THE USE OF IRON ORE TAILING AS ADMIXTURE IN CEMENT MODIFICATION OF BLACK COTTON SOIL

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DECLARATION

I declare that the work in this thesis entitled **The Use of Iron Ore Tailing as Admixture in Cement Modification of Black Cotton Soil** has been carried out by me in the Department of Civil Engineering, Ahmadu Bello University, Zaria. The information derived from the literature has been duly acknowledged in the text and a list of references provided .No part of this thesis was previously presented for another degree or diploma at this or any other institution.

_______________	_______________	_______________
Paul Yohanna	Signature	Date

CERTIFICATION

The thesis titled **The Use of Iron Ore Tailing as Admixture in Cement Modification of Black Cotton Soil** by Paul Yohanna meets the regulations governing the award of the degree of Master of Science of the Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

Prof. K. J. Osinubi Chairman, Supervisory Committee	Signature	11.03.15 Date
Dr. A. O. Eberemu Member, Supervisory Committee	____________ Signature	________ Date
Dr. Y. D. Amartey Head of Department	___________ Signature	___________ Date
Prof. A. Z. Hassan Dean, School of Postgraduate Studies	___________ Signature	___________ Date

DEDICATION

With sincere thanks and profound gratitude, I wish to dedicate this project to God Almighty, the giver of life.

ACKNOWLEDGEMENTS

First of all I would like to thank the Almighty God for giving me life to be able to undertake in this programme. Special appreciation goes to my supervisors Prof. K. J. Osinubi, Dr. A. O. Eberemu and Dr. T. S. Ijimdiya for their guidance during the course of this work. I wish to acknowledge the cooperation and numerous supports received from members of my family and staff of Civil Engineering Department, Ahmadu Bello University (ABU), Zaria. The contribution of Mr. F. T. Azume of Metallurgical and Materials Science Engineering Department is highly appreciated. I also appreciate my classmates and other members of the postgraduate class for their contributions and support during this research work.

ABSTRACT

The black cotton soil (BCS) used in the study was classified as A-7-6(22) soil group of the AASHTO soil classification system and CH group in the Unified Soil Classification System (USCS). The effect of iron ore tailing (IOT) on ordinary Portland cement (OPC) modified soil was studied with respect to specific gravity, particle size distribution, Atterberg limits, cation exchange capacity, compaction characteristics and shear strength parameters, (cohesion and angle of internal friction using three (3) compactive efforts (i.e., British Standard light, BSL, West African Standard, WAS or 'Intermediate' and British Standard heavy, BSH). Microanalysis was carried out on specimens cured for 7 and 28 days and batch equilibrium tests results were evaluated to determine the effects of pozzolanic and particle inter-surface activities on the properties listed above as well as determine the leachability of IOT into the soil. Generally, treatment of BCS with OPC /IOT blend improved the soil properties and workability. BSL, WAS and BSH compaction energies effectively altered the shear strength parameters of BCS at 4 % cement 6 % IOT treatment. Tests results show that specific gravity of the soil increased while fine fraction and cation exchange capacity (CEC) decreased; liquid limit and plastic limit decreased; MDD increased while OMC decreased; cohesion decreased while angle of internal friction increased for all cement contents considered when admixed with up to 6 % IOT content by dry weight of soil. The Microsoft Excel Analysis Tool Pak Software Package was used to carry out statistical analysis tests results. A two-way analysis of variance (ANOVA) without replication was carried out to determine the levels of contributions of cement and IOT to the improvements recorded. Study of leaching potential of iron into the environment using batch equilibrium test showed that the desorbed values of iron and pH for the optimally modified soil falls within the permissible value recommended by the World Health Organisation (WHO) and the Nigeria Industrial Standard (NIS). The modified soil did not meet the Nigerian General Specifications requirements when used as a subgrade material in road construction. However, an optimal blend of 4 % cement 6% IOT treated black cotton soil compacted with BSH) energy is recommended for use as subgrade material for lightly trafficked road.

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CHAPTER ONE

INTRODUCTION

1.1 Preamble

Industrial waste disposal is constantly throwing up challenges in terms of the cost of their safe disposal; hence researches are carried out to determine their suitability as road pavement material. Problematic expansive soil (also known as black cotton soil) on the other hand abounds in many parts of the world such that by-passing it becomes impossible in places where the deposits are extensive. Various researchers (Ola, 1983; Balogun, 1991; Osinubi, 1995, 1999; Osinubi *et al,* 2009b, 2010) have attempted to improve the Nigerian black cotton soil with different types of additives with varying degrees of success.

Black cotton soils are expansive clays with potential for shrinking or swelling under changing moisture condition. These soils cause more damage to structures, particularly light buildings and pavements, than any other natural hazard, including earthquakes and floods (Ola, 1983). They are produced from the breakdown of basic igneous rocks where seasonal variation of weather is extreme. The soils are formed under conditions of poor drainage from basic rocks or limestone under alternating wet or dry climatic conditions. They usually exhibit high shrink-swell characteristics with surface cracks, opening during the dry seasons which are more than 50 mm or more wide and several millimeters deep. These cracks close during the wet season and an uneven soil surface is produced by irregular swelling and heaving. Such soils are especially troublesome as pavement sub-grades. These soils are the major problem soils in Nigeria where they occupy an estimated area of 104,000 km^2 in the north eastern part of the country (Ola, 1983; Osinubi et al., 2011).

The Nigerian black cotton soils are formed from the weathering of shaly and clayey sediment and basaltic rocks. They contain more of montmorillonite with subsequent manifestation of swell properties and expansive tendencies (Ola, 1983). These soils when road pavements are constructed over them and subjected to vehicular traffic heave and crack due to swelling and shrinkage (Sridevi *et al*, 2005; Pankaj *et al.*, 2012; Salahudeen *et al*., 2014). The wetting and drying process of a sub-grade layer composed of black cotton soil (BCS) result into failure of pavements in form of settlement and cracking. Therefore, prior to construction of a road on such sub-grade, it is important either to remove the existing soil and replace it with a non-expansive soil or to improve the engineering properties of the existing soil by stabilization or modification.

Soil improvement could either be by modification or stabilization or both. Soil modification and stabilization increases the workability, strength, bearing capacity and durability of the soil (Gidigasu, 1976). Various types of soil modifiers (e.g., cement, bitumen, lime) and locally available wastes (e.g., bagasse ash, fly ash, slate dust, rice husk ash, iron ore tailing, etc.) are used for modification 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 such as cement, lime and others have kept the cost of construction of stabilized road financially high (Neville, 2000). Thus, the use of industrial and agricultural wastes such as iron ore tailings, fly ash, coconut husk ash or coir fibre ash, etc. will considerably reduce the cost of construction as well as the environmental hazards they cause.

Oluremi et al. (2012) define wastes as either solid or liquid inevitable products of the bulk of man's activities whether in urban or rural areas. Their type, amount and composition vary with the type of activity which may be domestic, agricultural or industrial in nature. 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, socioeconomic 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, mine tailings, silt, etc. that may pollute the environment heavily. Therefore, comprehensive utilization of waste/tailings is important in saving resources, improving surroundings and for sustainable development (Mangalpady, 2012). Iron ore tailings (IOT) are mining and mineral waste from the iron ore mining industry. In Nigeria, the Itakpe and Agbaja iron ore deposits have generated a 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 %. The Agbaja iron ore is an acidic oolite ore consisting of goethite and magnetite with alumina, silica and phosphorus as its major impurities (Adedeji and Sale, 1984).

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.

1.2 Statement of the Problem

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).

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).

Researchers (Ferguson, 1993; Osinubi, 2000; Amadi, 2010a; Moses *et al*., 2012; Moses and Saminu, 2012) have carried out studies on the suitability of cheaper admixtures that can be used to substitute the expensive industrially manufactured soil improving additives (bitumen, cement, lime, etc.). The rising cost of industrially manufactured additives has led to the consideration of industrial and agricultural waste products with pozzolanic properties such as iron ore tailings, fly ash, rice husk ash baggasse ash, etc. as admixtures in soil improvement.

1.3 Justification for the Study

The use of industrial and agricultural wastes (e.g., iron ore tailing, fly ash, bagasse ash, locust bean waste ash, etc.) for soil improvement is significantly beneficial to the environment (Saranjeet *et al*., 2011)**.** The bulk utilization of iron ore tailing for soil improvement is possible by using it in the construction of structures such as embankments, pavements, and earth retaining structures where soil is used as a construction material. Previous investigations yielded positive results (Roy *et al*., 2007; Mallikarjuna *et. al*, 2008; Ramesh *et.al*, 2012).

The conventional improvement of the soil with lime and ordinary Portland cement has been confirmed in its requirement for construction works (Ola, 1983; Balogun, 1991; Matawal and Tomarin, 1996) but the cost of blending cement with the soil is usually very expensive (Osinubi and Oyelakin, 2012). Study of modification of lateritic soil with iron ore tailing by Ishola (2014) has shown that it can only be used as an admixture. Therefore, improvement of the properties of black cotton soil with iron ore tailings admixed with ordinary Portland cement and the determination of the optimum quantity to be used, if found economical and suitable, will provide a lot of road making material at minimal cost. Also, the environmental problems associated with the waste will be minimized. Mine tailings can be effectively utilized for civil engineering constructions which will minimize the disposal problems and reduce the environmental hazards (Pebble Project, 2005).

1.4 Aim and Objectives

The aim of the study was to evaluate the effect of iron ore tailing on cement modified black cotton soil. The following specific objectives were designed to be achieved:

i. Determination of the physico-chemical properties of the natural and modified soil.

ii. Evaluation of the moisture-density relationship of the natural and modified soil using three compactive efforts (British Standard light, West African Standard or Intermediate'and British Standard heavy).

iii. Determination of the shear strength parameters of the modified soil.

iv. Determination of the optimum blend of cement and IOT required for the modification of black cotton soil and efficacy of the proposed technique.

v. Microanalysis of the optimally modified soil using scanning electron microscope(SEM).

vi. Statistical analysis of test results using two-way analysis of variance (ANOVA) without replication.

vii. Study of the leaching potential of the iron ore modified soil on the environment using batch equilibrium test.

1.5 Scope of the Study

The research was limited to the feasibility of using iron ore tailing as admixture in cement modification of black cotton soil in road construction. Tests were carried out to determine the optimum amount of iron ore tailing that produced the desired workability of the treated soil in stepped concentrations of 0, 1, 2, 3 and 4 % for ordinary Portland cement and 0, 2, 4, 6, 8 and 10 % for iron ore tailing. Compaction tests were carried out using three energies namely, British Standard light (BSL), West African Standard (WAS) or 'Intermediate' and British Standard heavy (BSH). All tests were carried out on the natural black cotton soil and modified soil in accordance with BS 1924(1990) and BS 1377(1990), respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1 Expansive Soils

Problematic soils such as expansive soils are normally encountered in foundation engineering designs for highways, embankments, retaining walls backfills, etc (Moses and Osinubi, 2013). Expansive soils are normally found in semi – arid regions of tropical and temperate climate zones and are abundant, where the annual evaporation exceeds the precipitation and can be found anywhere in the world. Black cotton soil is a type of expansive soils it is so referred to in some parts of the world because the cotton plant thrives well on them. They have colours ranging from light grey to dark grey and black. Two groups of parent rock materials have been associated with the formation of expansive soils. The first group comprises sedimentary rock of volcanic origin, which can be found in North America, South Africa and Israel, while the second group of parent materials is basic igneous rocks found in India, Nigeria and South Western U.S.A (Plait, 1953).

The mineralogy of this soil is dominated by the presence of montmorillonite, which is characterized by large volume change from wet to dry seasons and vice versa Deposits of black cotton soil in the field show a general pattern of cracks during the dry season of the year. Cracks measuring 70 mm wide and over 1 m deep have been observed and may extend up to 3 m or more in cases of thick deposits. Maclean,(1953) gives the engineering definition for tropical black clay as dark grey to black soil with a high content of clay, usually over 50% in which montmorillonite is the principal clay mineral.

It was reported by Sani (2012) that expansive soil refers to soil material that has the potential for swelling and shrinking due to changing moisture conditions. Expansive soils are problematic for civil engineers; because of their unconventional behaviour, these soils show large volume changes with respect to variation of seasonal moisture content. These soils when subjected to vehicular traffic, road pavement gets heaved and cracked due to swelling and shrinkage. Expansive soil subgrades have low strength in wet conditions and lead to sub grade intrusion into overlying layer and penetration of sub base material into it. Pavements over expansive soil subgrades exhibit cracks resulting from alternate heave and settlement that lead to ultimate failure of pavements (Salahudeen *et al.,* 2014). Emphasis was given to the review of previous works on treatment methods of expansive sub-grade soils.

2.1.1 Identification of expansive soils

By using mineralogical identification, indirect index property tests or direct expansion potential tests, expansive soils can be recognized. Expansivity of a soil is governed by the type and proportion of clay minerals it contains. Knowledge of the type and proportion of the clay mineral in a soil gives a clue on the swelling potential (Chen, 1988). Fell *et al*. (2005) demonstrated intensively the identification techniques of clay minerals in soils and recommended to apply at least two of them at a time. The mineralogical identification techniques, X-ray diffraction, scanning electron microscope and differential thermal analysis and the indirect index property methods, Casagrande's plasticity chart and the activity of the soil which is the ratio of the plasticity index and clay fraction are recommended to identify expansive soils.

Pedarla (2009) reported that the durability of chemically modified soil depends on its cation exchange capacity(CEC), specific surface area of soil samples and total potassium to know the dominating clay mineral in a soil sample since these methods are cheap and are not skill oriented. The liquid limit and plasticity index are useful for determining the swelling characteristics of most clays (Holtz and Gibbs, 1956).

2.1.2 Origin and formation of black cotton soil

Black cotton soils (BCS) are black clays that are produced from the breakdown of basic igneous rocks, where seasonal variation of weather is extreme (Moses and Saminu, 2012). Black cotton soil is so named because of their suitability for growing cotton. Black cotton soils have colours ranging from light grey to dark grey and black. Black cotton soils are confined to the semi arid regions of tropical and temperate climatic zones and are abundant where the annual evaporation exceeds the precipitation. (Chen, 1988; Balogun, 1991; Warren and Kirby, 2004) reported that black cotton soils occur in continuous stretches as superficial deposits and are typical of flat terrains with poor drainage. The absence of quartz in the clay mineralogy enhances the formation of fine-grained soil material, which is impermeable and waterlogged.

Morin (1971) reported that the Lake Chad Basin is the only extensive lacustirne deposit of black cotton soil in Africa. The black cotton soils of North Eastern Nigeria were laid during the tertiary and quaternary periods of the Chad formation and are composed of a sequence of lacustrine and fluviatile clays and sands of Pleistocene age. These sediments (lacustrine sands, lagoonal clays, deltaic sands and clays, beach sands and gravels as well as aeolian sands) underlie the country North and East and extend along the plains of Borno and Lake Chad and beyond (Ola, 1983).

Ola (1983) and Osinubi *et al.,* (2011) reported that black cotton soils occupy an estimated area of 104 x 10^3 km^2 in Northeastern Nigeria. Figure 2.1 below shows a map of Nigeria showing the distribution of the soil type.

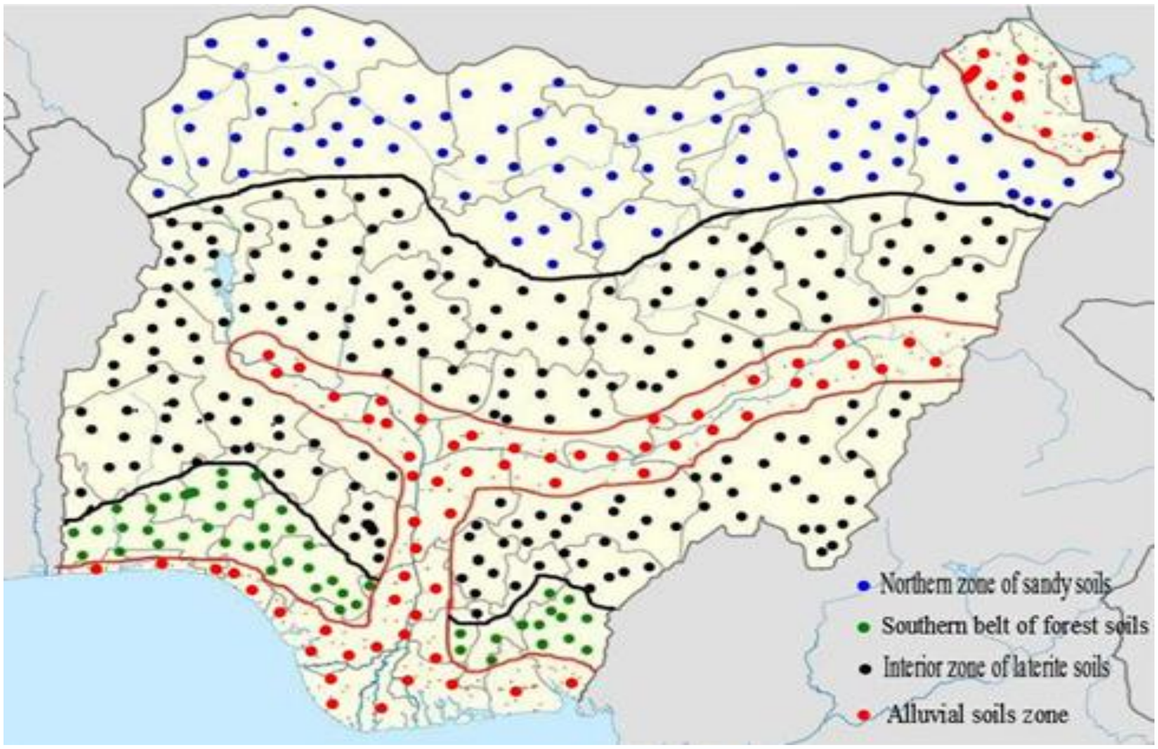

Fig 2.1 Map showing soil zones and types in Nigeria (Source; Eroarome, 2009)

The mineralogy of this soil is dominated by the presence of montimorillonite which is characterized by large volume change from wet to dry seasons and vice versa. Deposits of black cotton soil in the field show a general pattern of cracks during the day season of the year. Cracks measuring 70mm wide and over 1m deep have been observed and may extend up to 3m or more in case of high deposit (Adeniji 1991).

Nigerian black cotton soils are formed from the weathering of shaly and clayey sediments and basaltic rocks (Ola, 1983).The Nigerian BCS contains more of montmorillonite with subsequent manifestation of swell properties and expansive tendencies. The parent igneous rocks are made up of calcium-rich feldspar and dark minerals which are high in the weathering order and all the constituents are weathered to form amorphous hydrous oxide and under suitable conditions clay minerals develop. The absence of quartz leads to the formation of fine grained plastic soil highly impermeable and easily waterlogged. Other conditions favoring the formation of black cotton soil are evaporation exceeding precipitation, poor leaching, alkaline conditions and retention of magnesium and calcium in the soil (Ola, 1983).

2.1.3 Mineralogy and chemical composition of black cotton soil

Clay minerals are crystalline hydrous alumino-silicates derived from parent rock by weathering (Chen, 1988; Murray, 2007). The basic building blocks of clay minerals are the silicate terahtedron and the alumina octahedron and combine into tetrahedral and octahedral sheets to form the various types of clays. Kaolinite, illite and montimorillonite (smectite) are the common groups of clay minerals most important in engineering studies (Chen, 1988). Montmorillonite and kaolinite are the two predominant clay minerals found in black cotton soil.

Gourley *et al*. (1993) indicated the swelling property of illites which are formed from weathering of potassium and aluminum rich rocks under high pH conditions. Ola (1983) reported that the Nigerian black cotton soil contains about 70 % montmorillonite and 30 % kaolinite. The swell and shrink characteristics of the soil are largely due to montmorillonite minerals while kaolinite is likely responsible for high strength value because of its inability to swell with adsorbed water.

The montmorillonite group clays on the other hand have a 2-1layer structure formed by an octahedron sandwiched between two tetrahedrons. These groups of clays can have significant amounts of magnesium and iron substituting into the octahedral layers. The most important aspect of the montimorillonite group is the ability for water molecules to be absorbed between the layers, causing the volume of the minerals to increase when they come in contact with water (Nelson, 2010). The montmorillonite clay structure consists of layer sheet formed and stacked one above the other and the bonding between successive layers is by van der Waals forces and by cation that may be present to balance charge deficiencies in the structure. These bonds are, however, weak and easily separated by cleavage or adsorption of water and other liquids. There is an extensive isomorphous substitution for aluminium and silicon within its lattice which gives the clay a net negative charge resulting in the water absorbing tendencies and an attraction for hydroxyl ions and water molecules to the clay surface (Nelson and Miller, 1992).

2.1.4 General Characteristics of Black Cotton Soil

Expansive soils usually encounter as sub-grade material during any road construction project and these sub-grades soils may vary from highly expansive to expansive in nature (Solomon, 2011). Black cotton soil is a highly clayey soil. It is so hard that the clods cannot be easily pulverized for treatment for its use in road construction developing cracks, often measuring 70 mm wide and 1.0 m deep (Adeniji,1991). This poses serious problems as regards to subsequent performance of the road. Moreover, the softened subgrade has a tendency to up heave into the upper layers of the pavement, especially when the sub-base consists of stone soling with lot of voids. Gradual intrusion of wet black cotton soil invariably leads to failure of the road.

The roads laid on black cotton soil bases develop undulations at the road surface due to loss of strength of the subgrade through softening during rainy season. The black colour in black cotton soil is due to the presence of titanium oxide in small concentration. The black cotton soil has a high percentage of clay, which is predominantly montmorillonite in structure and black or blackish grey in colour. The physical properties of black cotton soil vary from place to place. As such black cotton soil has very low bearing capacity and high swelling and shrinkage characteristics (Ola, 1983).

Rao (2007) described the nature and characteristics of expansive soils. It was reported that expansive soils absorb water heavily, swell, become soft and lose strength. These soils are easily compressible when wet and possess tendency to heave during wet condition and shrink in volume and develop cracks during dry seasons of the year. These soils are characterized by extreme hardness and cracks when dry. Soils are called highly expansive when the free swell index exceeds 50 % and such soils undergo volumetric changes leading to pavement distortion, cracking and general unevenness due to seasonal wetting and drying.

The variation of the physical properties of black cotton soils from place to place. According to Seehra (2008) about 40 to 60 % of the black cotton soils have grain sizes less than 0.001 mm. These soils generally have higher liquid limit and plasticity index and extremely low CBR value. At the liquid limit, the volume change is of the order of 200 to 300 % and results in swelling pressure as high as 785 - 981 kNm^{-2}. Due to very low CBR values of this soil, excessive pavement thickness is required for designing of flexible pavement which can cause costly construction of pavements. Holland and Rechards (1982) reported that the seasonal changes in volume of expansive soil are manifested by horizontal and vertical movements. The horizontal movements lead to fissure opening during drying and closing during wetting where as the vertical movements lead to cyclic changes in soil levels.

2.2 Soil Modification

Soil modification essentially involves the improvement of the soil frictional characteristics and the reduction of its plasticity characteristics (workability). This is distinct from soil stabilization, which is the improvement of the strength of the soil (Ovuarume, 2011). Soil modification/stabilization can also be defined as the improvement of the original soil properties to meet specific engineering requirements. It 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; Gillot, 1987; Osinubi, 1995; Nicholas and Lester, 1999; Portelinha *et .al.,* 2012).

The industrially manufactured additives for modifying soils are lime, cement and bitumen. Therefore, in view of increasing demand for safe and cost-effective engineering 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 use, This explains why effort is being directed to material conversion of industrial wastes for engineering use (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 and rice husk ash to modify soils such as black cotton 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. Procurement of materials that meet specification requirement is increasingly becoming uneconomical. However, in order to make soil useful and meet foundation engineering design requirements 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, 2014).

Osinubi (1995) reported that in regions where problem soils are located, most deposits have been found to cover sufficiently large areas that avoiding or by-passing them is not always feasible. In soil modification, the strength of the soil may not have to increase to the optimal, but its workability can be improved upon in the process. The choice of appropriate modifying agent and the quantity of the agent required will depend on the impact of the agent on the physical properties of the soil that is of interest, particularly, its plasticity and shear strength. Modifying such a soil will involve mixing the modifier in proportion to the dry weight of the soil. In the process the modifier may have changed water film on the soil particles, the clay minerals in the soil, swelling potential and plasticity index of the soil (Atkins, 1997).

2.2.1 Benefits of soil modification

The benefits derived from improved soil properties such as reduction in the amount of agent required for soil improvement, rendering it usable, which could not otherwise be stabilized with agents like cement and bitumen was reported by Ingles and Metcalf (1972). Furthermore, there will also be a reduction in the tendency of picking up under rollers during compaction probably due to the more friable nature of the soil after modification. The direct implication of the second benefit is the increase in the range of usable soils for road construction (Ovuarume, 2011).

2.2.2 Mechanism of cement modification

Hydration is the first phase of cement modification reaction (Gillot, 1987). Cement hydration produces a cementitious compound; a product of cement and water. It generates bonding between the reaction products (Calcium silicate hydrates and aluminium hydrates) and the soil particles. It results in agglomeration and flocculation of the clay particles due to exchange of ions at the surface of the particles which manifest in an early strength development, immediate swell, and shrinkage and plasticity reduction. In highway construction, Portland cement is normally added to soils at optimum moisture content (OMC) and allowed to cure while the soil cement mixtures hardens by the process of 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 results in the formation of calcium silicate hydrates (CSH), which are cementing substances and are responsible for the initial strength development. 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 tlme and cement content. O'Glesby and Hicks (1982) attributed the effects of OPC in the strength properties of soil. When OPC hydrates, it liberates calcium silicates and aluminum ions into the water and these subsequently combine to form hydrated calcium silicate, which constitute the matrix of the hardened cements (Neville and Brooks, 1994).

