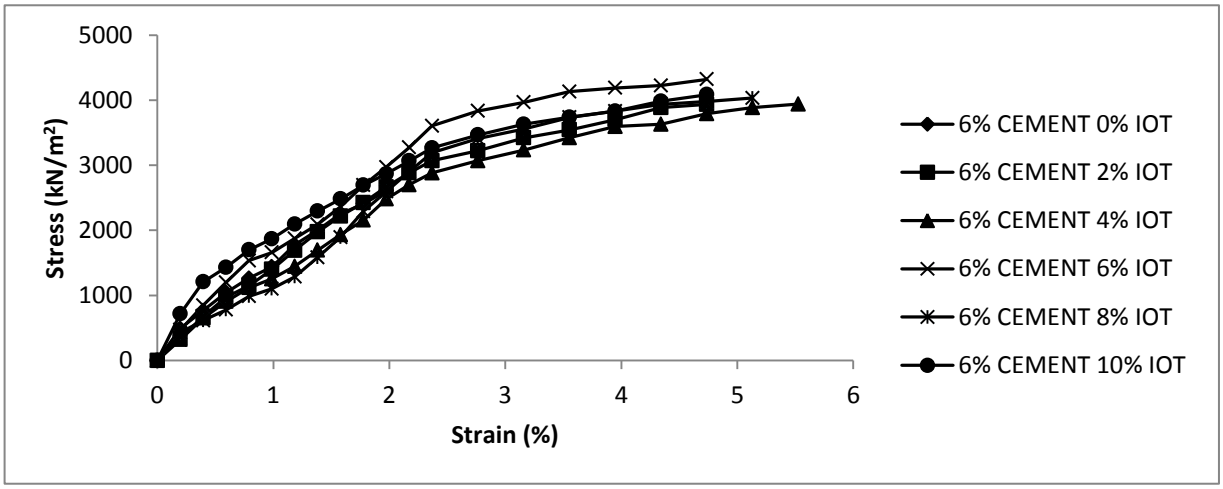


Figure B29: Stress-strain graph for lateritic soil – 6 % cement (28 days curing period) for varying iron ore tailings content (BSH compaction)

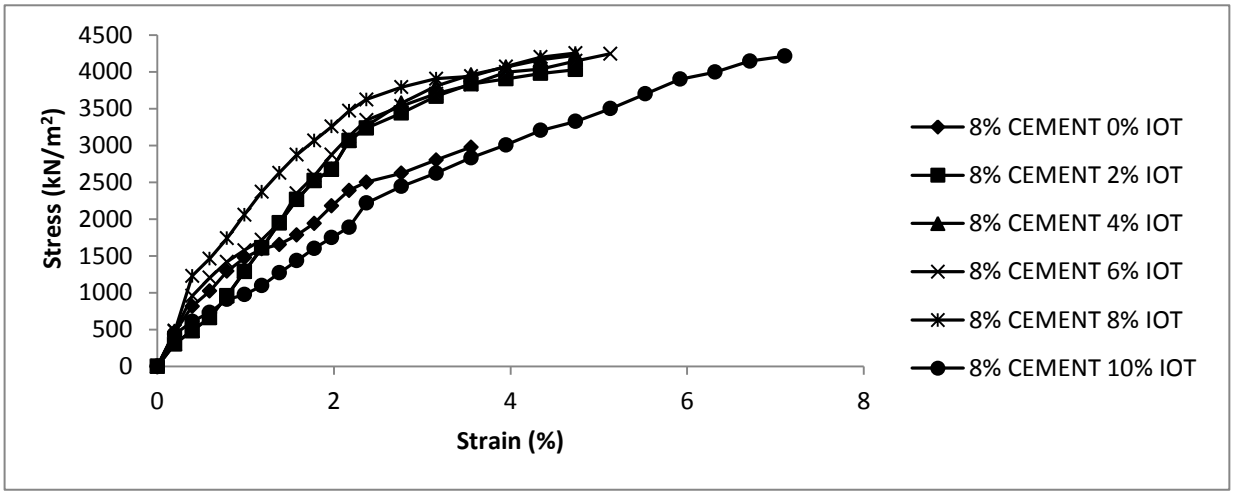


Figure B30: Stress-strain graph for lateritic soil – 8 % cement (28 days curing period) for varying iron ore tailings content (BSH compaction)