2.2.3 Mechanical modification

Mechanical techniques of soil modification include compaction, vibration (of various techniques) and blasting. Mechanical method of soil improvement by compaction is the densification of the soil by the application of mechanical energy (Sani, 2012). This technique involves the modification of the water content as well as the gradation of the soil. Cohesionless soils are compacted by some means of confining the soil coupled with vibration energy. 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, sheeps foot 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).

2.2.4 Chemical modification

The addition of chemical compounds, to expansive soils increases their frictional characteristics, workability, strength, bearing capacity and durability of the soil. These organic or inorganic chemical compounds perform as cementitious and bonding agents or water proofers/repellants (Slate and Johnson, 1953). Organic compounds including resinous and bituminuous materials act as water proofers and sometimes behave similar to glue. These water proofing agents reduce the capacity for water intake and help the soil to retain its dry strength, even under wet conditions (Bowles, 1979). Inorganic agents for soil modification include Portland cement, lime, slag, sodium silicate, etc. (Balogun, 1991).

2.2.5 Cement modification

Modification of soils with cement usually involves the mixing of predetermined quantities of the additive with pulverized soil particles; and the mixture is termed 'soil-cement'. Soil-cement mixtures have been used for road sub base or base course for many years. Modifying soils with ordinary Portland cement (OPC) produces hardened materials which are capable of bearing loads for engineering purposes. TRRL (1977) recommended a minimum of 15 % for soil fraction passing 0.425 mm sieve and plasticity index greater or equal to 10. Broderick and Daniel (1990) reported that Red Earth soil treated with cement or lime improve their engineering properties.

Researchers (Yoder and Witzak, 1975; Nelson and Miller, 1992; Indraratna et al. 1995) reported a decrease in liquid limits, plastic limits and swelling potentials of clays when treated with cement. Also, researchers (Maclean 1953; Ingles and Metcalf, 1972; Ibrahim, 1983) reported that cement modification may not be effective for soils of high plastic limit or liquid limit in excess of about 45 to 50 % and high organic matter as well as montmorillonite–rich soil. Brandl (1981) attributed the increase in strength of ordinary Portland cement (OPC) modified soils to the increase in the friction angle and the cohesion of the soil-OPC mixture.

2.2.6 Admixture modification

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 black cotton soil, many chemical/agricultural or industrial additives have been mixed with lime or cement or both (Osinubi, *et al*, 2009, 2011; Osinubi and Gadzama, 2009; Osinubi and Muazu, 2010; Moses and Osinubi, 2013; Ochepo and Osinubi, 2013;Yamusa *et al*, , 2013).

2.2.7 Chemical admixture modification

Studies conducted in the past (Slate and Johnson, 1953; Krishna and Ramesh, 2012) describes the behaviour of black cotton soil treated with calcium chloride ($CaCl_2$). From the immediate compaction and unconfined compressive strength test, it was observed that black cotton soil with 3 % $CaCl_2$ (by weight of soil) combination found to be optimum percentage. It was reported that the modification of clay properties with $CaCl_2$ is several times greater than conventionally used lime. The field cyclic seasonal movements and laboratory tests on undisturbed and disturbed black cotton soil samples revealed that the $CaCl_2$ could be a promising chemical modifier instead of conventionally used lime not only due to its multifold influence on heave control, plasticity reduction and swell properties but also its easy application in the form of solution without any need for pulverization and mixing (Ramana and Krishna, 2007).

Balogun (1991) reported that a significant increase in the geotechnical properties of black cotton soil is achieved with addition of 2 % sodium chloride with lime–clay mixture. An increase in dry unit weight as well as the strength of black cotton soil was also reported by Sambhandharasksa and Moh (1971) on the admixture of high sodium chloride with lime. Maclean (1953) used water soluble calcium chloride simultaneously with cement to modify clay soils with appreciable amount of organic matter; noting that the absorption capacity of the organic matter for calcium ions permits the calcium from OPC to complete reaction with the other compounds in the normal way. Shivapullaiah *et al*. (2003) as well as Shivapullaiah and Lakshmikanth (2005) reported that addition of bentonite with lime or cement improved the geotechnical properties of Red Earth soil.

2.2.8 Industrial /agricultural wastes admixtures modification

It is worthy to note that most industrial or agricultural wastes possess a pozzolanic property, that is, having cementituous tendencies on exposure to moisture (O'Flaherty, 1988). Pozzolanas are siliceous and aluminuous materials which themselves possess little or no cementituous value but, will, in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature, to form compounds possessing cementitious properties (Robert, 1993). Several reseachers (Fakiyesi and Osinubi, 1995; 1996; Osinubi, 1997; Sridevi *et al*., 2005; Mu'azu, 2007; Oyelakin, 2011; Laxmikant *et.al*., 2011; Azige, 2012) have shown that industrial and agricultural wastes could be used for the modification of expansive 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 black cotton soils (Ferguson, 1993; Osinubi, 2000; Osinubi and Stephen, 2005; 2006a, b; 2007; Osinubi and Ijimdiya, 2008; 2009; Osinubi and Mustapha, 2005; 2008; 2009; Osinubi and Eberemu, 2006; Osinubi et al., 2007a, b, c; 2008a, b; 2009a, b; 2010; 2011; Srirama and Rama, 2008; Amadi, 2010b; Osinubi and Oyelakin, 2012).

Roy et.al. (2007) examines 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. Stephen (2006) studied the potential of bagasse ash as a modifier on black cotton soil while and Moses (2006) studied the potential of admixed baggase ash with lime and cement in modifying black cotton soil. Both results have shown that baggase ash resulted in significant improvement of the black cotton soil.

2.3 Microanalysis of Soil

Bennett, *et.al* (1991) reported that understanding the nature of materials/soil and their structures has always been significant. 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).

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).

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 (Wiliams and Carter, 2009). This device has also been employed for imaging soil nanostructure (Citeau *et al*., 2006). 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).

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

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

The micro fabric of this sediment section is most likely in the initial stages of consolidation, where the microstructure has sufficient strength to resist the stresses of the small overburden load impressed upon it (Bolt 1956; Lambe 1958; Ingles 1968; Bryant, *et al*., 1991).The micro pores in soil 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 pores structure 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).

2.3.2 Relationship between microstructure and engineering properties

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

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

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

2.4 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). Analysis of variance 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 (Viv *et. al,* 2004).

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 the a 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 treatments result in altered effects.Additionally, it can be used in cases of two samples 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 basics assumptions on which this test is performed:

2.4.1Assumptions:

2.4.1.1 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.

2.4.1.2 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.

2.4.1.3 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.

2.4.2 Types of Analysis of variance (ANOVA).

2.4.2.1 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).

2.4.2.2 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).

2.4.2.3 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).

2.4.3 Key terms and concepts:

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

2.4.3.2 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.

2.4.3.3 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..

2.4.3.4 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.

2.4.3.5 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.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Black cotton soil

The soil sample used in this study was collected along Gombe - Biu road in Yamatu Deba Local Government Area (Latitude 10° 19'N and longitude 11° 30'E) of Gombe state using the method of disturbed sampling. The study area lies within the North eastern part of Nigeria bothered by Adamawa, Bauchi, Borno and Benue state and is extensively covered by black cotton soils noted for swelling and heaving with changes in seasonal moisture (Ola, 1983). The top soil was removed to a depth of 0.5m before the soil samples were collected in sacks and some were sealed in plastic bags and put in sacks to avoid loss of moisture during transportation. The soil samples were then 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).In terms of extent of deposit, black cotton soils are not restricted to the area of study but are widespread throughout the north– eastern Nigeria (Moses and Folagbade, 2010).

A study of the geology of the area (Akintola 1982) and (Areola 1982) showed that black cotton soils belong to the group of ferruginous tropical soils derived from acid igneous and metamorphic rocks which when weathered formed black cotton soils. Ola(1983) reported other parent materials from which these soils are generally formed which include the sedimentary rocks of volcanic origin. The tuffs and ashes are made up of volcanic dust which is generally a collection of minute particles of volcanic glass. These materials readily weather to form montmorillonite clays, the major clay mineral of the black cotton soil. Generally, other conditions which favours the formation of black cotton soil clays are: evaporation exceeding precipitation, poor leaching, alkaline conditions prevail in the area of occurrence of the Nigerian black cotton soil (Ola, 1983).

3.1.2 Iron ore tailing

The iron ore tailing 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.

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 0.01g (m_1). Soil sample was placed in the containers and weighed as m_2. After weighing, the containers with the soil samples were placed in the oven for 24 hours at temperature of 105˚C. After 24 hours the samples were removed from the oven and allowed to cool. The oven dried samples in the container were weighed m_3. The moisture content was calculated using the expression.

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

where;

w= Moisture content (%)

M_1 = weight of empty container (g)

M_2 = weight of container+ wet soil (g)

M_3 = weight of container dry soil (g)

3.2.2 Specific gravity

The specific gravity of the soil was determined in accordance with BS 1377 (1990) Test (B) for fine-grained soils. Density bottle with the stopper was weighed m_1. Some quantity of the soil was transferred into the bottle to fill about one third (⅓) of the bottle and was weighed m_2.Sufficient distilled water was added gradually and was stirred gently to remove air bubbles before placing the stopper. The stopper was then inserted and allowed to stay for 24 hours then weighed m_3. The bottle was then cleaned completely filled with distilled water and the stopper inserted, then weighed as m_4. The specific gravity was then calculated using the equation.

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

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

3.2.4 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 distilled was collected. The NH_4-borate was titrated with a standard acid 0.1N HCl. The cation exchange capacity (CEC) was calculated using the formula:

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

where:

B = Blank

NA = Normality of acid

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

3.2.5 Batch equilibrium

The procedures adopted for Batch Equilibrium Adsorption Test was in accordance with that described by Shackelford and Daniel (1991). Batch equilibrium tests were performed with black cotton 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 were also measured. The mass of solute adsorbed/desorbed per mass of soil solid was determined using the following expression:

$$C_s = \frac{(Ci - Cf\,) \times V}{Ms} \tag{3.4}$$

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)

3.2.6 Sieve analysis

3.2.6.1 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 sieve to remove clay and silt particles using BS No 200 sieve (0.075 mm aperture) under tap water. Washing was done carefully to avoid damage to the sieve. After washing, the sample retained 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 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; percentage passing against sieve sizes. The same process was repeated for the remaining percentages of the admixtures.

3.2.6.2 Dry sieving

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

3.2.7 Atterberg limits

Atterberg limits tests include the determination of the liquid limit, plastic limit and the plasticity index for the natural soil and the modified soils. They were also conducted in accordance with Test 1(A) BS 1377 (1990) Part 2 for the natural soil and BS 1924 (1990) for the modified soils.

3.2.7.1 Liquid limit

The soil sample for liquid limit (LL) test was air-dried and 200 g of the material passed through BS No. 40 sieve (425 μm aperture) was obtained and thoroughly mixed with water to form a homogeneous paste on a flat glass plate A portion of the paste was then placed in the cup of the Casagrande apparatus, leveled off parallel to the base and divided by drawing the grooving tool along the diameter through the centre of the hinge. The cup was then lifted up and drops by turning the crank until the two parts of the soil come into contact at the bottom of the groove. The number of blows at which that occurs is recorded and a little quantity of the soil was taken and its moisture content was the measure in accordance with the above procedure (section 3.2.3.1). The test was performed for well–spaced out moisture content from the drier to the wetter states. The values of the moisture content (determined) and the corresponding number of blows was then plotted on a semi–logarithmic graph and the liquid limit was determined as the moisture content corresponding to 25 blows. This same procedure was then repeated for each of the sample with cement and IOT admixture for the percentages listed earlier.

3.2.7.2 Plastic Limit

A portion of the soil/soil–cement–IOT mixtures used for the liquid limit test was retained for the determination of plastic limit (PL). The ball of the soil / treated soil was moulded between the fingers and rolled between the palms of the hand until it dried sufficiently. After the liquid limit test has been determined, small portion of the soil paste were taken and then tried to roll into a 3mm thread. The moisture content at which the soil can be rolled into a thread of 3 mm without crumbling is the plastic limit of the soil. A portion of the rolled soil thread was then put in to the oven for moisture content determination. This experiment procedure was repeated three times in other to get the average moisture content which corresponds to the plastic limit. The same procedure was repeated for all the percentages of the admixtures.

3.2.7.3 Plasticity Index

The plasticity index (PI) of the soil/soil–cement–IOT mixture is the difference between the liquid limits of the natural/various mixes of the soil and their corresponding plastic limits. Mathematically it is expressed as

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

where

PI=Plasticity Index (%)

LL=Liquid Limit (%)

PL= Plastic Limit (%)

3.2.7.4 Linear shrinkage

The test was conducted in accordance with Test 5 BS 1377 (1990). It involves the mixing of about 125 g of soil,passing the 425 μm sieve (BS No. 40 sieve) with water in order to obtain a homogenous paste (the water added to the natural soil corresponded to the moisture content at liquid limit). With the same sample used for the liquid limit, a portion of the paste was also used to fill the shrinkage mould whose inner surface was oiled to prevent sticking of the sample to the mould. The top of the mould was levelled and smoothen. The same sample was then put into the oven for 24 hours at 105^0C.The length of the shrinkage mould and the length of the dry soil in the mould were measured. This same procedure was then repeated for each of the sample with cement and IOT admixture for the percentages listed earlier. Linear shrinkage was calculated using the expression:

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

3.2.7 Compaction characteristics

3.2.8.1 Maximum dry density

The compaction tests were carried out for the natural soil and the modified 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. The soil weighed was crushed to a powdered form on a metallic tray. Using varying percentages of water content at an increment of 4 % equivalent added for every compaction. Compaction was carried out in three different compaction energies.

In the British Standard light (BSL), soil samples were compacted in three (3) layers, 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 leveled to the brim of the mould using edge. The mould and the compacted soil were weighed. The compacted soil specimen was removed from the mould for moisture content determination. The whole soil sample was removed from the mould and placed on a large mixing tray, Another 4 % water equivalent was added to the sample and mixed properly. The compaction was repeated using the same no of blows and layers as described above. Successive increments of 4 %

water equivalents were added until when the weight of the mould and the soil sample started reducing. 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. A smooth curve 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 is given by

$$\ell_b = \frac{Mş}{Vş} \tag{3.7}$$

where ;

ℓ_b = Bulk density (kN/m³)

$m_ş$ = Mass of compacted soil (kN)

$v_ş$ = Volume of Mould (m³)

The dry unit weight was determined using the expression

$$\ell_d = \frac{\ell b}{1+w} \tag{3.8}$$

where ;

ℓ_d=Dry unit weight (kN/m³)

ℓ_b =Bulk density (kN/m³)

w =Optimum moisture content (%).

3.2.8.2 Optimum moisture content

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

3.2.9 Shear strength parameters

The shear strength tests were performed using the undrained triaxial test procedure in accordance with BS 1377(1990) using the British Standard Light (BSL), West African Standard (WAS) and British Standard heavy (BSH) energy levels. The natural soil samples and the treated soil (soil - cement - IOT mixtures) 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 then weighed before carrying out the test. Record was taken simultaneously of the axial deformation and the axial force at regular intervals until failure of the sample occurred. The compressive stress was calculated using the equation (Head, 1992).

$$\sigma = \frac{[R \times Cr \times (100 - E\%) \times 100kN/m2]}{(100 \times Ao)} \qquad (3.9)$$

where

E % $= l / l_o$

E % = Strain Percent

l = 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 the specimen.

A_o = Initial cross sectional area

б =Compressive stress at strain E.

3.2.10 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 electrization. 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. The signals that derive from electron-sample interactions revealed information about the sample including external morphology (texture), chemical composition (EDS), and crystalline structure and orientation of materials making up the sample.

3.2.10.1 Sample preparation and launching

Soil sample was collected, sieved through BS No 4 and compacted at optimum moisture content using British standard light (BSL) compaction, cured for seven and twenty eight 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 a spatial variations in their properties. Areas ranging from approximately 1 cm to 5 microns in width can were as imaged in a scanning mode using conventional SEM techniques (magnification ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm).

The SEM also performed analyses of selected point locations on the sample; this approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions using Energy Dispersive Spectroscopy (EDS). Essential components of all SEM include the following: Electron Source (Gun), Electron Lenses Sample Stag, Detectors for all signals of interest.

3.2.10.2 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

3.2.10.3 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 x 10^{-5} Torr. A high vacuum pressure was pumped required for a variety of reasons. Thus, 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 was 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.

3.2.10.4. Electron beam specimen interactions

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 and help 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 EDS (energy dispersive x-ray spectroscopy) analysis of characteristic x-ray signals.

3.2.10.5 Image formation in the SEM

SEM images of three-dimensional objects was interpreted by and electron lenses. 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 was 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.

3.2.10.6 Lenses in the SEM

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 labeled, “spot size”, “condenser”, or “resolution”.The design of the lenses often incorporates space for the scanning coils, the stigmator, and the beam limiting aperture.

3.2.10.7 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 oluminescence 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.

3.2.10.8 Image formation

The SEM image is a 2D intensity map in the analog 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 analog signal for display on a monitor.

3.2.10.9 Magnification in the SEM

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 two 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.

3.3.1 .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 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 effects on the varrious black cotton soil – cement – iron ore tailing mixtures.

CHAPTER FOUR

DISCUSION OF RESULTS

4.1 Properties of Materials Used in the Study

4.1.1 Natural soil

Results of preliminary investigations conducted on the natural properties of the soil showed that the soil is fine-grained, having greyish black colour with a natural moisture content of 19.5 %. The index properties are summarized in Table 4.1, while its oxide composition is summarized in Table 4.2. The particle size distribution curve of the natural soil is shown in Fig. 4.1 The soil belongs to the CH group in the Unified Soil Classification System, USCS (ASTM, 1992) or A-7-6(22) soil group of the AASHTO soil classification system (AASHTO, 1986). The soil is greyish black in colour (from wet to dry states) with a liquid limit of 56 %, plastic limit of 25 % and plasticity index of 31 %. The soil has a free swell of about 40 %, cohesion values of 64, 68 and 73 kN/m^2 for British Standard light, BSL, West African Standard, WAS and British Standard heavy, BSH compactions, respectively and corresponding angle of internal friction values of 3, 6 and 7 degrees, respectively. Based on its index properties the soil is of low plasticity and falls below the standard recommendation for most geotechnical construction works especially highway construction. This finding is consistent with that reported by Butcher and Sailie (1984). Detailed test results are shown in Tables A4.1-4 in the Appendix.

Table 4.1: Properties of the natural soil

Property	**Quantity**
Percentage Passing BS No. 200 Sieve	74.2
Natural Moisture Content, %	19.5
Liquid Limit, %	56
Plastic Limit, %	25
Plasticity Index, %	31
Linear Shrinkage, %	16.32
Free Swell, %	40
Specific Gravity	2.46
AASHTO Classification	A-7-6 (22)
USCS	CH
NBRRI Classification	Low swell potential
Maximum Dry Density, Mg/m^3	
British Standard light	1.56
West African Standard	1.64
British Standard heavy	1.68
Optimum Moisture Content, %	
British Standard light	23.5
West African Standard	20
British Standard heavy	19.3
Cohesion, kN/m^2	
British Standard light	64
West African Standard	73
British Standard heavy	86
Angle of Internal Friction (degree)	
British Standard light	3
West African Standard	6
British Standard heavy	7
Cation Exchange Capacity, Cmol/Kg	52.52
pH	6.24
Colour	Greyish black
Dominant clay mineral	Montmorillonite

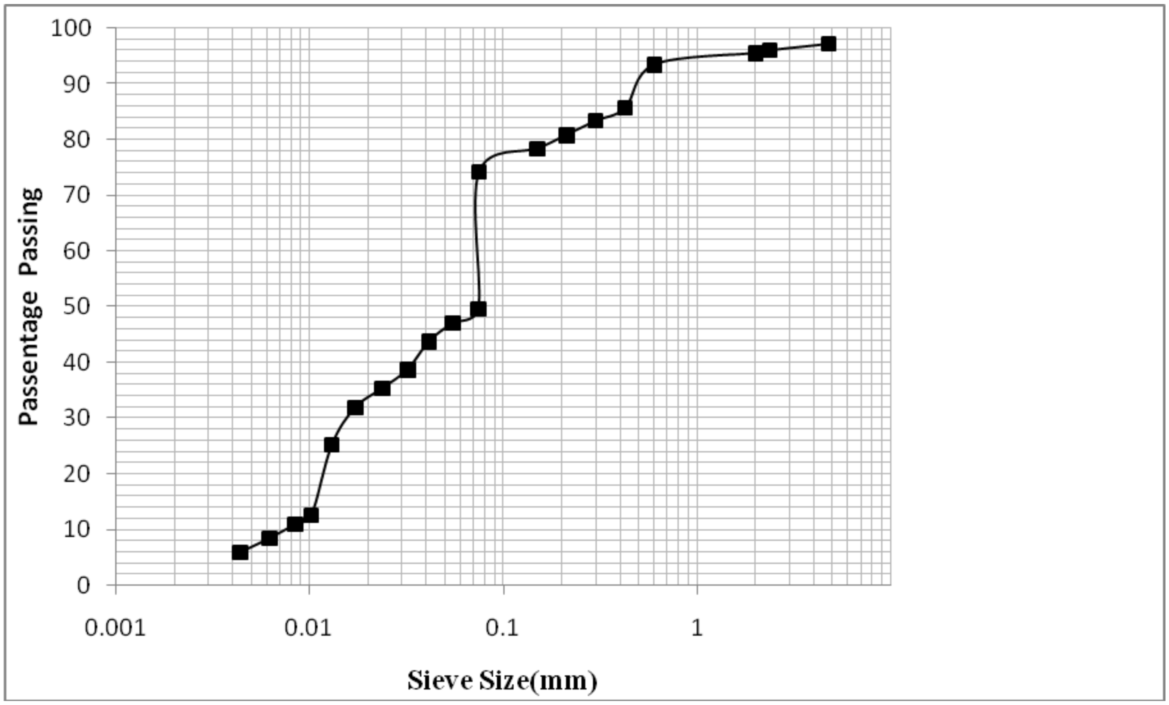

Fig.4. 1: Particle size distribution curve of the natural soil

4.1.2 Additives

Tailings are the waste materials (by-products) of the mining industry. 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). Most mill tailings mass-produced worldwide are dumped in large surface impoundments

The oxide composition of ordinary Portland cement (OPC) and iron ore tailings (IOT) was determined at the Defense Industry Cooperation of Nigeria (DICON),Kaduna, using the method of X-Ray Fluorescence (Nuclear Energy Test). A comparison of the calculated compound composition of IOT and OPC is shown in Table 4.2. The cementing characteristics of IOT are dependent on its oxide composition. The quantity of CaO (0.567 %) in IOT is very low compared to about 63 % in OPC , while the silicon oxides in IOT on the other hand are higher than that in OPC (see Table 4.2).

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

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
Mg0	-	0.393
Loss on Ignition	2.0	3.0

*Czernin (1962)
**Ishola (2014)

Iron ore tailing is a pozzolana and is classified as Class F in the classification of pozzolanas as given by ASTM C618-12a is summarized 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 Modification on Black Cotton Soil

4.2.1 Specific gravity

The variation of specific gravity of black cotton soil-cement mixtures with iron ore tailing content is shown in Fig. 4.2. It was observed that specific gravity of all the black cotton soil – cement mixtures considered increased with higher iron ore tailing content. The value of specific Gravity of the soil increased from 2.46 for the natural soil to a peak value of 2.56 at 0% cement /10 % IOT blend.

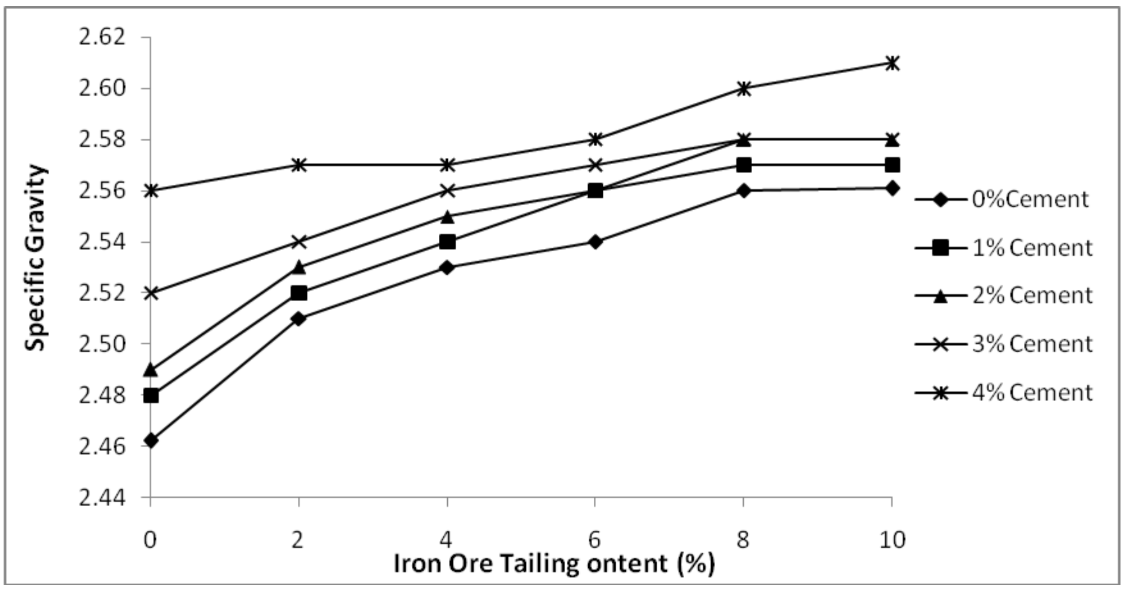

Fig. 4.2: Variation of specific gravity of soil – cement mixtures with iron ore tailing content.

The increase could be attributed to high specific gravity of the additives replacing the soil with low specific gravity value of 2.46. Similar behaviour was observed by Amadi, (2010a). The specific gravity of IOT (3.29) recorded is 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). Detailed test results are shown in Tables A4.4 in the Appendix.

The two – way analysis of variance (ANOVA) test on specific gravity results summarized in Table 4.4 show that the effects of cement and IOT were statistically significant with IOT having a more pronounced effect. Detailed test results are shown in Tables A4.14 in the Appendix.

Table 4.4: Two-way analysis of variance result for specific gravity of black cotton soil-cement-iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Specific Gravity	Cement	4	25.283	1.408E-07	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	43.356	4.652E-10	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.2 Cation exchange capacity

The variation of cation exchange capacity (CEC) of black cotton soil-cement mixtures with iron ore tailing (IOT) content is shown in Fig. 4. 3. The CEC values for cement and IOT are 28.4 and 24.6 Cmol/kg, respectively. Generally, the CEC of soil – cement mixtures decreased with higher IOT content. The value decreased from 52.5 Cmol/kg for the natural soil to a value of 50 Cmol/kg at 0 % Cement / 10 % IOT treatment (see Fig. 4. 3). The decrease in CEC was as a result of decrease in the clay size fraction of the soil (Warrick, 2002; Salahedin, 2013). The decrease in CEC of BCS could also be attributed to the reduction in pH of black cotton 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). Detailed test results are shown in Tables A4.5 in the Appendix.

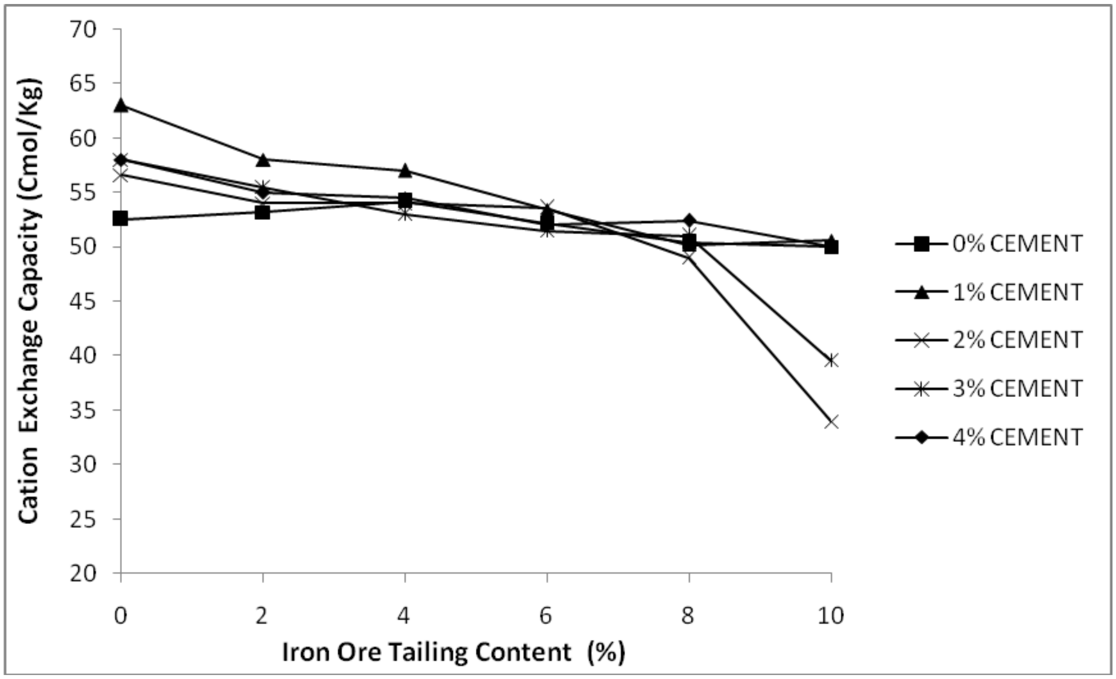

Fig. 4.3: Variation of cation exchange capacity of black cotton soil – cement mixtures with iron ore tailing content.

The two – way analysis of variance (ANOVA) test on the CEC results (see Table 4.5) shows that the effect of cement on black cotton soil was not statistically significant, while the effect of IOT was statistically significant. Detailed test results are shown in Tables A4.15 in the Appendix.

Table 4.5: Two-way analysis of variance result for cation exchange capacity of black cotton soil- cement-iron ore tailing mixtures

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
CEC	Cement	4	2.173	0.109115	2.866	$F_{CAL}<F_{CRIT}$, No Significant effect
	IOT	5	8.952	0.000137	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.3Particle sze distribution

4.2.3.1 ***Wet sieving***

The particle size distribution obtained from hydrometer test of black cotton soil - cement - iron ore tailing mixtures is shown in Fig. 4.4a – e. Generally, percentage fines of the soil – cement mixtures decreased with increase in iron ore tailing content. It can be observed that the percentage fines reduced from 74.2 % for the natural soil to 65.5 % at 0 % Cement / 4 % IOT (see Fig. 4.4a). Similar trends were observed for the various cement contents considered. The decrease in fines fraction with increase in IOT content could be attributed to flocculation and agglomeration of the black cotton soil-cement mixtures which enabled the clay fraction to form larger soil sizes (Akinmade, 2008; Oyelakin, 2010; Amadi, 2010a; Al karagooly, 2012; Portelinha *et al*., 2012). The aggregation or clusters of clay minerals and clay-size mineral fragments due to ion exchange at the surface of the soil particles resulted in more stable silt-sand-like structures. The soil-cement mixture became more granular with up to 6 % IOT content.This is in agreement with the findings 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 Fig. 4.4a - e) 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, 2010). The subsequent increase in fines to about 77.0 % at 6% IOT content could be assumed to be due to excess IOT that was not used in the agglomeration process and hence the soil-IOT mixture became finer. A reduction in the silt fraction of the soil from 40.9 % to 0 % at 2 % Cement / up to 8 % IOT was observed (see Fig. 4.4c). Similarly, there was also a reduction in the silt fraction of the soil from 37.4 % to 0 % at 3 % Cement / up to 10 % IOT (see Fig. 4.4d) where the soil was completely modified from clayey silt to sandy silt. These results agree with the findings of similar works on modification of soils by Yoder and Witczak (1975), Osinubi (1995), Portelinha *et al*. (2012) and Sarkar *et.al.* (2012).

The reduction in fines content could also be due to cation exchange between the additives and black cotton soil particles. This reduction also may not be unconnected with the flocculation and agglomeration of the clay particles that led to ion exchange at the surface of the clay particles; as the excess Ca^{2+} in the additives reacted with the lower valence metallic ions in the clay structure (Akinmade, 2008; Oyelakin, 2010; Al karagooly, 2012; Portelinha *et al,* 2012). Detailed test results are shown in Tables A4.7(a) in the Appendix.

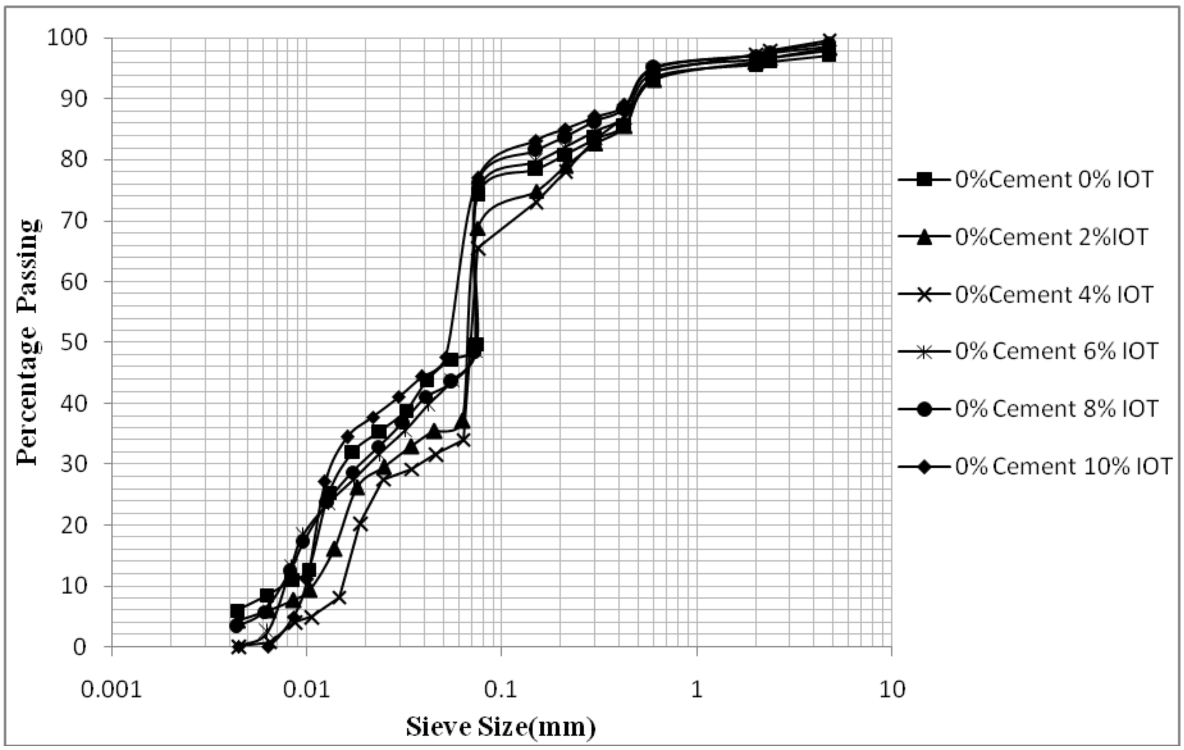

Fig. 4.4a: Particle size distribution curves for black cotton soil –0 % cement – iron ore tailing mixtures

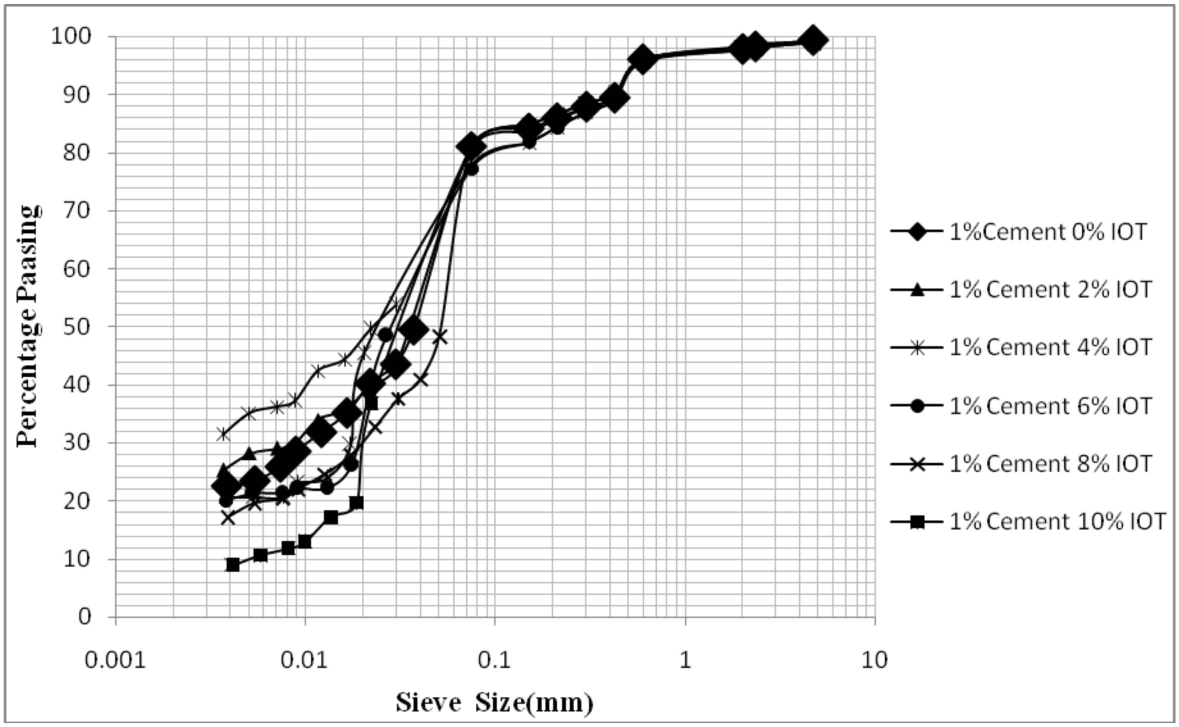

Fig. 4.4b: Particle size distribution curves for black cotton soil - 1 % cement – iron ore tailing mixtures.

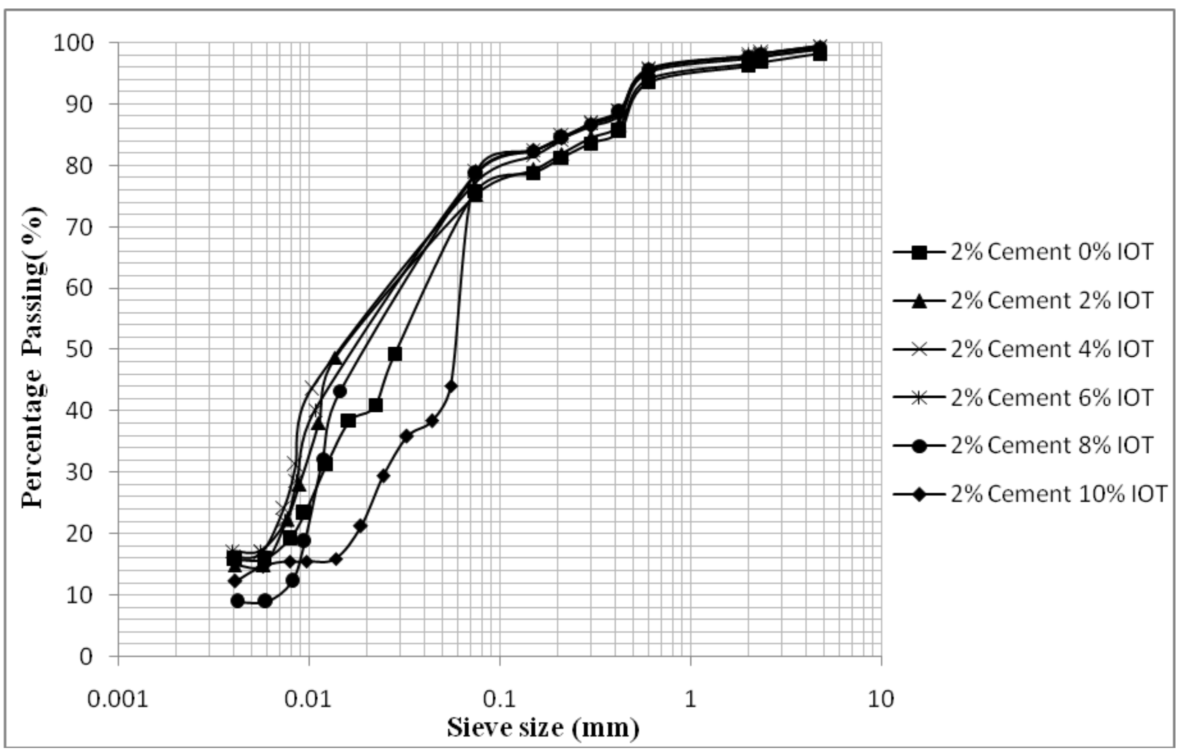

Fig. 4.4c: Particle size distribution curves for black cotton soil - 2 % cement – iron ore tailing mixtures

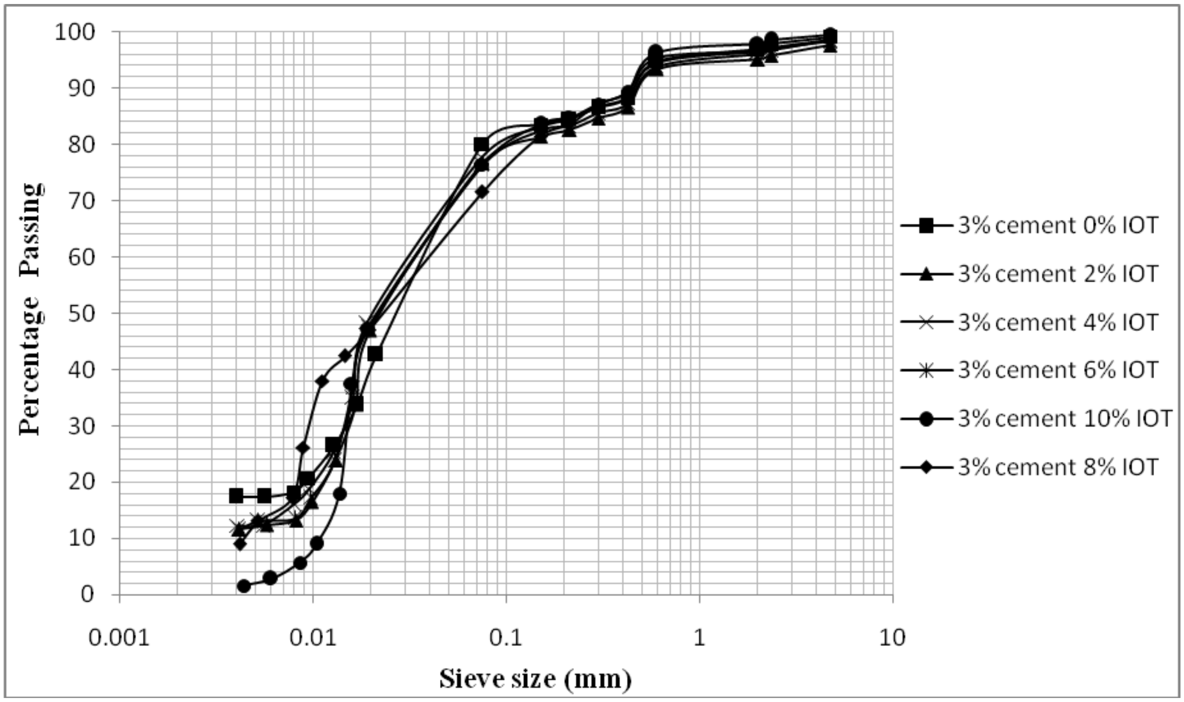

Fig. 4.4d: Particle size distribution curves for black cotton soil - 3 % cement – iron ore tailing mixtures.

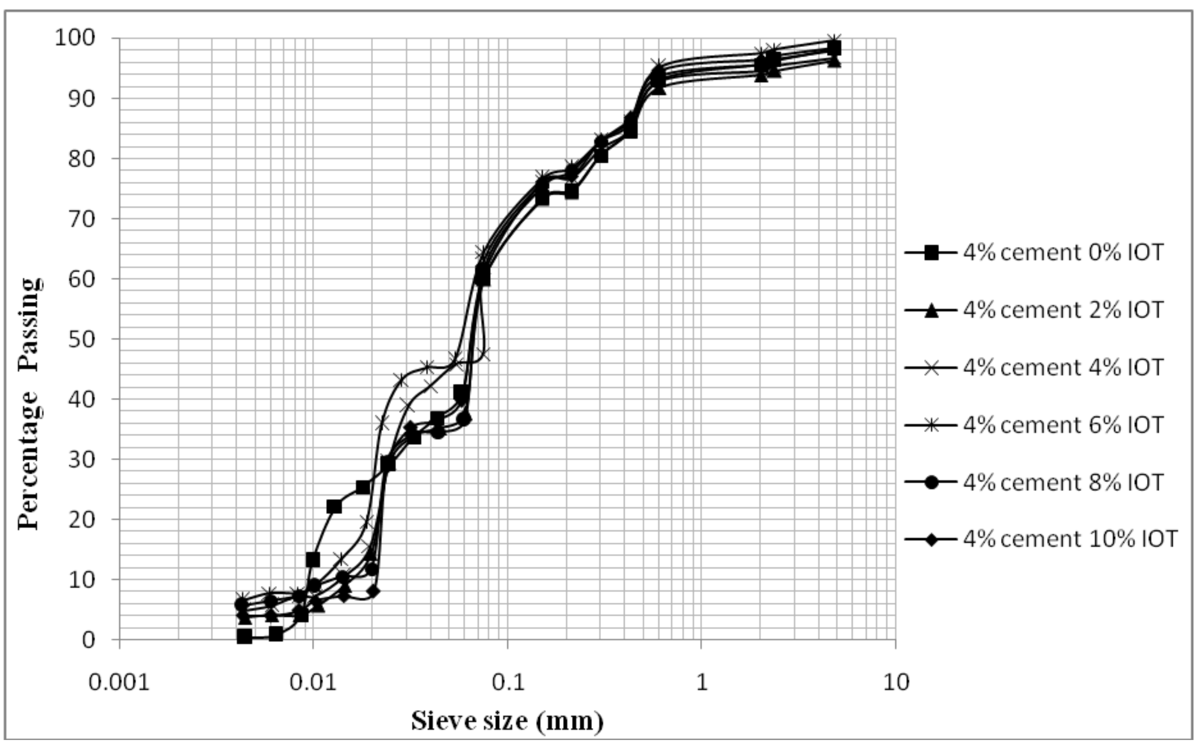

Fig. 4.4e: Particle size distribution curves for black cotton soil - 4 % cement – iron ore tailing mixtures.

4.2.3.2 *Dry sieving*

4.2.3.2a Using optimum moisture content from British Standard light compaction.

The particle size distribution curves for the admixture modified black cotton soil for BSL compaction is shown in Fig.4.5a - e. It was observed that the high moulding moisture content 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). An initial reduction of fines at 4% IOT was observed. For all cement contents considered, incremental change in sizes with higher percentages of admixtures can also be noticed in the coarse sizes (see Fig. 4.5a - e). 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 modified soil became more flocculated and agglomerated, resulting in coarser particles to form pseudo silt to sand sizes (Osula, 1991; Obeahon, 1993 ; Amadi, 2010a; Sarkar *et.al*., 2012; Al karagooly, 2012; Portelinha *et al*., 2012).

Test results generally indicate that the introduction of cement and IOT improved the gradation characteristics of the lateritic soil by reducing the amount of clay size particles through their flocculation and agglomeration. With increase in cement and IOT contents, the quantity of free silt and clay progressively reduced and coarser material was formed (see Fig. 4.5a - e) in agreement with the findings reported by Kedzi (1979) and Amadi (2010a). The increase in the coarser particle could be due to high moisture content available for pozzolanic reaction and hydration of free lime and silica in the additives. Detailed test results are shown in Tables A4.7(b) in the Appendix.

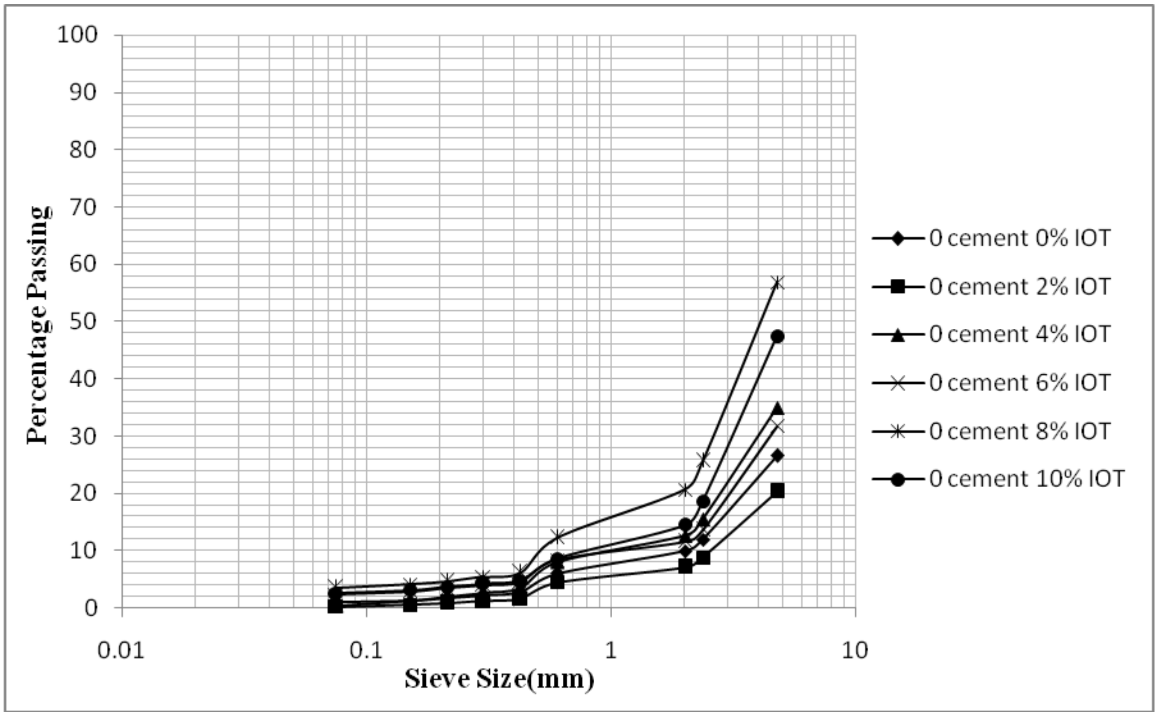

Fig 4.5a: Particle size distribution curves for black cotton soil - 0 % cement - iron ore tailing mixtures (BSL compaction).

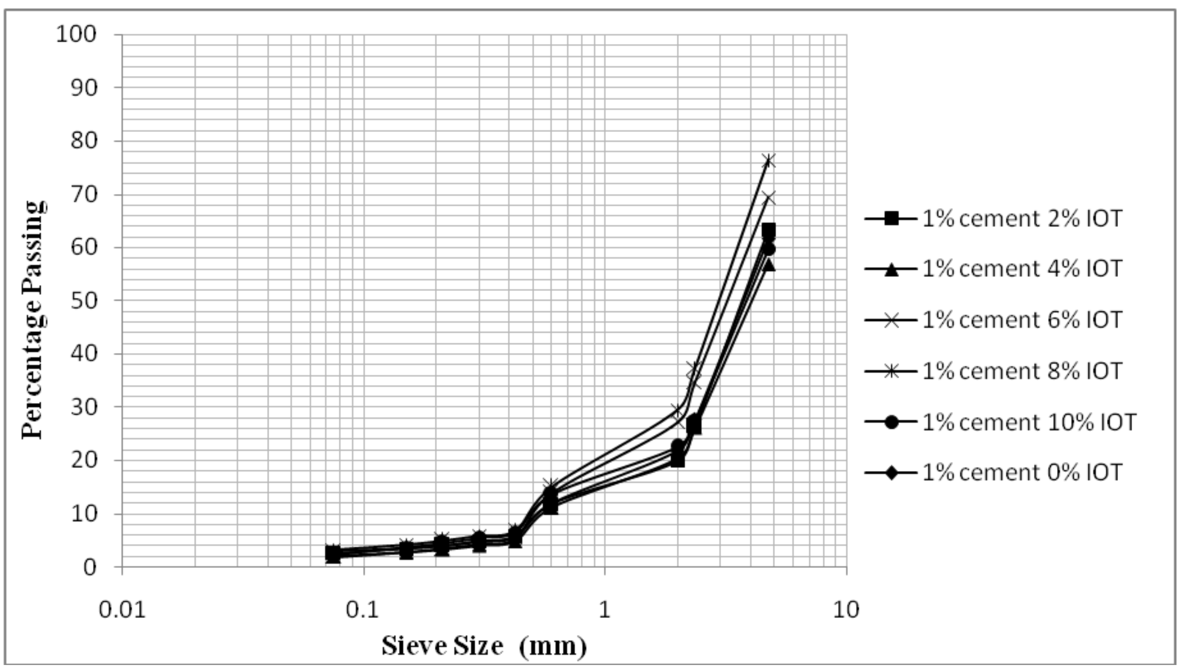

Fig. 4.5b: Particle size distribution curves for black cotton soil – 1 % cement – iron ore tailing mixtures (BSL compaction)

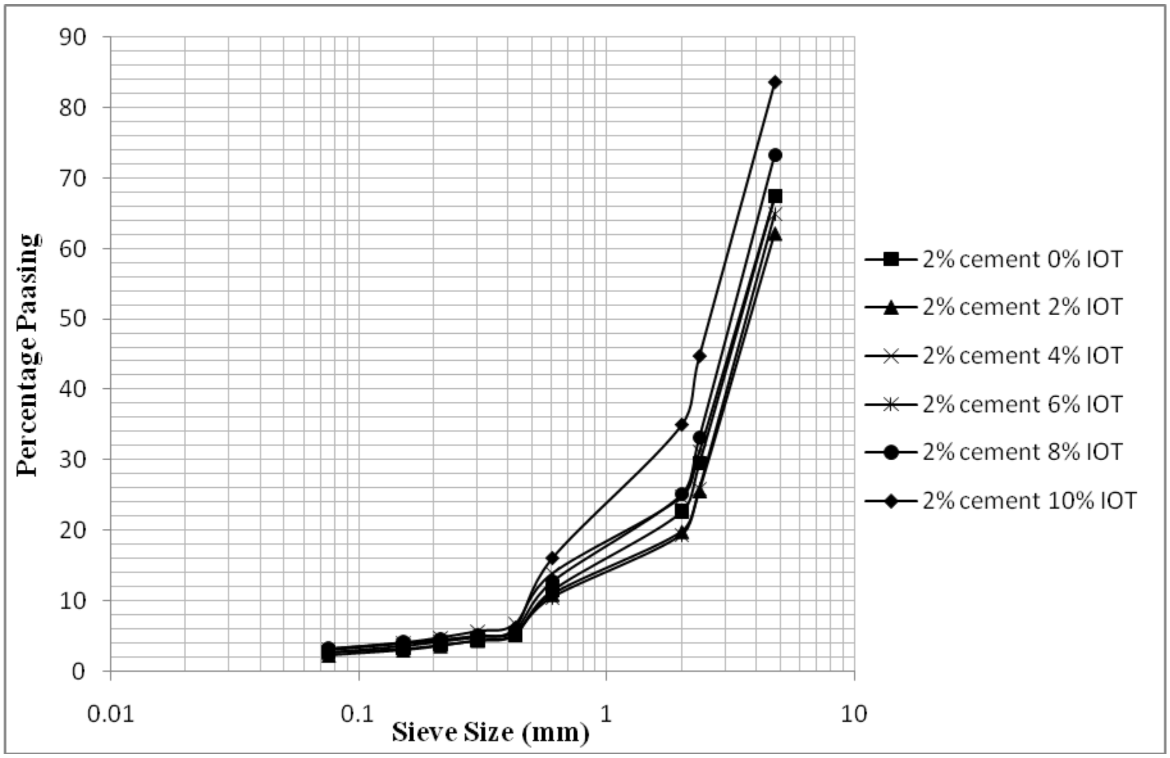

Fig 4.5c: Particle size distribution curves for black cotton soil – 2 % cement – iron ore tailing mixtures (BSL compaction).

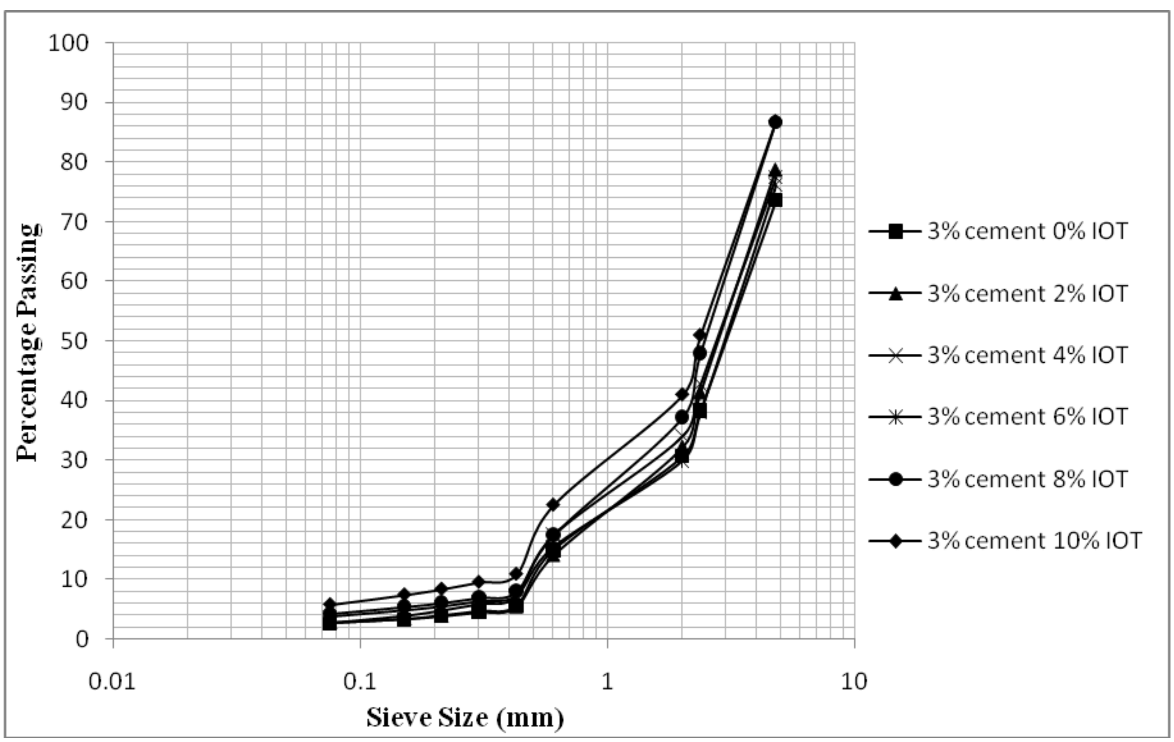

Fig 4.5d: Particle size distribution curves for black cotton soil – 3 % cement – iron ore tailing mixtures (BSL compaction).

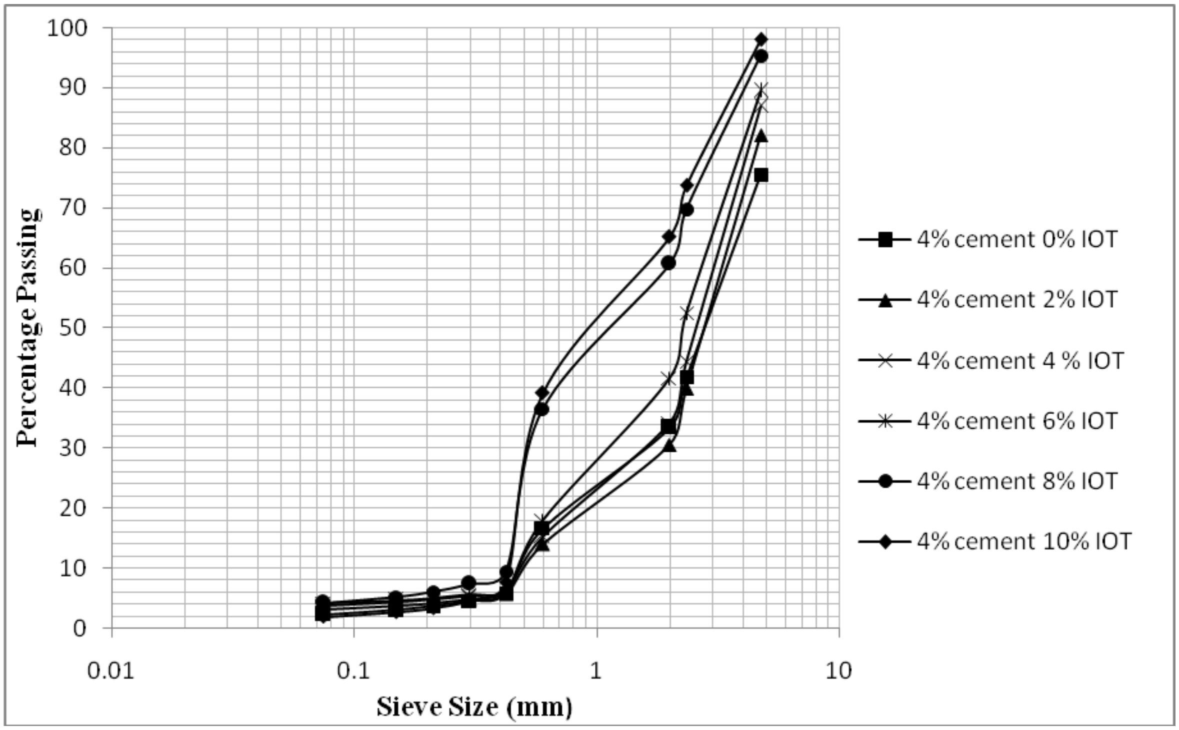

Fig 4.5e: Particle size distribution curves for black cotton soil – 4 % cement – iron ore tailing mixtures (BSL compaction).

4.2.3.2b Using optimum moisture content from West African Standard compaction.

The particle size distribution curve for the modified soil for WAS compaction is shown in Figs. 4.6a – e. It was observed that the available moulding moisture content facilitated the agglomeration of the soil particles to form macro structural particles. The moulding moisture content decreased with this higher compactive effort (when compared with BSL compaction).

An initial decrease in fines content was observed with up to 4 % IOT content (see Fig. 4.6a - e) and thereafter increased for the IOT contents considered with respect to the cement treatments considered. This could be due to excess IOT that did not take part in the agglomeration of the soil particle but only influenced the flocculation of the soil particles. 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(Winterkorn,*et.al,* 1951; Clare and O'Reilly,1960; Osula,1991;Obeahon, 1993; Al karagooly, 2012; Portelinha *et al.,*2012). Incremental change in coarse fraction sizes with higher percentages of admixtures was also observed, With increase in cement and IOT, the quantity of free silt and clay progressively reduced and coarser material was formed in agreement with the findings reported by Kedzi (1979). Also, the increase in the courser particles could be due to high moisture content available for pozzolanic reaction and hydration of free lime and silica in the additives (Osula, 1991; Obeahon, 1993). Detailed test results are shown in Tables A4.7(c) in the Appendix.

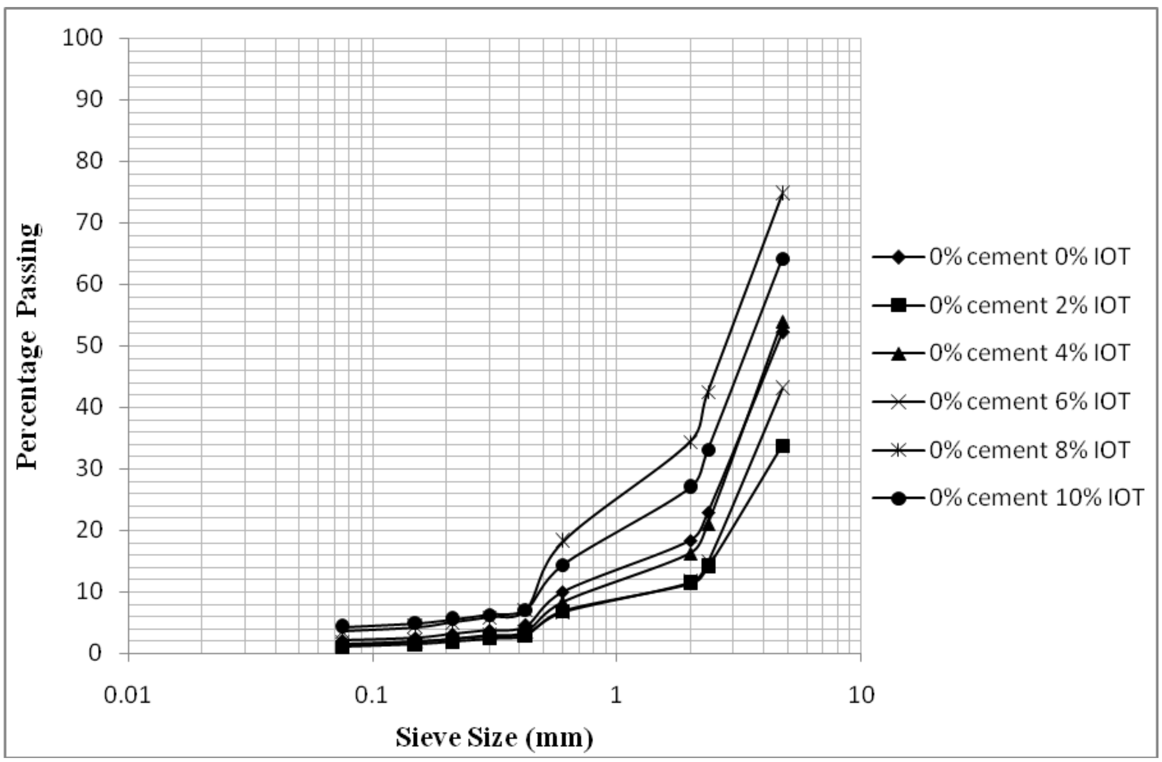

Fig. 4.6a: Particle size distribution curves for black cotton soil – 0 % cement – iron ore tailing mixtures (WAS compaction)

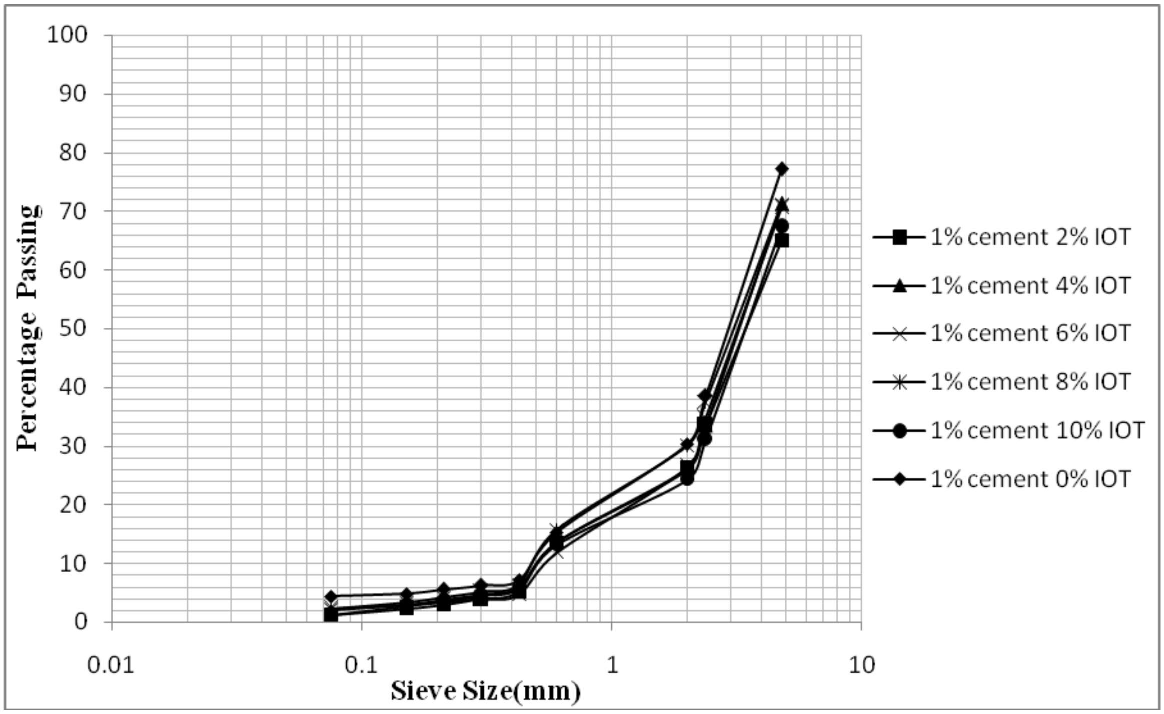

Fig. 4.6b: Particle size distribution curves for black cotton soil – 1 % cement – iron ore tailing mixtures (WAS compaction)

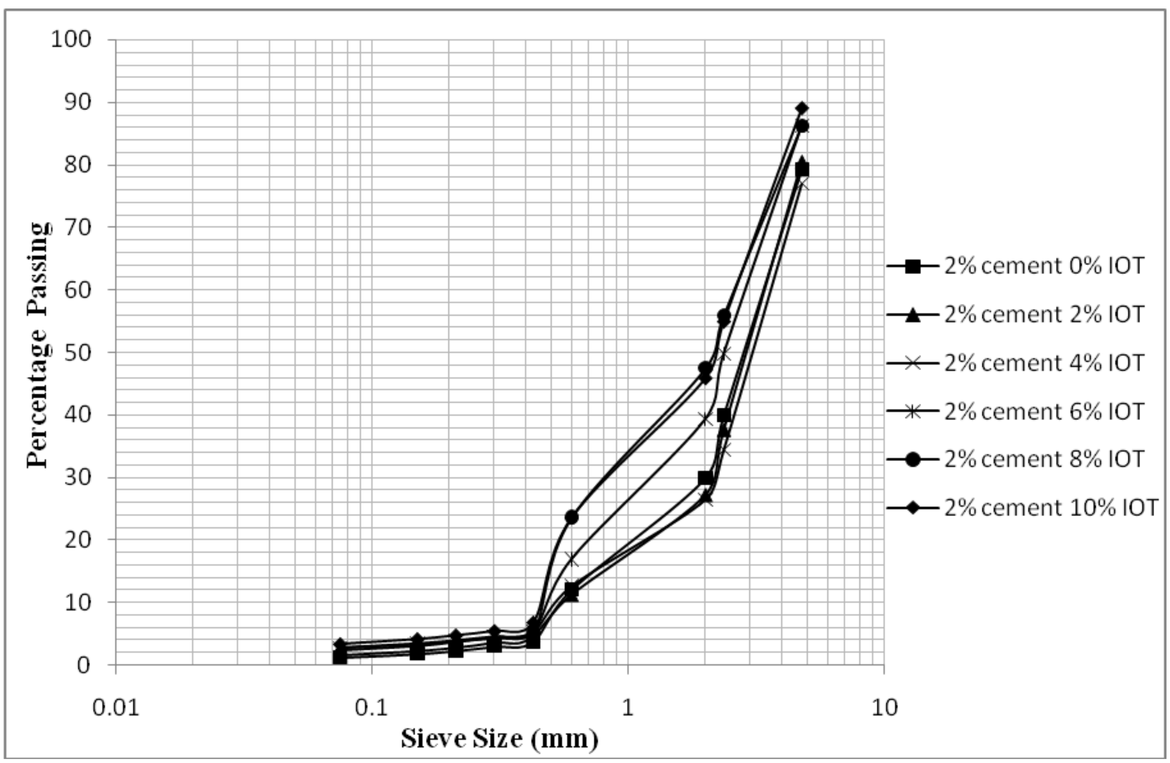

Fig. 4.6c: Particle size distribution curves for black cotton soil – 2 % cement – iron ore tailing mixtures (WAS compaction)

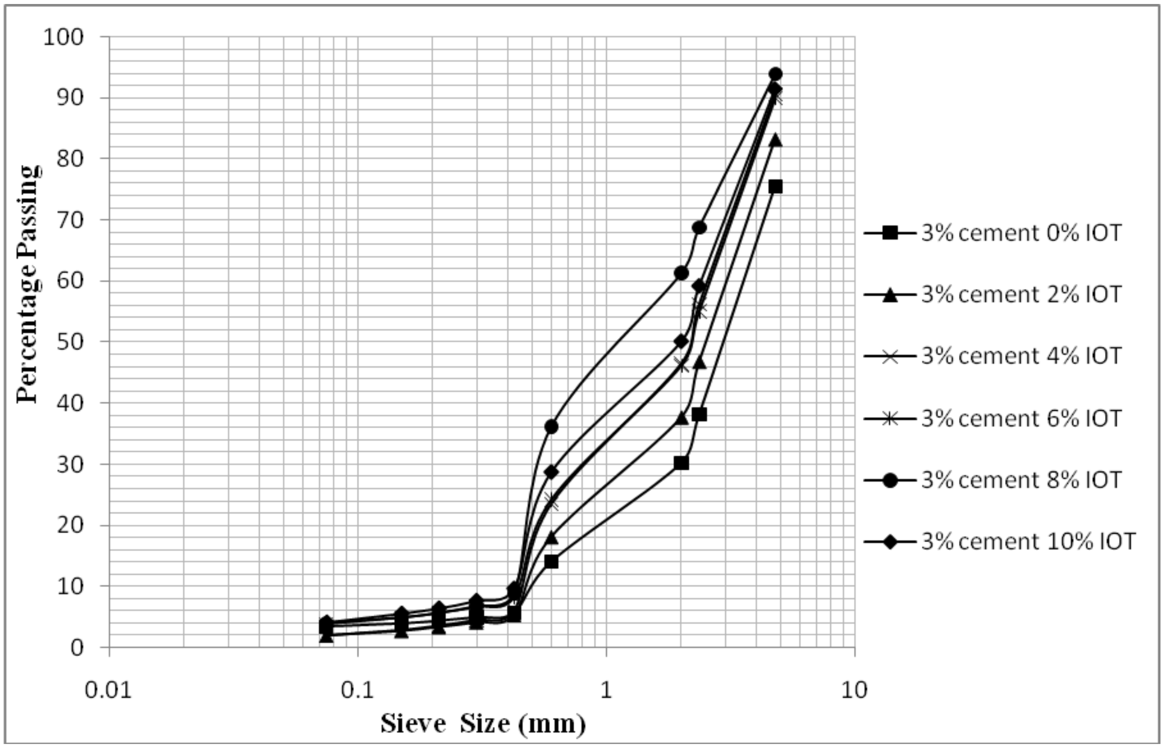

Fig. 4.6d: Particle size distribution curves for black cotton soil – 3 % cement – iron ore tailing mixtures (WAS compaction).

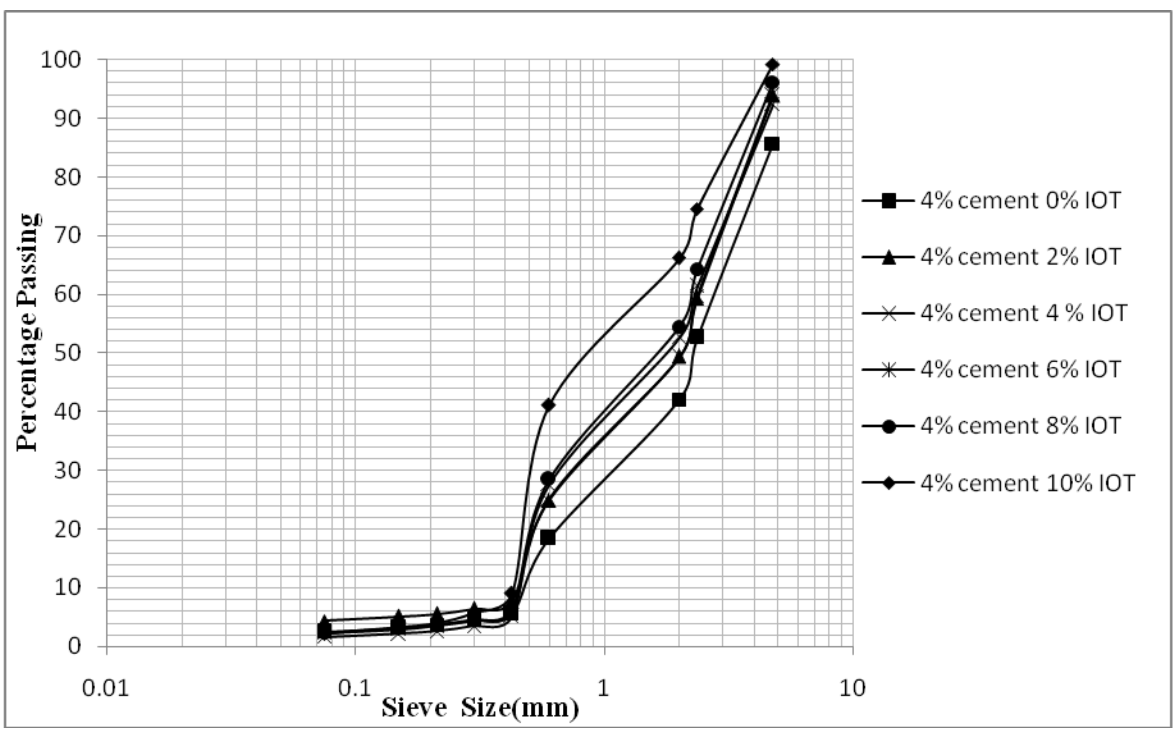

Fig. 4.6e: Particle size distribution curves for black cotton soil – 4 % cement – iron ore tailing mixtures (WAS compaction).

4.2.3.2c Using optimum moisture content from british standard heavy compaction

The particle size distribution curve for the modified soil for BSH compaction is shown in Fig. 4.7a – e. It was observed that the available moulding moisture content facilitated the agglomeration of the soil particles to form macro structural particles. The moulding moisture content decreased with this higher compactive effort (when compared with WAS compaction) such that the agglomeration of the soil particle decreased with increase in the percentage of the additives.

An initial reduction in the percentage of fines with up to 4 % IOT content (see Fig. 4.7a – e) but thereafter an increase was observed for all the cement contents considered. This could be due to excess IOT that flocculated the soil particles but did not take part in their agglomeration. The initial reduction in the fines content may be due to pozzolanic reaction and hydration accompanying that resulted in the formation of coarser particles. The results are consistent with the findings reported by Winterkorn et.al. (1951), Clare and O'Reilly (1960), Osula (1991), Obeahon (1993), Amadi (2010a) and Al karagooly (2012). Detailed test results are shown in Tables A4.7(d) in the Appendix.

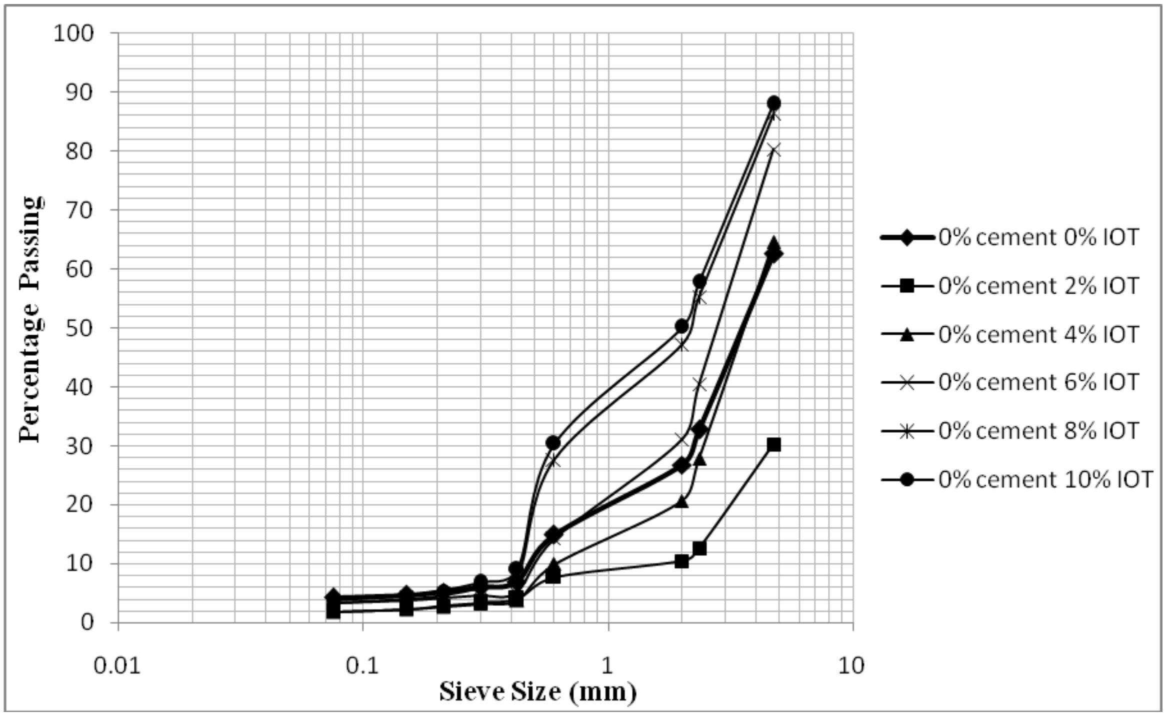

Fig. 4.7a: Particle size distribution curves for black cotton soil – 0 % cement – iron ore tailing mixtures (BSH compaction)

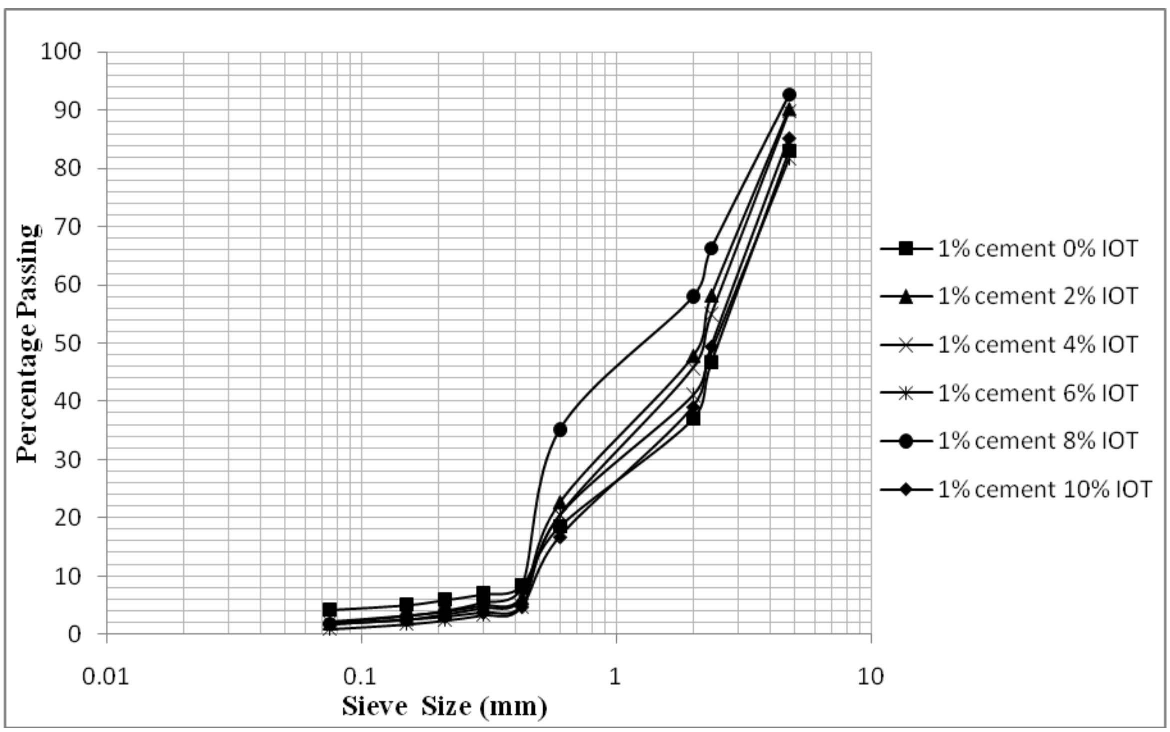

Fig. 4.7b: Particle size distribution curves for black cotton soil – 1 % cement – iron ore tailing mixtures (BSH compaction)

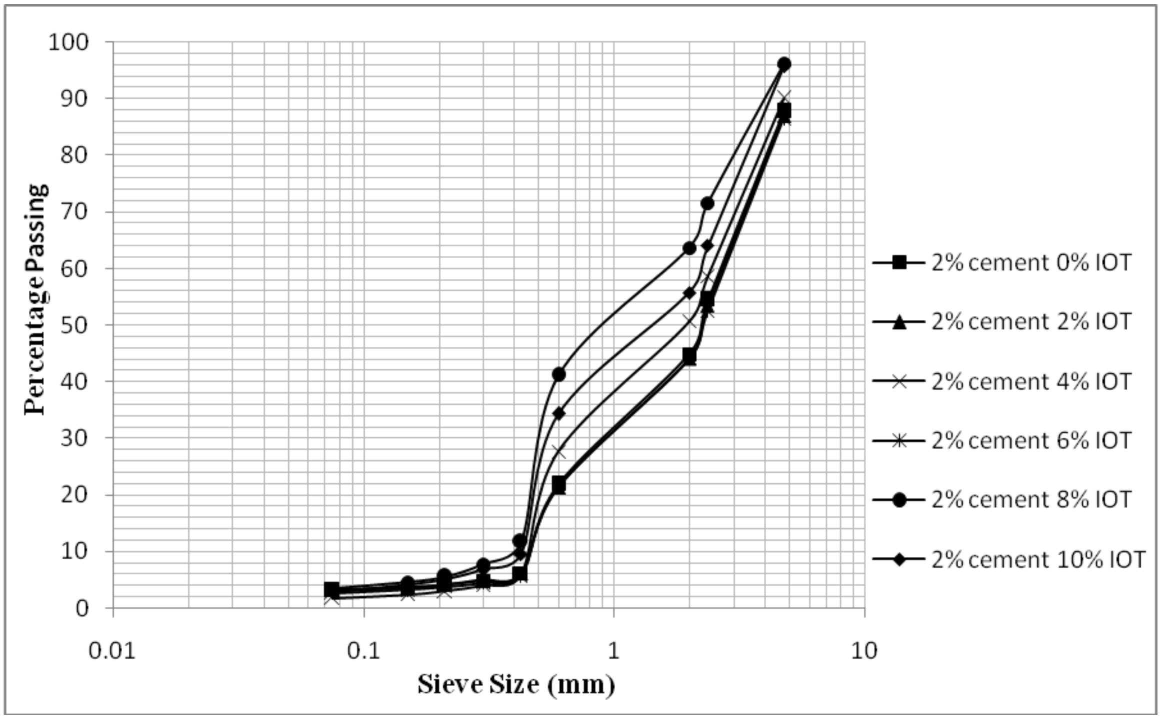

Fig. 4.7c: Particle size distribution curves for black cotton soil – 2 % cement – iron ore tailing mixtures (BSH compaction)

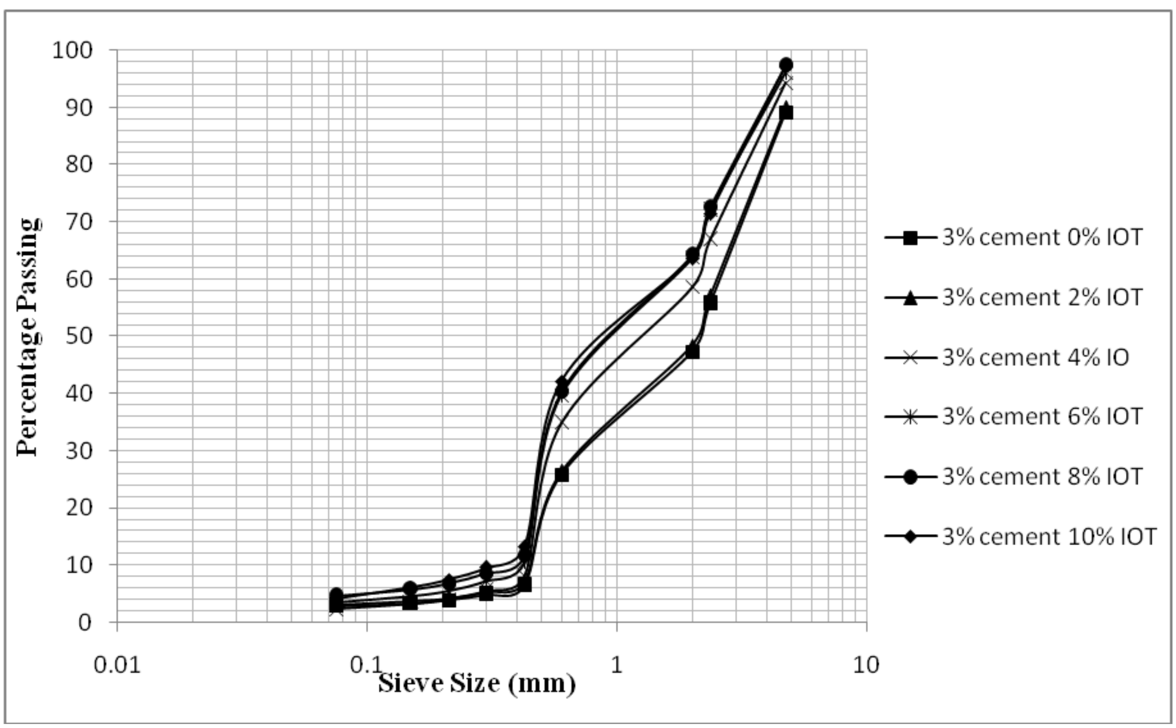

Fig. 4.7d: Particle size distribution curves for black cotton soil – 3 % cement – iron ore tailing mixtures (BSH compaction)

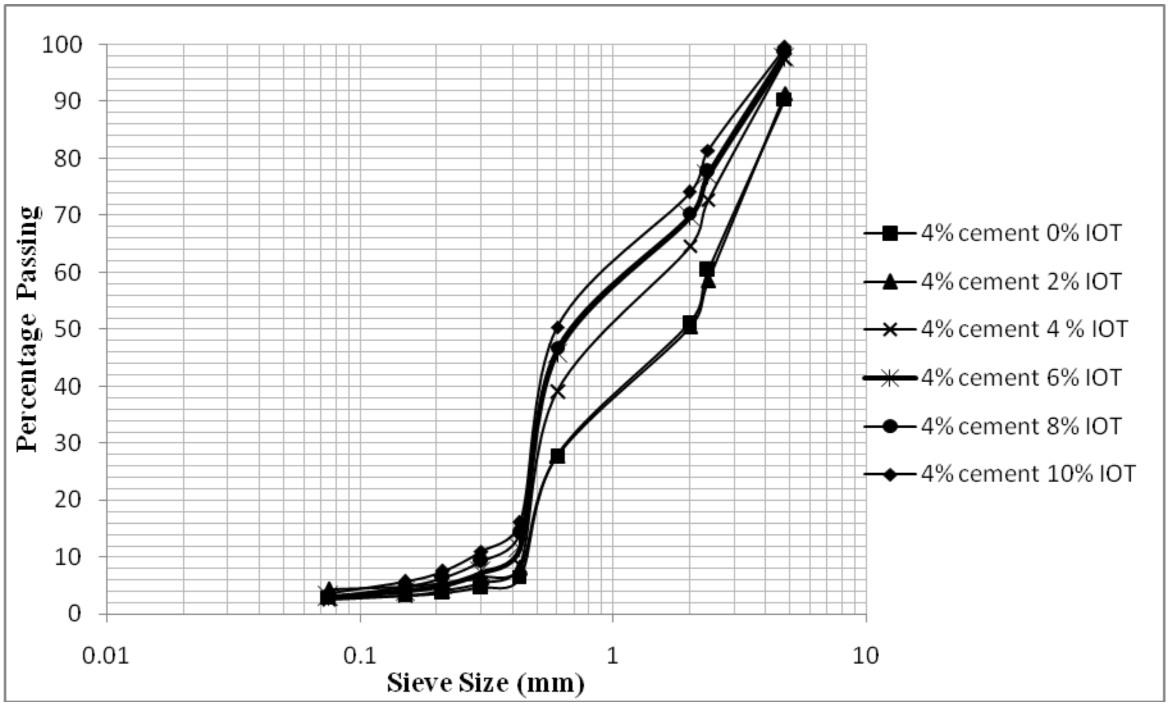

Fig. 4.7e: Particle size distribution curves for black cotton soil – 4 % cement – iron ore tailing mixtures (BSH compaction)

4.2.4 Atterberg limits

4.2.4.1 Liquid limit

The variation of liquid limit of black cotton soil - cement mixtures with iron ore tailing content is shown in Fig.4.8a. It was observed that the liquid limit decreased with increase in the contents of additives. Similar behaviour was reported by Zaman *et al*. (1992), Al-Refeai, *et al*.(1998),Phanikumar *et al*.(2004),Brooks *et al*.(2011) and Alkaragooly (2012). The decrease may be due to flocculation and agglomeration arising from cation exchange reactions whereby Ca^{+} in the additives reacted with ions of lower valence in the clay structure. The observed reduction in liquid limit value is in agreement with the findings reported by Obeahon (1993), Osinubi and Umar (2003), Osinubi and Alhassan (2008), Al-Zoubi (2008) and Ramesh *et al*. (2013). The addition of cement and IOT 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. Detailed test results are shown in Tables A4.8(a) in the Appendix.

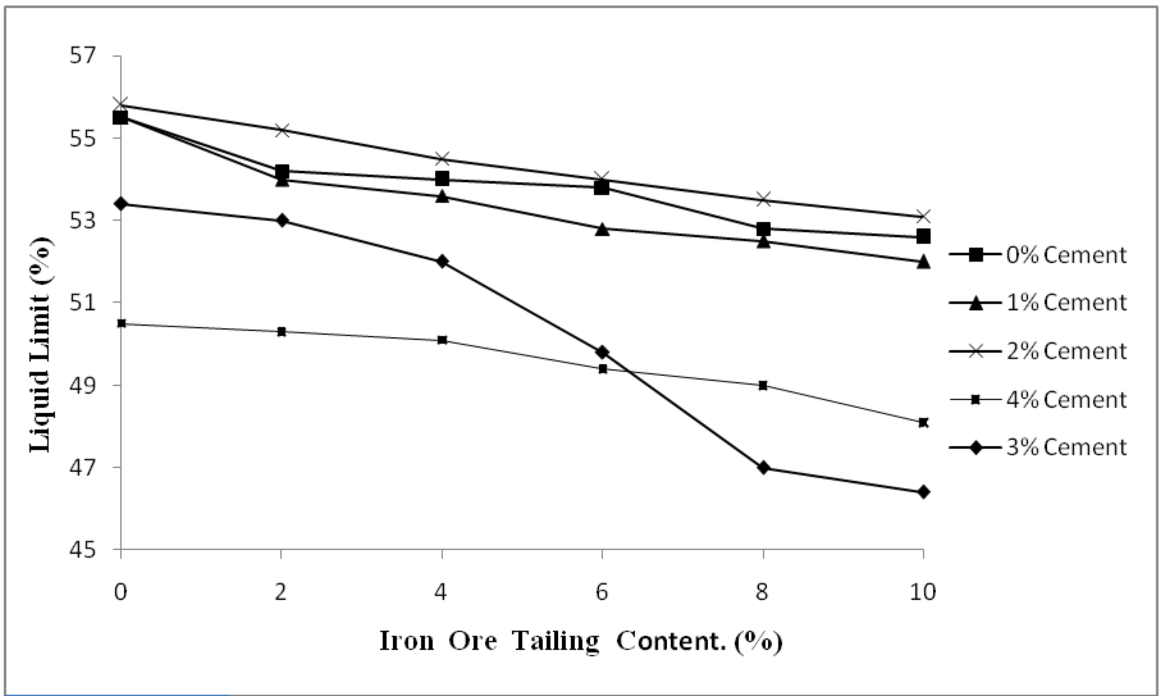

Fig.4.8a: Variation of liquid limit of black cotton soil – cement mixtures with iron ore tailing content.

The two – way analysis of variance (ANOVA) test on the liquid limit result is given in Table 4.6. The result shows that the effects of cement and IOT on black cotton soil were statistically significant for cement (F_{CAL} = 31.914> F_{CRIT} = 2.866) for cement and IOT (F_{CAL} = 11.419> F_{CRIT} =2.711) with cement having a more pronounced effect than IOT. Detailed test results are shown in Tables A4.17(a) in the Appendix.

Table 4.6 Two-way analysis of variance results for liquid limit results of black cotton soil – cement – iron ore tailing mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Liquid Limit	Cement	4	31.914	2.01E-08	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	11.419	2.62E-05	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.4.2. Plastic limit

The variation of plastic limit of black cotton soil - cement mixtures with iron ore tailing content is shown in Fig. 4.8b. The plastic limit of the natural soil reduced from 25 % for the natural soil to 18.2 % at 0 % cement / 10 % IOT. The non-plastic nature of IOT led to the reduction in plastic limit. The observed decrease of plastic limit may be due to cation exchange reaction that liberated adsorbed water particles in the soil leading to the flocculation and aggregation of the soil (Osinubi, 1995). The results recorded are in agreement with the findings reported by Amadi,(2010a) and Ramesh *et al.* (2013). Detailed test results are shown in Tables A4.8(b) in the Appendix.

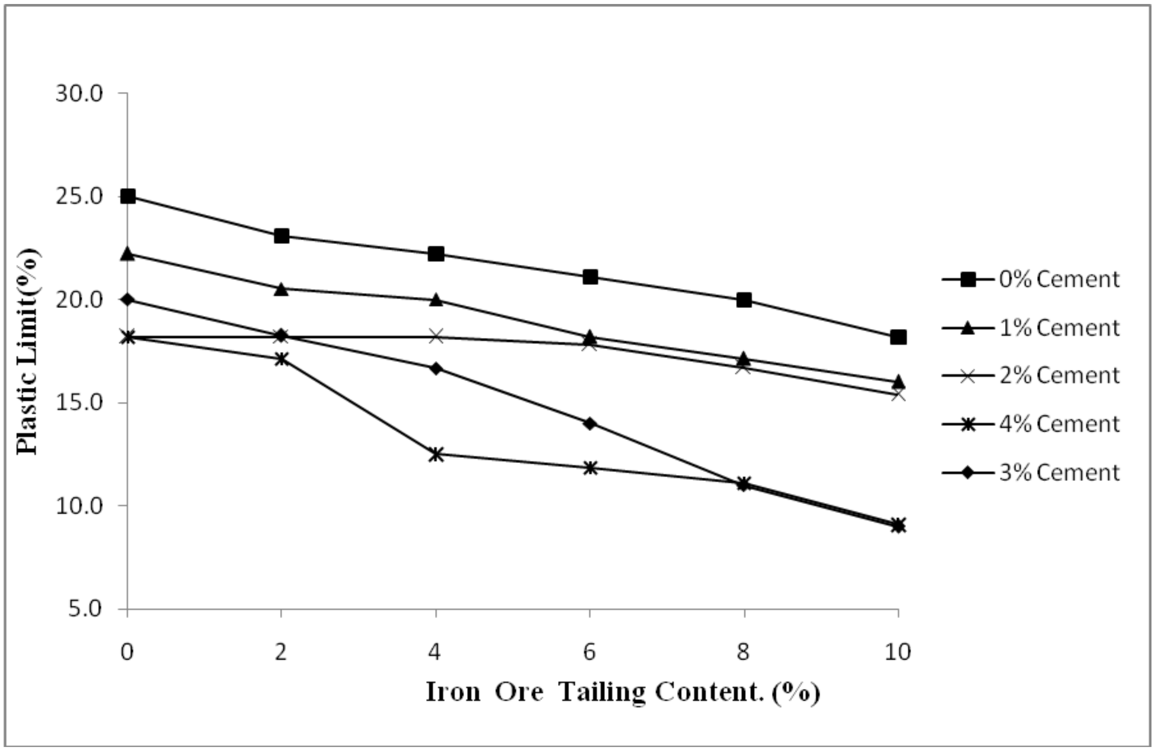

Fig.4.8b: Variation of plastic limit of black cotton soil – cement mixtures with iron ore tailing content.

The results of the analysis of variance (ANOVA) of plastic limit (see Table 4.7) shows that the effects of cement and IOT on black cotton soil were statistically significant for cement (F_{CAL}= 34.133>F_{CRIT} = 2.866) and IOT (F_{CAL}= 18.726>F_{CRIT} = 2.711) with cement having a more pronounced effect than IOT. Detailed test results are shown in Tables A4.17(b) in the Appendix.

Table 4.7: Two-way analysis of variance for Plastic limit results of black cotton soil – cement – iron ore tailing mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Plastic Limit	Cement	4	34.133	1.13E-08	2.866	F_{CAL}>F_{CRIT}, Significanteffect
	IOT	5	18.726	6.23E-07	2.711	F_{CAL}>F_{CRIT}, Significant effect

4.2.4.3 Plasticity index

The variation of plastic limit of black cotton soil - cement mixtures with iron ore is shown in Fig 4.8c. The plasticity index value for the natural soil ranged from 31 to 34.4 %.

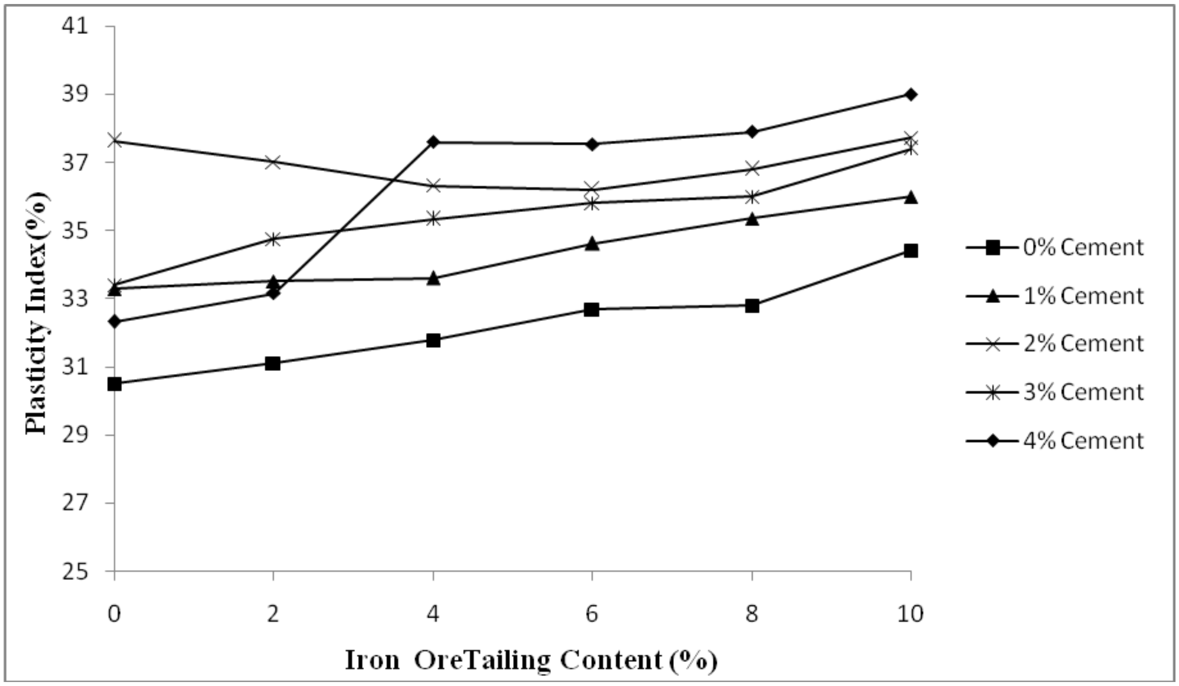

Fig.4.8c: Variation of plasticity Index of black cotton soil – cement mixtures with iron ore tailing content.

On treatment with 1, 2, 3 and 4 % cement / up to 10 % IOT content, it was observed that plasticity index (PI) increased from 33.3 to 36 %, 37.6 to 37.7 %, 33.4 to 37.4 % and 32.3 to 39 %, respectively, Detailed test results are shown in Tables A4.8(c) in the Appendix.

The analysis of variance (ANOVA) of plasticity index results (see Table 4.8) shows that the effects of cement (F_{CAL} = 16.064>F_{CRIT} = 2.866) and IOT (F_{CAL} = 6.318>F_{CRIT} = 2.711) on black cotton soil were statistically significant with the effect of cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.17(c) in the Appendix.

Table 4.8 Two-way analysis of variance for Plasticity index results of black cotton soil – cement – iron ore tailing mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Plasticity Index	Cement	4	16.064	4.899E-06	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
	IOT	5	6.318	0.0011344	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.4.4 Linear shrinkage

The variation of the linear shrinkage of black cotton soil – cement mixtues with iron ore tailing content is shown in Fig. 4.8d. It was observed that the linear shrinkage decreased from 16.3 % for the natural soil to 7.5 % at 10 % IOT content. On treatment with 1, 2, 3 and 4% cement / up to 10 % IOT content, the linear shrinkage progressively decreased. Detailed test results are shown in Tables A4.8(d) in the Appendix.

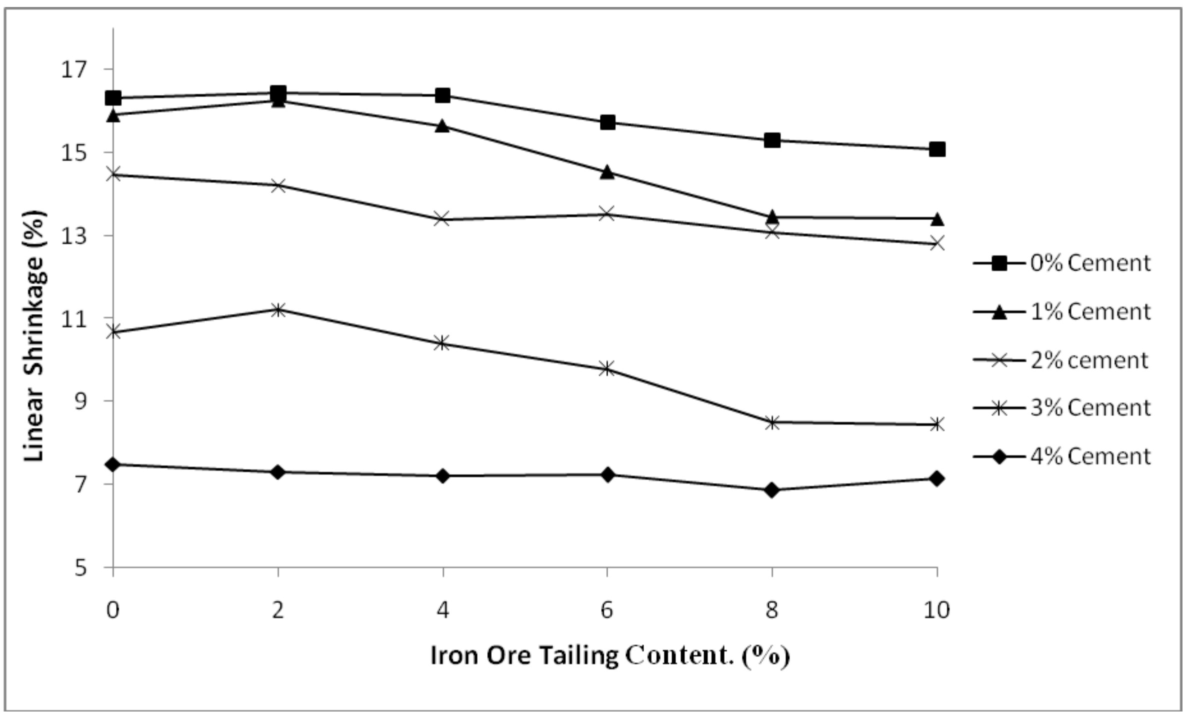

Fig. 4.8d: Variation of linear shrinkage of black cotton soil – cement mixtures with iron ore tailing content.

The analysis of variance (ANOVA) of linear shrinkage results (see Table 4.9) shows that the effects of cement (F_{CAL} = 340.945>F_{CRIT} = 2.866) and IOT (F_{CAL} = 11.905>F_{CRIT} = 2.711) on black cotton soil were statistically significant with the effect of cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.17(d) in the Appendix.

Table 4.9 Two-way analysis of variance for linear shrinkage results of black cotton soil – cement – iron ore tailing mixtures.

Property	Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Linear Shrinkage	Cement	4	340.945	4.32E-18	2.866	F_{CAL}>F_{CRIT}, Significant effect
	IOT	5	11.905	1.95E-05	2.711	F_{CAL}>F_{CRIT}, Significant effect

4.2.5 Compaction characteristics

4.2.5.1 Maximum dry density

The effect of IOT on the maximum dry density (MDD) of black cotton soil - cement mixture is shown in Fig. 4.9a-c for BSL, WAS and BSH compactions. It was observed that MDD increased with higher cement and IOT contents for the three energy levels considered. Similar results were reported by Phanikumar *et al*. (2004), Jadhao and Nagarnaik (2008) as well as Kumar and Puri (2013). The observed increase in MDD could be due to cement and IOT that occupied the void within the soil matrix and in addition, the flocculation and agglomeration of the clay particle due to exchange of ions. This is in agreement with the findings reported by Osinubi, (1999; 2000), Moses (2008), Oriola and Moses (2010; 2011), Amadi (2010a) as well as Osinubi and Oyelakin (2012). The increase in MDD could also be attributed to high specific gravity of the additives replacing the soil particles with lower specific gravity. Detailed test results are shown in Tables A4.9(a-c) in the Appendix.

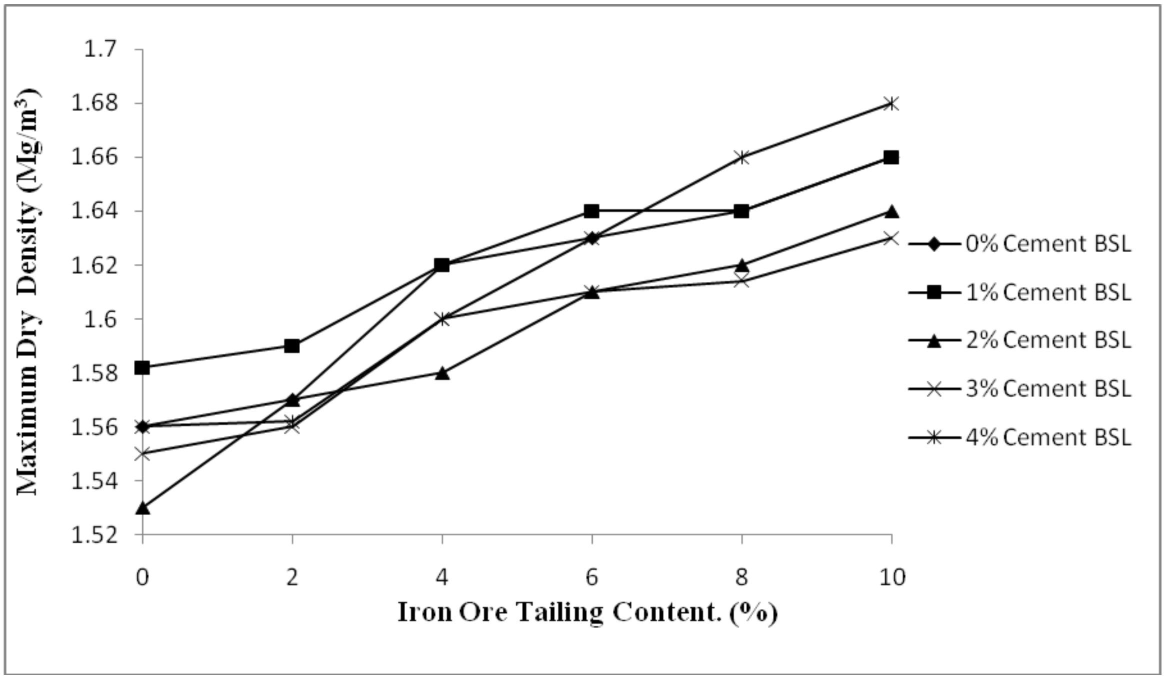

Fig. 4.9a: Variation of maximum dry density of black cotton soil – cement mixtures with iron ore tailing content (BSL compaction)

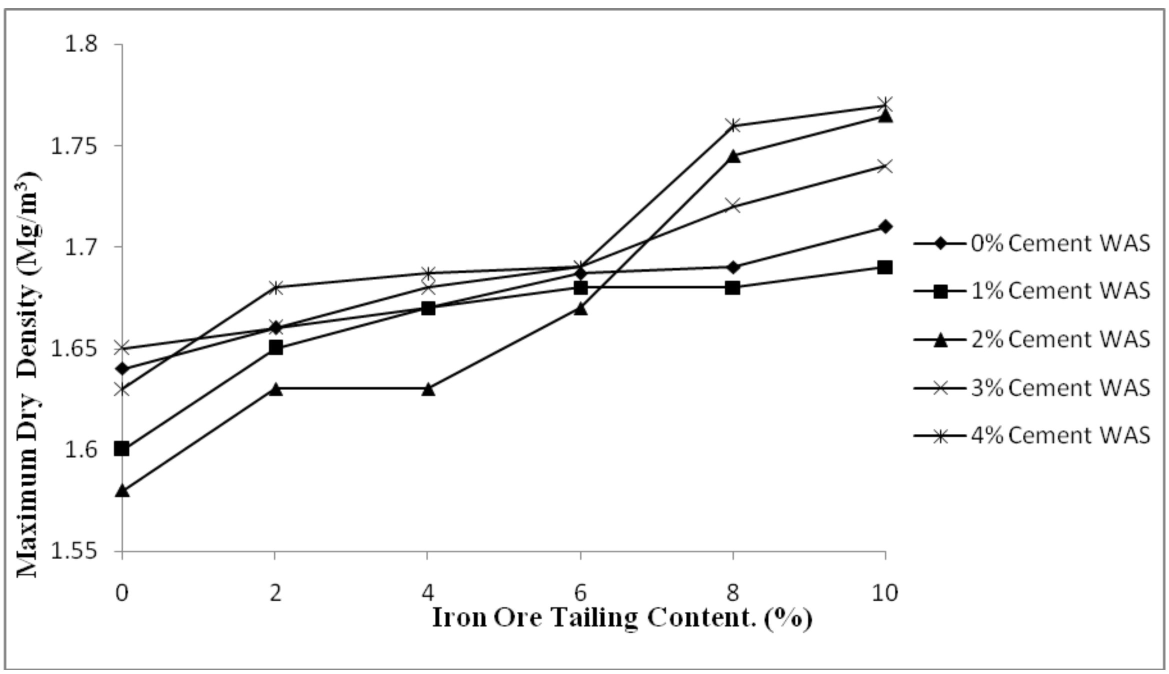

Fig. 4.9b: Variation of maximum dry density of black cotton soil – cement mixtures with iron ore tailing content (WAS compaction)

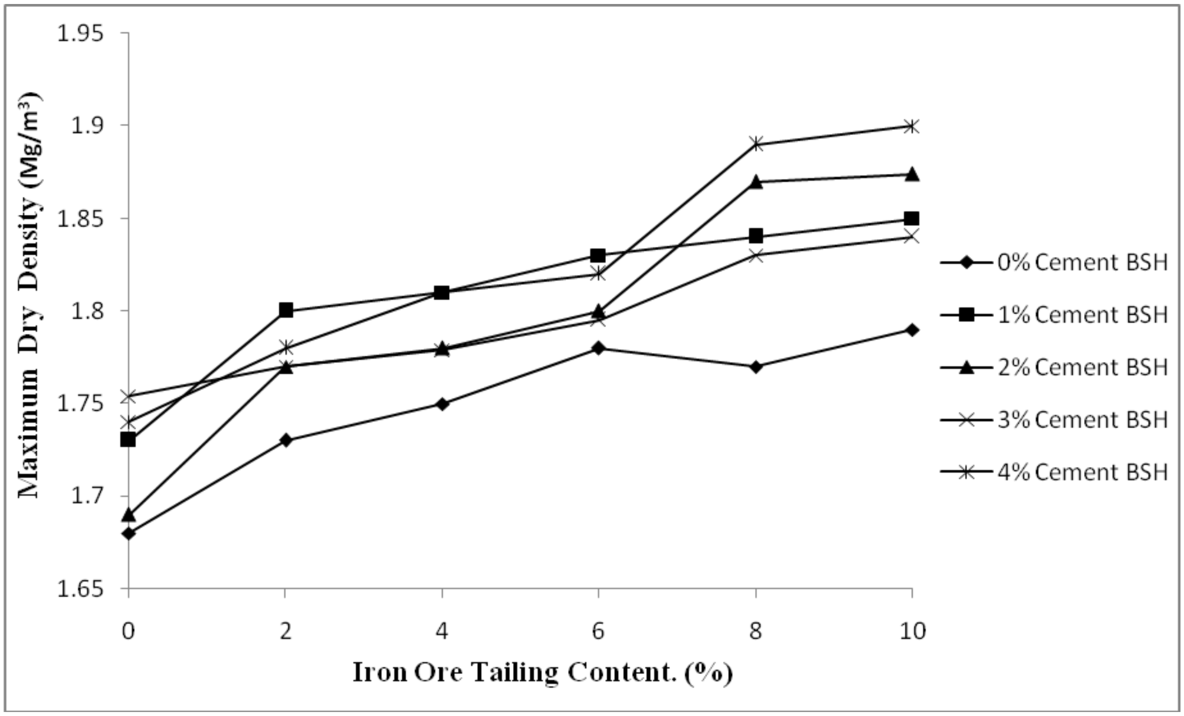

Fig. 4.9c: Variation of maximum dry density of black cotton soil – cement mixtures with iron ore tailing content (BSH compaction)

The two – way analysis of variance (ANOVA) test on MDD results for the three compactive efforts considered is given in Table 4.10. The analysis shows that the cement (F_{CAL} = 9.829> F_{CRIT} = 2.866) and IOT (F_{CAL} = 63.722> F_{CRIT} = 2.711) significantly affected MDD values of the modified soil. However, the effect of IOT on the MDD of black cotton soil was much more significant for BSL compaction. Detailed test results are shown in Tables A4.18(a) in the Appendix.

Table 4.10: Two-way analysis of variance for maximum dry density of black cotton soil-cement-IOT mixtures.

Property		Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
BSL	MDD	Cement	4	9.829	1.45E-04	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	63.722	1.35E-11	2.711	F_{CAL}>F_{CRIT}, Significant effect
WAS	MDD	Cement	4	3.199	3.49E-02	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	17.689	9.81E-07	2.711	F_{CAL}>F_{CRIT}, Significant effect
BSH	MDD	Cement	4	11.908	4.11E-05	2.866	F_{CAL}>FCRIT, Significant effect
		IOT	5	30.514	1.05E-08	2.711	F_{CAL}>F_{CRIT}, Significant effect

The analysis shows that the cement (F_{CAL} = 3.199> F_{CRIT} = 2.866) and IOT (F_{CAL} = 17.689>F_{CRIT} =2.711) significantly affected MDD values of the modified soil when subjected to WAS compaction. However, the effect of IOT on the MDD of black cotton soil was much more significant for WAS compaction. Detailed test results are shown in Tables A4.18(b) in the Appendix.

The analysis shows that the cement (F_{CAL} = 11.908> F_{CRIT} = 2.866) and IOT (F_{CAL} = 30.514> F_{CRIT} = 2.711) significantly affected MDD values of the modified soil when subjected to BSH compaction. However, the effect of IOT on the MDD of black cotton soil was much more significant for BSH compaction. Detailed test results are shown in Tables A4.18(c) in the Appendix.

4.2.5.1a Regression analysis for maximum dry density

Results of regression analysis showed that the maximum dry density was influenced by the grading properties, specific gravity and compactive effort applied. This agrees with previous statements by Gidigasu (1976) who stated that the behaviour of soil used in pavement structure has been found to depend mainly on their particle size characteristics, the nature and strength of the particles and the degree to which the soils have been compacted. The geotechnical properties considered for this analysis include the cement content, iron ore tailing content, sand, silt and clay alongside their respective specific gravities using compactive effort as a deterministic parameter with compactive effort index values of –1, 0 and 1 for British Standard light, West African Standard and British Standard Heavy compactive efforts respectively. The regression equations (see equation 4.1) revealed the extent to which these parameters influences the maximum dry density which is a function of the coefficient of each parameter. The specific gravity and compactive effort has the most significant effect on the maximum dry density having higher coefficient than the others parameters. 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 correlation coefficient values (R^2) shows a strong relationship between maximum dry density and the parameters with R^2 value of 92.2%.

The regression equations is

$$\mathrm{MDD} = 0.622 + 0.00330\mathrm{C} + 0.00779\ \mathrm{IOT} + 0.00011\ \mathrm{Cl} + 0.00100\mathrm{Si} + 0.00024\mathrm{Sa} + 0.384\ \mathrm{Gs} + 0.0939\ \mathrm{CE} \qquad (4.1)$$

R^2= 92.2%

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

The two – way analysis of variance (ANOVA) test for MDD is given in Table 4.11. The analysis shows that the IOT (F_{CAL} = 12.152> F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 585.984> F_{CRIT} = 3.156) significantly affected MDD values of the modified soil. However, the effect of Compactive effort on the MDD of black cotton soil was much more significant.

Table 4.11: Two-way analysis of variance for regression analysis on maximum dry density of black cotton soil-cement-IOT mixtures

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
MDD	IOT	29	12.152	1.41E-15	1.663	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	585.984	3.41E-39	3.156	F_{CAL}>F_{CRIT}, Significant effect

4.2.5.2 Optimum moisture content

The variation of optimum moisture content (OMC) of black cotton soil - cement mixture with iron ore tailing for BSL, WAS and BSH compactions is shown in Fig. 4.10 a-c. It was observed that the OMC decreased with higher cement and IOT contents for all the compactive efforts considered. This was probably due to self - desiccation of the mixture during which all the water was used, resulting in low hydration. When no water movement to or from soil-IOT-cement matrix is permitted, the water is used up in the hydration until too little is left to saturate the solid surfaces and hence the relative humidity within the paste decreases (Osinubi, 2001; Moses *et.al.,* 2012). The process described above might have affected the reaction mechanism of cement-IOT treated black cotton soil. This is in conformity with the findings of Osinubi and Stephen (2007), Moses (2008), Oriola and Moses (2010; 2011) as well as Kumar and Puri (2013). Detailed test results are shown in Tables A4.10(a-c) in the Appendix.

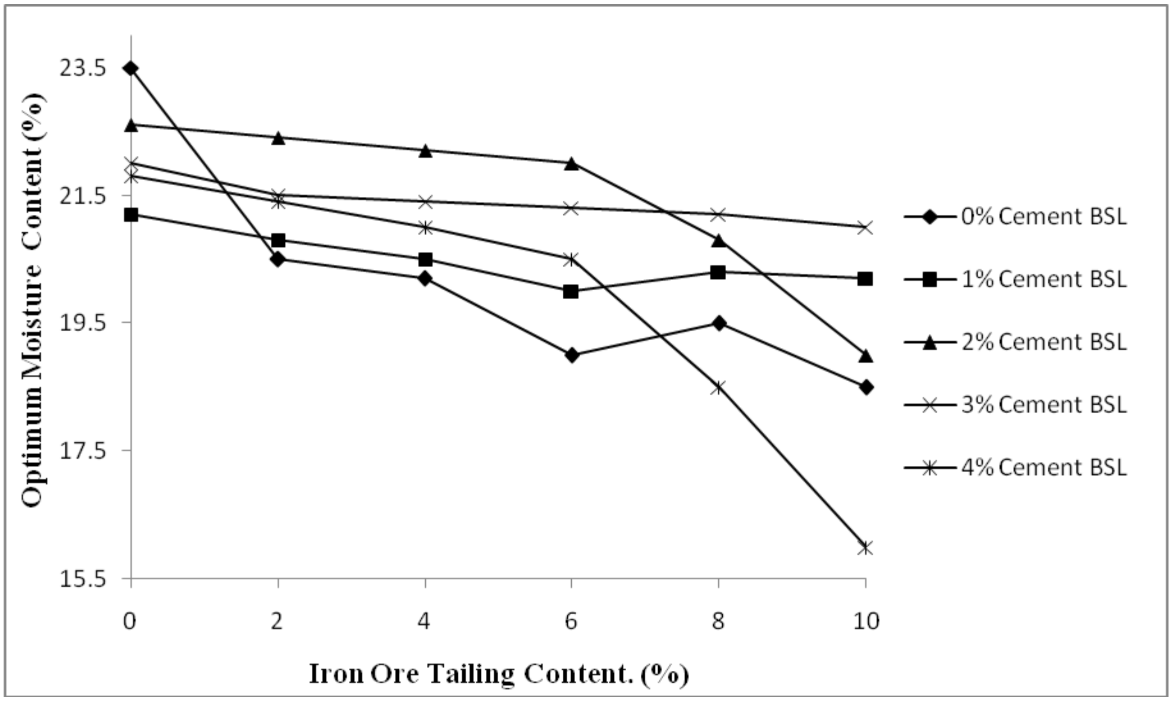

Fig.4.10a: Variation of optimum moisture content of black cotton soil – cement mixtures with iron ore tailing content (BSL compaction)

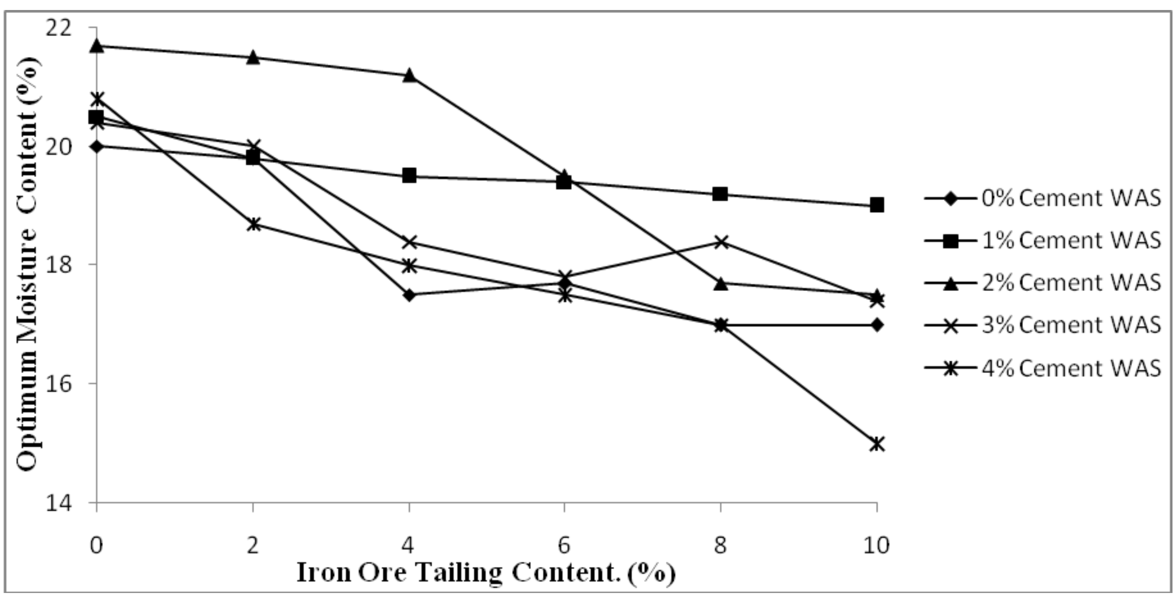

Fig. 4.10b: Variation of optimum moisture content of black cotton soil – cement mixtures with iron ore tailing content (WAS compaction)

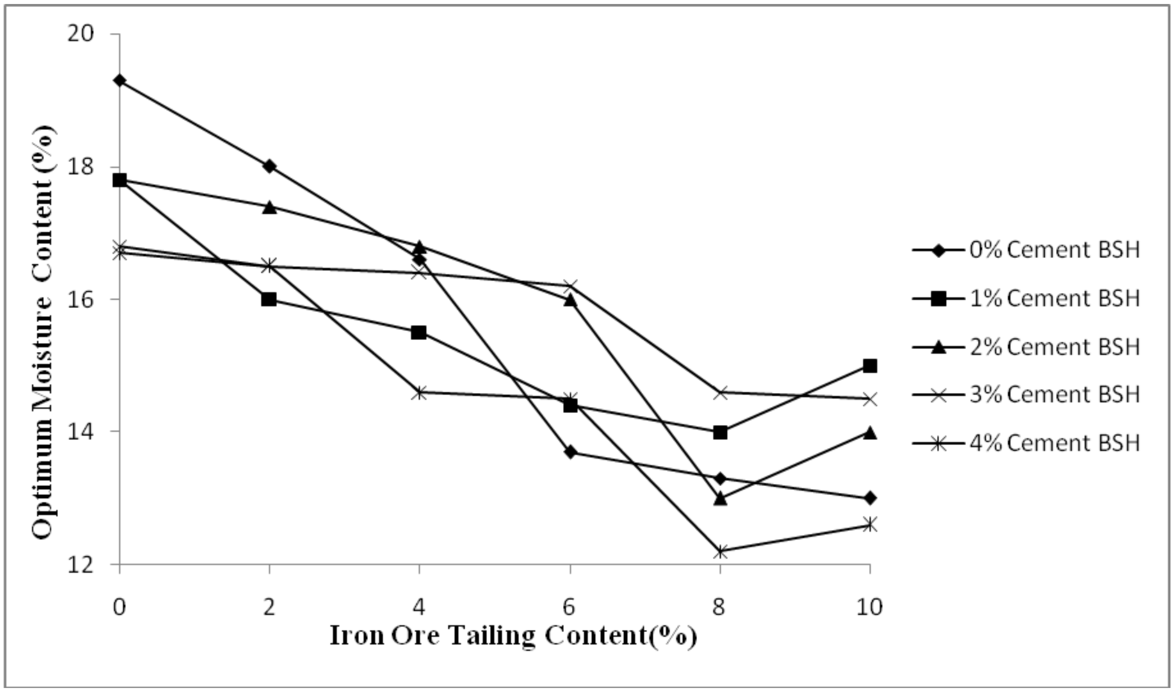

Fig. 4.10c: Variation of optimum moisture content of black cotton soil – cement mixtures with iron ore tailing content (BSH compaction)

Table 4.12 Two-way analysis of variance for Optimum moisture contents of soil-cement-IOT mixtures.

Property		Source of Variation	Degree of Freedom	F_{CAL}	p-value	F_{CRIT}	Remark
BSL	OMC	Cement	4	3.223	3.40E-02	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
		IOT	5	6.455	1.01-03	2.711	$F_{CAL}>F_{CRIT}$, Significant effect
WAS	OMC	Cement	4	7.653	6.55E-04	2.866	$F_{CAL}>F_{CRIT}$, Significant effect
		IOT	5	14.456	4.67E-06	2.711	$F_{CAL}>F_{CRIT}$, Significant effect
BSH	OMC	Cement	4	2.362	8.79E-02	2.866	$F_{CAL}<F_{CRIT}$ No Significant effect
		IOT	5	18.710	6.28E-07	2.711	$F_{CAL}>F_{CRIT}$, Significant effect

The two – way analysis of variance (ANOVA) test on the OMC result for BSL compaction (see Table 4.12) shows that the effects of cement (F_{CAL} = 3.223> F_{CRIT} =

2.866) and IOT (F_{CAL} = 6.455> F_{CRIT} = 2.711) on OMC result were statistically significant. The effect of IOT on the OMC result for BSL compaction effort was more pronounced than that of cement. Detailed test results are shown in Tables A4.19(a) in the Appendix.

The two – way analysis of variance (ANOVA) test on the OMC result for WAS compaction (see Table 4.12) shows that the effects of cement (F_{CAL} = 7.653> F_{CRIT} = 2.866) and IOT (F_{CAL} = 14.456> F_{CRIT} = 2.711) on OMC result were statistically significant. The effect of IOT on the OMC result for WAS compaction effort was more pronounced than that of cement. Detailed test results are shown in Tables A4.19 (b) in the Appendix.

The two – way analysis of variance (ANOVA) test on the OMC result for BSH compaction (see Table 4.12) shows the effects of cement on OMC values (F_{CAL} = 2.362< F_{CRIT} = 2.866) of the modified soil is not statistically significant when subjected to BSH compaction while the effects of IOT on OMC values (F_{CAL} = 18.710> F_{CRIT} = 2.711) of the modified soil is statistically significant when subjected to BSH compaction. The effect of IOT on the OMC result for BSH compaction effort was more pronounce than that of cement. Detailed test results are shown in Tables A4.19 (c) in the Appendix.

4.2.5.2a Regression analysis for optimum moisture content.

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

The correlation coefficient values (R^2) shows a strong relationship between optimum moisture content and the parameters with R^2 value of 86.9%.. Generally the correlation coefficient values (R^2) of 92.2% for maximum dry density and 86.9% for optimum moisture content shows that the parameters are more correlated to the maximum dry density than optimum moisture content.

The regression equation for optimum moisture content is

$$OMC = 46.9 + 0.138C - 0.242IOT + 0.069Cl + 0.021Si - 12.2Gs - 2.62CE \qquad (4.2)$$

$R^2 = 86.9\%$

Where OMC=Optimum moisture content, C= Cement content, IOT= Iron ore tailing content, Cl= Clay, Si= Silt, Gs= Specific gravity, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for OMC is given in Table 4.13. The analysis shows that the IOT ($F_{CAL} = 11.638 > F_{CRIT} = 1.663$) and Compactive effort ($F_{CAL} = 361.715 > F_{CRIT} = 3.156$) significantly affected OMC values of the modified soil.

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

Table 4.13: Two-way analysis of variance for regression analysis on optimum moisture content of black cotton soil-cement-IOT mixtures

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
OMC	IOT	29	11.638	3.8E-15	1.663	$F_{CAL}>F_{CRIT}$, Significant effect
	Compactive effort	2	361.715	1.76E-33	3.156	$F_{CAL}>F_{CRIT}$, Significant effect

4.2.6 Shear strength parameters

4.2.6.1 Cohesion

The variation of cohesion of black cotton soil - cement mixture with iron ore tailing for BSL, WAS and BSH compactions is shown in Fig. 4.11a-c. Generally, for all cement contents considered cohesion values initially decreased up to 6 % IOT content and thereafter increased with higher IOT content.

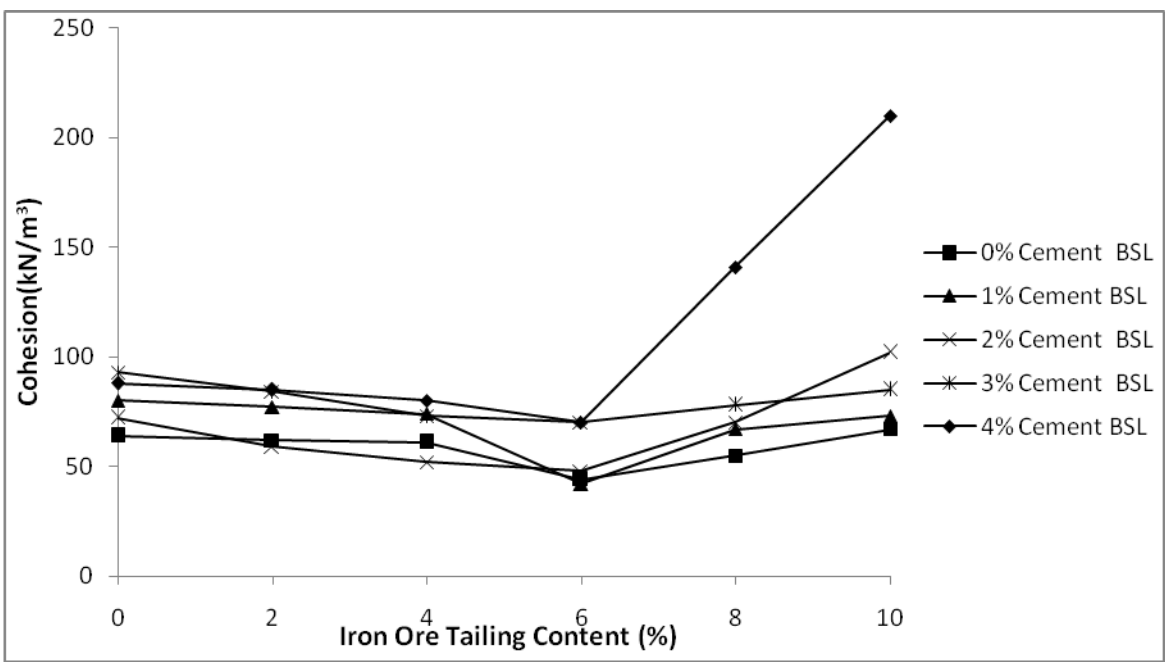

Fig 4.11a:Variation of cohesion of black cotton soil – cement mixtures with iron ore tailing content (BSL compaction).

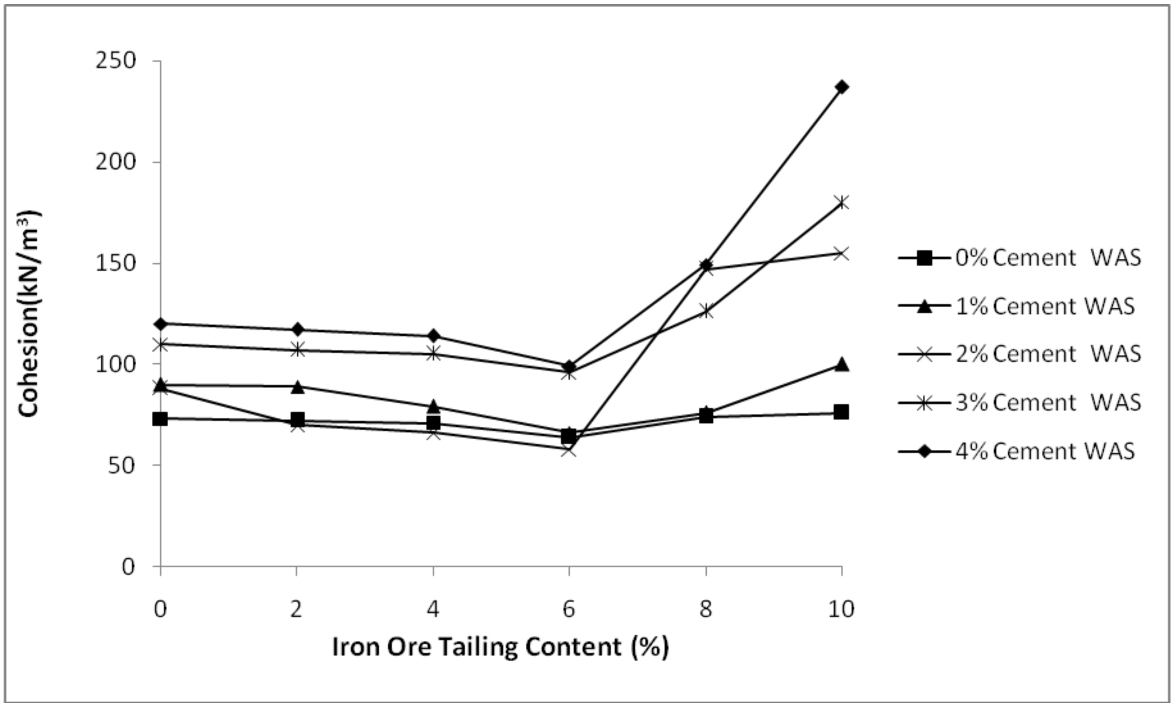

Fig 4.11b:Variation of cohesion of black cotton soil – cement mixtures with iron ore tailing content (WAS compaction)

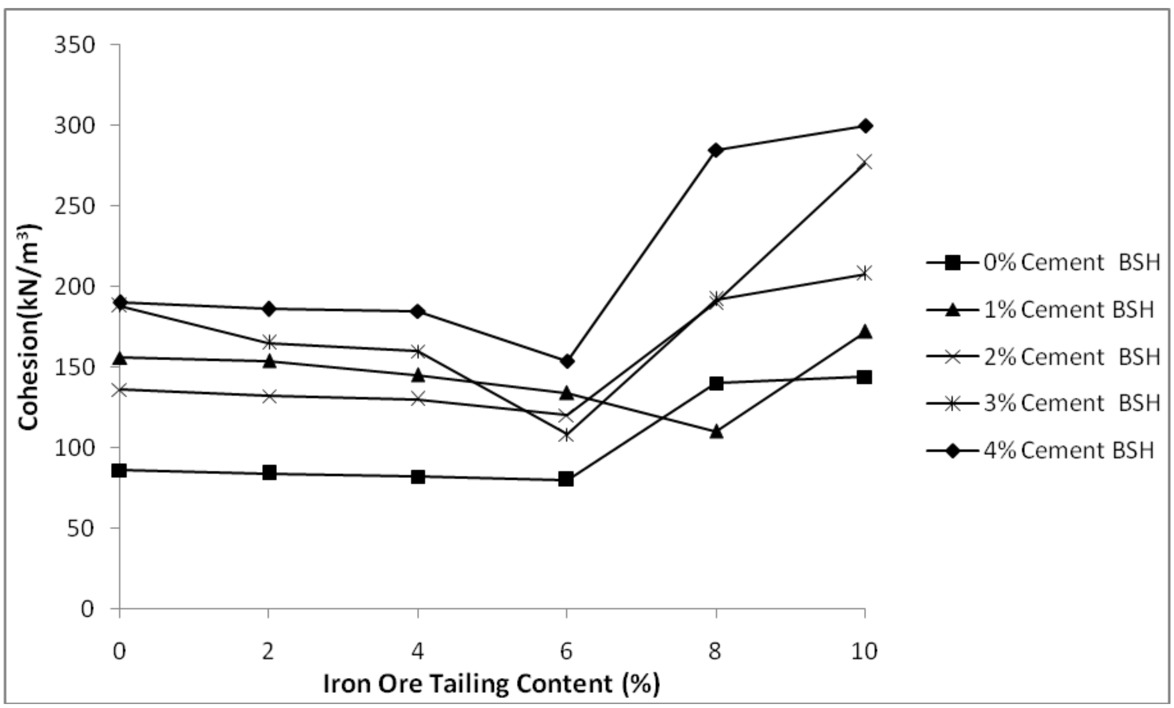

Fig 4.11c: Variation of cohesion of black cotton soil – cement mixtures with iron ore tailing content (BSH compaction).

For the natural soil the results obtained show that cohesion values increased with increase in compactive effort from 64, 73 and 86 kN/m^2 to peak values of 70, 99 and 154 kN/m^2 at 4 % cement / 6 % IOT treatment for BSL, WAS and BSH energies, respectively. The initial decrease in cohesion is associated with the breakdown of the weak forces holding the clay particles together to form stronger bonds thereby reducing the cohesive nature of the natural soil .Similar behaviour was observed by Azige (2012) who worked on locust bean waste ash (LBWA) modification of black cotton soil using cement kiln dust as an activator and found out that cohesion decreased up to 6 % LBWA treatment by dry weight of the soil. Detailed test results are shown in Tables A4.11(a-c) in the Appendix.

The two – way analysis of variance (ANOVA) of cohesion result for BSL compaction (see Table 4.14) shows that the effects of cement (F_{CAL} = 5.056> F_{CRIT} = 2.866 and IOT (F_{CAL} = 2.966 > F_{CRIT} = 2.711) on black cotton soil were statistically significant with the effect of cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.20 (a) in the Appendix.

Table 4.14 Two-way analysis of variance for cohesion of black cotton soil – cement – iron ore tailing mixtures

Property		Source of Variation	Degree of freedom	F_{CAL}`	p-value	F_{CRIT}	Remark
BSL	Cohesion (C)	Cement	4	5.056	5.57E-03	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	2.966	3.67E-02	2.711	F_{CAL}>F_{CRIT}, Significant effect
WAS	Cohesion (C)	Cement	4	8.890	2.70E-04	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	6.731	7.90-04	2.710	F_{CAL}>F_{CRIT}, Significant effect
BSH	Cohesion (C)	Cement	4	12.089	3.71E-05	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	7.716	3.50-04	2.711	F_{CAL}>F_{CRIT}, Significant effect

The two – way analysis of variance (ANOVA) of cohesion result for WAS compaction (see Table 4.14) shows that the effects of cement (F_{CAL} = 8.890> F_{CRIT} = 2.866 1and IOT (F_{CAL} = 6.731 > F_{CRIT} = 2.711) on black cotton soil were statistically significant with the effect of cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.20 (b) in the Appendix.

The two – way analysis of variance (ANOVA) of cohesion result for BSH compaction (see Table 4.14) shows that the effects of cement (F_{CAL} = 12.089 > F_{CRIT} = 2.866) and IOT (F_{CAL} = 7.716 > F_{CRIT} = 2.711) on black cotton soil were statistically significant with the effect of cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.20(c) in the Appendix.

4.2.6.1a Regression analysis for cohesion.

A regression analysis was performed for cohesion as a dependant variable and four geotechnical properties as independent variables. The geotechnical properties considered for these analyses include the cement content, iron ore tailing content, percentage fine and plasticity index using compactive effort as a deterministic parameter. Results of regression analysis showed that the cohesion of the modified soil was influenced by the cement content, iron ore tailing content, plasticity index and compactive effort all having positive coefficients. The regression equations (see equation 4.3) revealed the extent to which these parameters influences the cohesion of the modified soil which is a function of the coefficient of each parameter. The compactive effort has the most significant effect on the cohesion having the highest positive coefficient. The correlation coefficient value (R^2) shows a strong relationship between cohesion of the modified soil and the parameters with R^2 value of 65.2%.

The regression equation is

$$Co = 76.0 + 14.2C + 3.94IOT - 0.866PF + 1.52PI + 41.1CE \quad (4.3)$$

$R^2 = 65.2\%$

Where Co=Cohesion, C= Cement content, IOT= Iron ore tailing content, PF=Percentage fine, Pl= Plasticity index, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for Cohesion is given in Table 4.15. The analysis shows that the IOT (F_{CAL} = 11.773> F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 129.112> F_{CRIT} = 3.156) has significant affect on Cohesion of the modified soil. However, Compactive effort has a more pronounced effect.

Table 4.15: Two-way analysis of variance for regression analysis on Cohesion of black cotton soil-cement-IOT mixtures.

Property	**Source of Variation**	**Degree of freedom**	**F_{CAL}**	**p-value**	**F_{CRIT}**	**Remark**
Cohesion (C)	IOT	29	11.773	2.92E-15	1.663	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	129.112	4.36E-22	3.156	F_{CAL}>F_{CRIT}, Significant effect

4.2.6.2 Angle of internal friction

The variation of angle of internal friction of black cotton soil – cement mixtures with iron ore tailing content is shown in Fig. 4.12a-c for BSL, WAS and BSH compactive efforts, respectively. Generally, for all cement contents considered peak angle of internal friction were recorded at 6 % IOT content which thereafter decreased with increase in IOT content. For the natural black cotton soil the angle of internal friction increased with increase in compactive effort from 3^0, 6^0 and 7^0 to peak values of 6^0, 12^0 and 16^0 at 4 % cement / 6 % IOT treatment for BSL, WAS and BSH compactions, respectively. For all cement contents considered and up to 6 % IOT content the cohesion of soil-cement-IOT mixtures reduced while the angle of internal friction increased. Similar behaviour was reported by Krishna and Ramesh (2012).

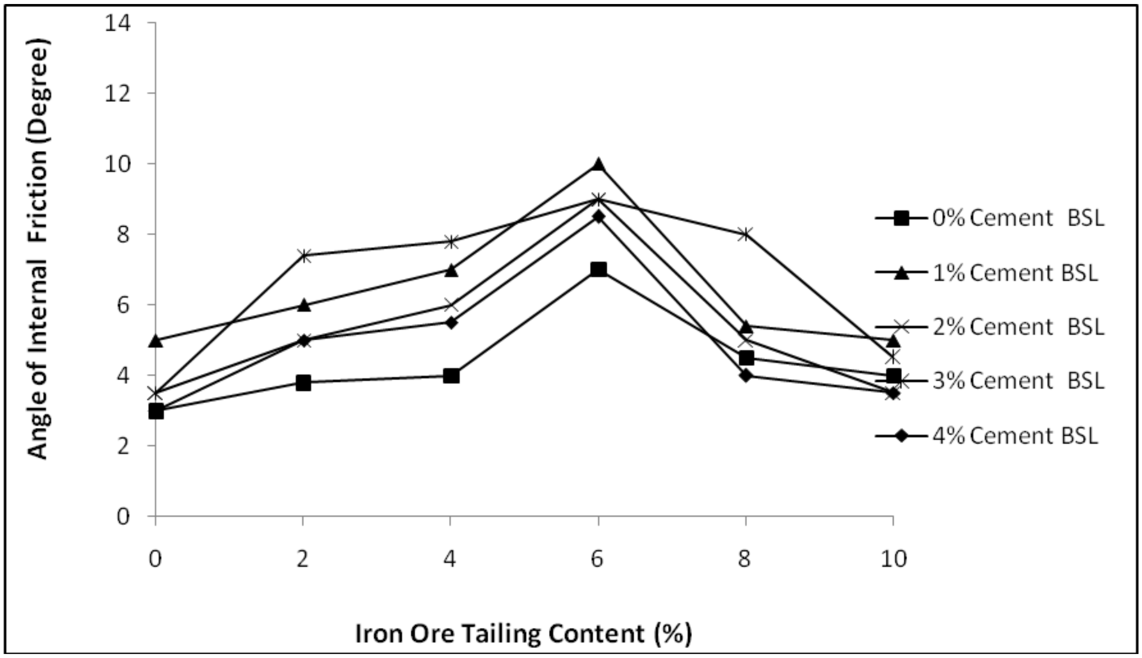

Fig 4.12a:Variation of angle of internal friction of black cotton soil – cement mixtures with iron ore tailing content (BSL compaction)

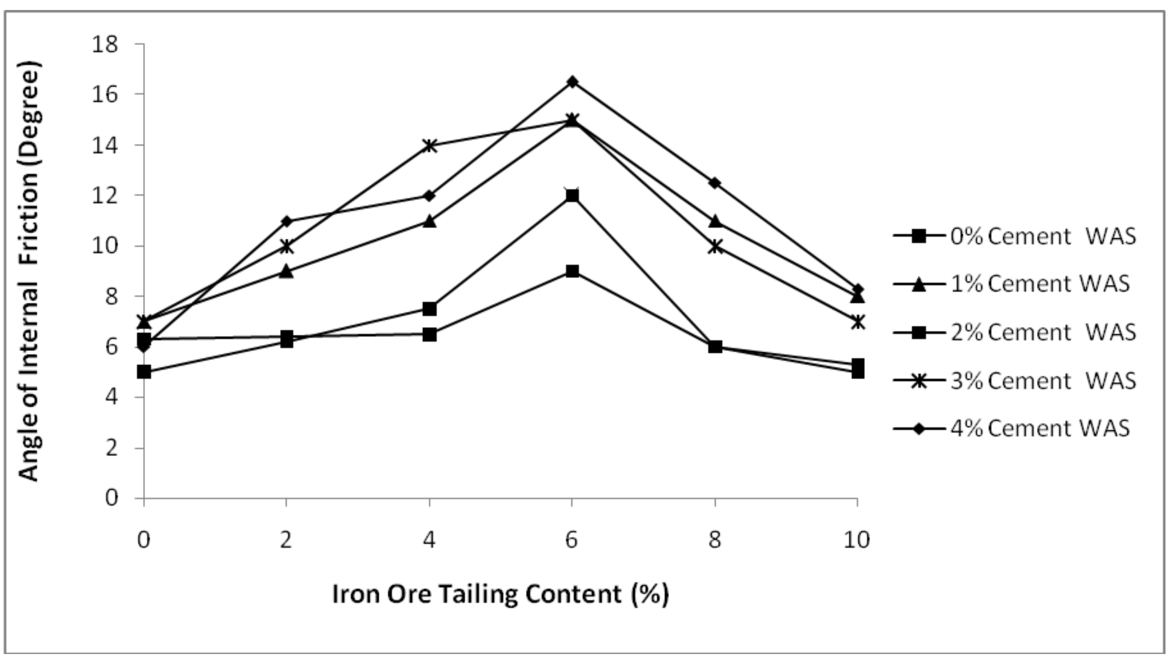

Fig 4.12b:Variation of angle of internal friction of black cotton soil – cement mixtures with iron ore tailing content (WAS compaction)

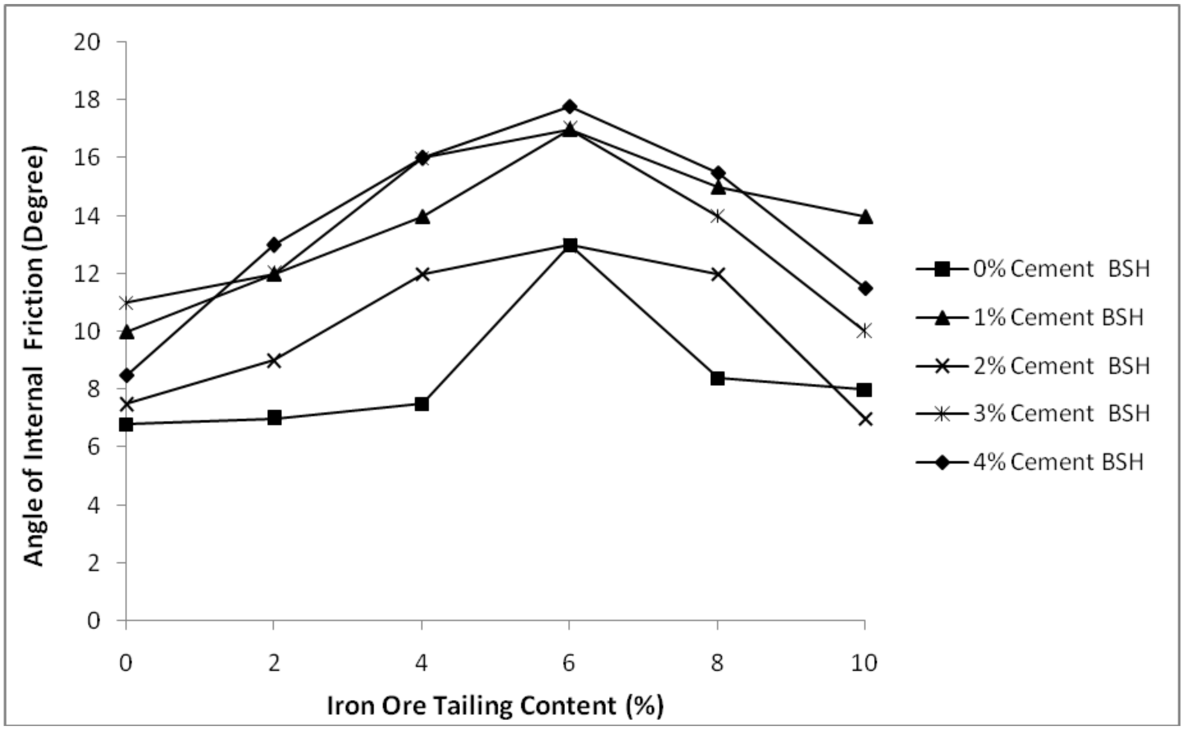

Fig 4.12c:Variation of angle of internal friction of black cotton soil – cement mixtures with iron ore tailing content (BSH compaction)

The observed results were due to the reduction in clay size fraction, which resulted from the ion exchange reaction that deposited free lime in the system. The initial increase in angle of internal friction and decrease in cohesion may also be attributed to the breaking of clay particles in the soil into 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). Results obtained are consistent with the findings reported by Lees et al. (1982), Osula (1991) and Osinubi (1995). Detailed test results are shown in Tables A4.12(a-c) in the Appendix.

The two – way analysis of variance (ANOVA) of angle of internal friction results for BSL compaction (see Table 4.16) show that the effects of cement (F_{CAL} = 10.083>

F_{CRIT} = 2.866) and IOT (F_{CAL} = 28.130 > F_{CRIT} = 2.711) on black cotton soil were statistically significant with IOT being more pronounced than that of cement. Detailed test results are shown in Tables A4.21(a) in the Appendix.

Table 4.16: Two-way analysis of variance for angle of internal friction of black cotton soil – cement – iron ore tailing mixtures.

Property		Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
BSL	Friction Angle(Θ)	Cement	4	10.083	1.23-04	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	28.130	2.12E-08	2.71	F_{CAL}>F_{CRIT}, Significant effect
WAS	Friction Angle(Θ)	Cement	4	15.826	5.47E-06	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	20.471	3.03E-07	2.711	F_{CAL}>F_{CRIT}, Significant effect
BSH	Friction Angle(Θ)	Cement	4	21.957	4.41E-07	2.866	F_{CAL}>F_{CRIT}, Significant effect
		IOT	5	19.036	5.46E-07	2.711	F_{CAL}>F_{CRIT}, Significant effect

The two – way analysis of variance (ANOVA) of angle of internal friction results for WAS compaction (see Table 4.16) show that the effects of cement (F_{CAL} = 15.826 > F_{CRIT} = 2.866) and IOT (F_{CAL} = 20.471 > F_{CRIT} = 2.711) on black cotton soil were statistically significant with IOT being more pronounced than that of cement. Detailed test results are shown in Tables A4.21(b) in the Appendix.

The two – way analysis of variance (ANOVA) of angle of internal friction results for BSH compaction (see Table 4.16) show that the effects of cement (F_{CAL} = 21.957 > F_{CRIT} = 2.866) and IOT (F_{CAL} = 19.036> F_{CRIT} = 2.711) on black cotton soil were statistically significant with cement being more pronounced than that of IOT. Detailed test results are shown in Tables A4.21(c) in the Appendix.

4.2.6.2a Regression analysis for angle of internal friction

Regression analysis for angle of internal friction are as shown in equation 4.4. Result showed that the angle of internal friction was influenced by the cement content, iron ore tailing content, percentage fine and compactive effort applied. This agrees with previous statements by Gidigasu (1976) who stated that the behavior of soil used in pavement structure has been found to depend mainly on their particle size characteristics, the nature and strength of the gravel particles and the degree to which the soils have been compacted. The geotechnical properties considered for these analyses include cement content, iron ore tailing content, percentage fine, and plasticity index alongside the compactive effort applied. The regression equation showed that the angle of internal friction of the modified soil is much more influenced by the cement content, iron ore tailing content, percentage fine and the compactive effort. The plasticity index has no significant effect on the angle of internal friction having negative coefficient.

The correlation coefficient value (R^2) shows a partial relationship between angle of internal friction and the parameters with R^2 value of 50.8%. Generally the correlation coefficient values (R^2) of 65.2% for cohesion and 50.8% for angle of internal friction shows the parameters are more correlated to the cohesion than angle of internal friction.

The regression equation is

$$FA = 5.16 + 1.22C + 0.203IOT + 0.108PF - 0.223PI + 3.15CE \quad (4.4)$$

$R^2 = 50.8\%$

Where FA= Angle of internal friction, C= Cement content, IOT= Iron ore tailing content, PF= Percentage fine, PI= Plasticity Index, CE= Compactive effort.

The two – way analysis of variance (ANOVA) test for friction angle is given in Table 4.17. The analysis shows that the IOT (F_{CAL} = 11.683> F_{CRIT} = 1.663) and Compactive effort (F_{CAL} = 156.758> F_{CRIT} = 3.156) has significant affect on friction angle of the modified soil. However, the effect of Compactive effort on the friction angle of black cotton soil was much more significant.

Table 4.17: Two-way analysis of variance for regression analysis on angle of internal friction of black cotton soil-cement-IOT mixtures.

Property	Source of Variation	Degree of freedom	F_{CAL}	p-value	F_{CRIT}	Remark
Friction Angle(θ)	IOT	29	11.683	3.48E-15	1.662	F_{CAL}>F_{CRIT}, Significant effect
	Compactive effort	2	156.758	4.07E-24	3.156	F_{CAL}>F_{CRIT}, Significant effect

4.2.7 Microanalysis of specimens

4.2.7.1 Scanning electron microscopy

Micro structural studies are increasingly used to improve understanding of the macroscopic behaviour and physical properties of compacted and natural soils. 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 microscope (SEM) include grain size, surface roughness, porosity, particle size distribution, material homogeneity, intermetallic distribution and diffusion.

4.2.7.1a Scanning electron microscopy for 7 days curing period

The results of microscopic analysis (using scanning electron microscope, SEM) of specimens of natural black cotton soil optimally treated with 4 % cement / 6 % IOT and cured for 7 days are shown on Plate 4.1a - d. The untreated and treated specimens were analysed by using SEM to determine their morphological characteristics. Micrographs of the samples at 10 μm and 100 μm magnifications were considered.

The micrographs illustrate the shape of the soil particles. It was observed that the natural soil has smooth and scaly surfaces while the modified soil developed a rough textured surface morphology. The possible explanation to the change in orientation and morphology of the modified soil is the reduction in the cohesiveness of the soil due to the cation exchange reaction that occurred. Similar behaviour was observed by Mitchell and Solymer (1983).The more active and higher valent cations (i.e., Ca^{2+}) in the additives replaced the weakly bonded ions in the clay structure leading to the agglomeration and liberation of water bonded at the outer layers. Similar behaviour was reported by Ishola (2014). The decrease in cohesion may be due to the pozzalanic reaction that resulted in the formation of calcium and alumina hydrate. Mitchell (1956) reported that the decrease in the cohesiveness is attributed to changes in the mineralogical composition and grain size distribution leading to the formation of a needle like morphology (rough textured surface). Changes in the quantities of chemical compounds such as carbonate, iron oxide, aluminium and silicon which precipitate at inter particle contact and act as cementing agent caused the changes in interparticle and fabric orientation of the soil.

The decrease in the cohesion and a change in the fabric orientation of the soil particle is an indication of improvement in the properties of the soil. It was observed that the workability and shear strength parameters of the soil improved due do the agglomeration of the soil after treatment as earlier discussed.

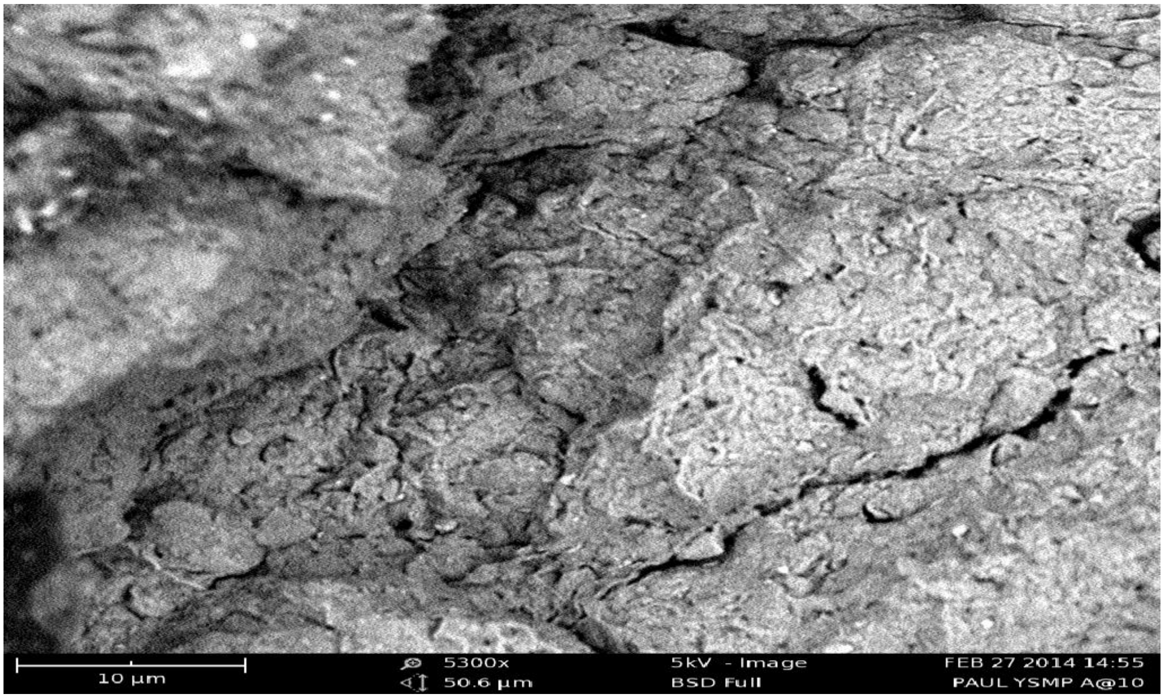

Plate 4.1a: Micrograph of the natural black cotton soil after 7 days curing at 10 µm magnification

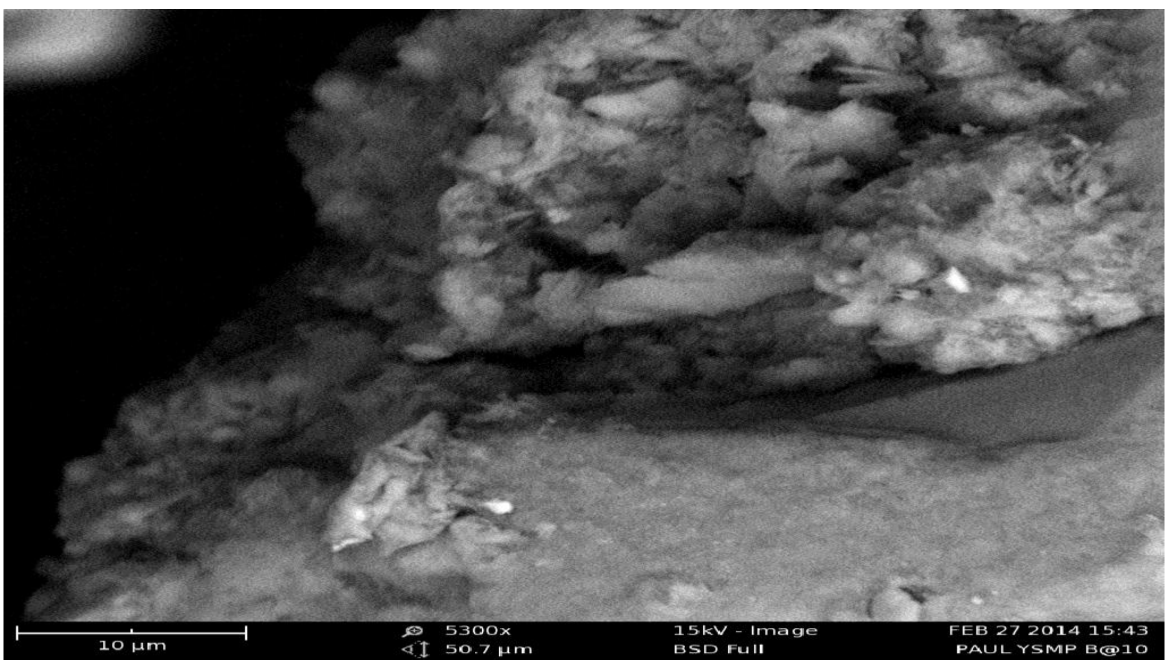

Plate 4.1b: Micrograph of optimally (4 % cement / 6 % IOT) modified black cotton soil after 7 days curing at 10µm magnification

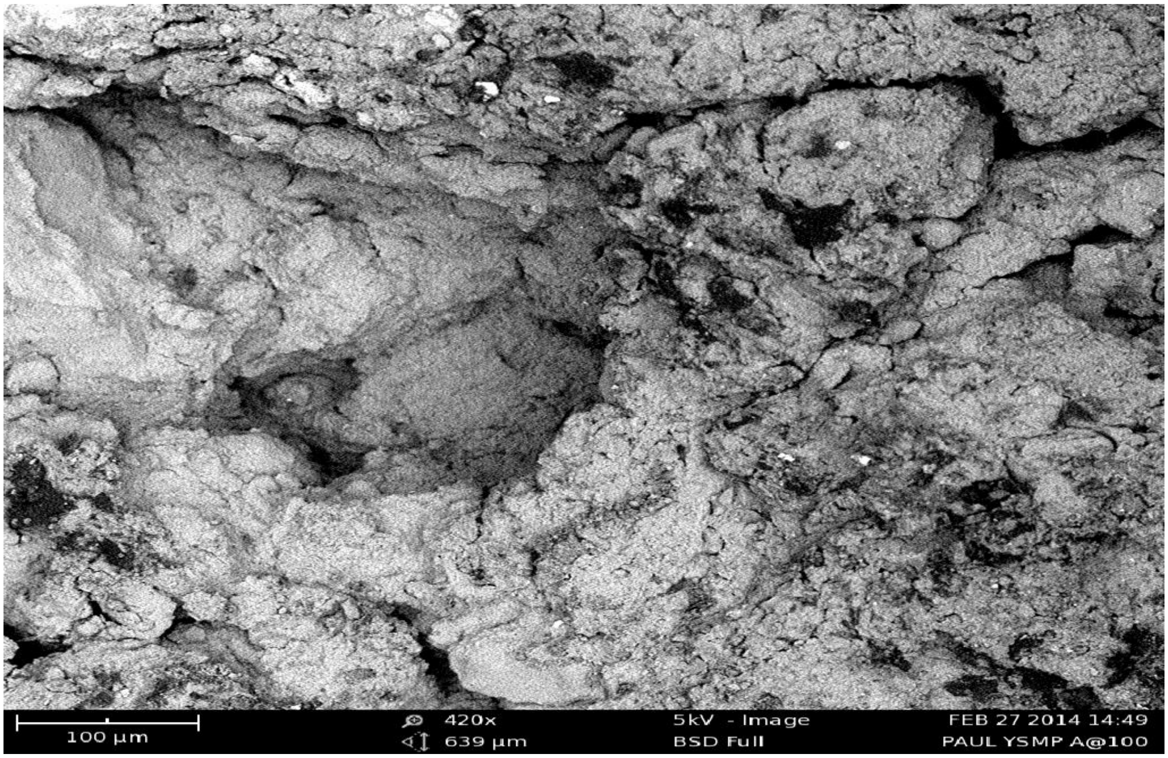

Plate 4.1c: Micrograph of the natural black cotton soil after 7 days curing at 100 µm magnification

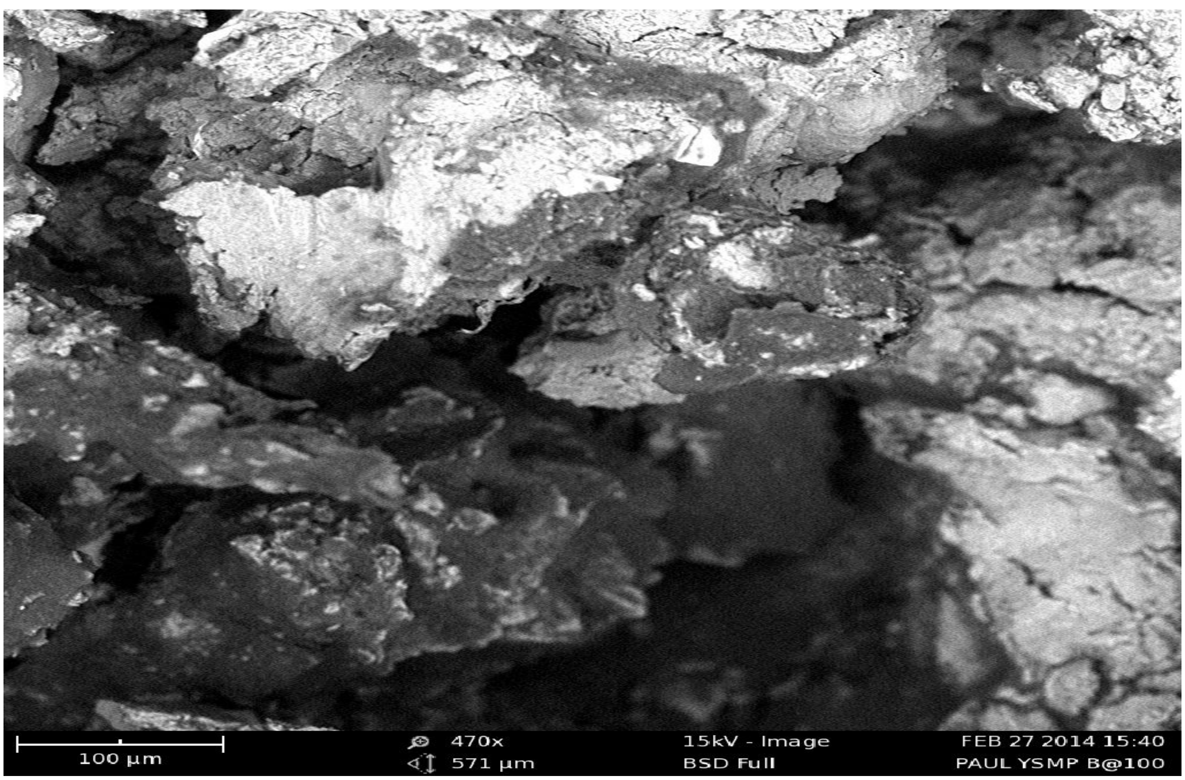

Plate 4.1d: Micrograph of optimally (4% cement / 6 % IOT) modified black cotton soil after 7 days curing at 100 µm magnification.

4.2.7.1b Scanning electron microscopy for 28 days curing period

The micrograph of the natural soil compacted with BSL energy after 28 days curing period are shown in Plate 4.2a - d. It was observed that the structural particle arrangements appeared to be different from those of specimens cured for 7 days, but there was not much difference in turbidity or obscurity. It was observed that specimens of the natural and modified soil cured for 28 days had smooth and scaly surface morphologies that are indicative of the clay particles becoming more flocculated with increase in additives contents.

The flocculation of clays is caused by negative particle surface to positive particle edge electrostatic attractive forces, resulting in random particle orientation (Mitchell, 1956). Hydration and ionic exchange could have led to the breaking of electrostatic and molecular bonds that resulted in the flocculent state with a reduction in the cohesiveness for both the natural and the modified soil after curing (see Plate 4.2a - d). Mitchel (1956) reported that the increase in the attractive forces over repulsion force with curing period suggest the flocculent nature of the soil.This also suggests the reduction in the pore spaces between the soil particles with increasing curing period. The workability of the soil decreases as the soil becomes more flocculent with increasing curing period.

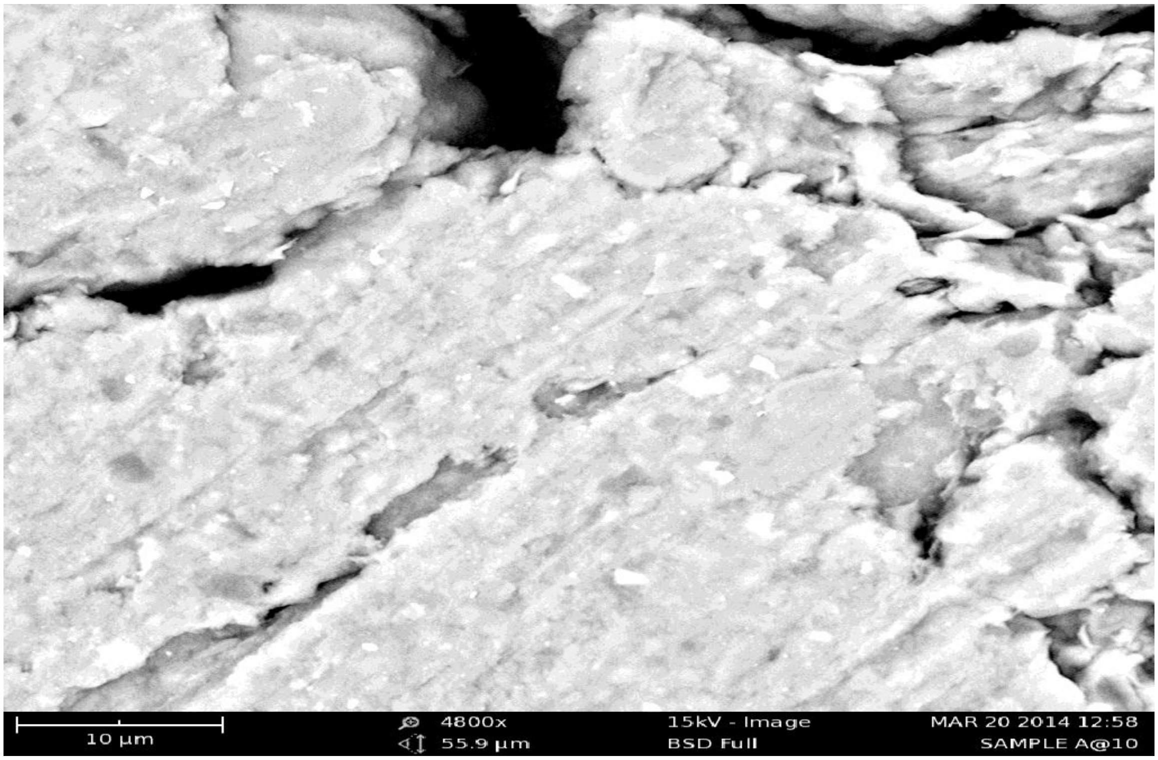

Plate 4.2a: Micrograph of the natural black cotton soil after 28 days curing at 10 µm magnification.

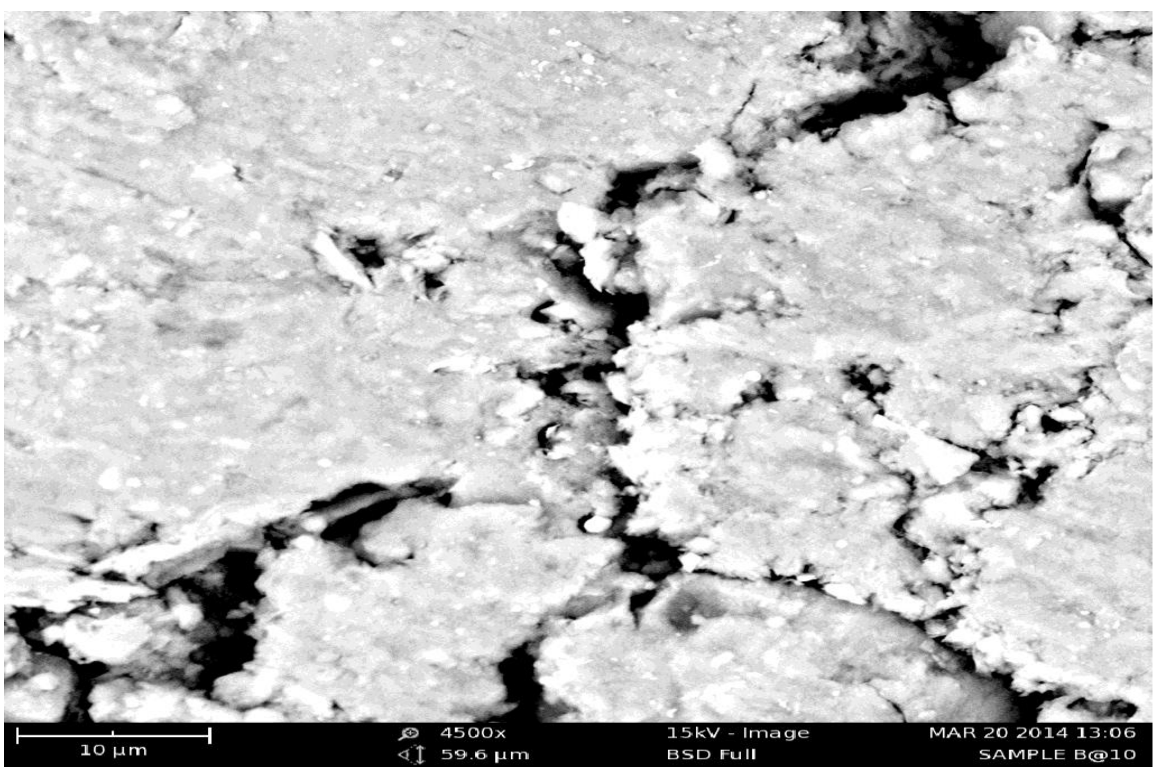

Plate 4.2b: Micrograph of optimally (4 % cement / 6 % IOT) modified soil after 28 days curing at 10 µm magnification

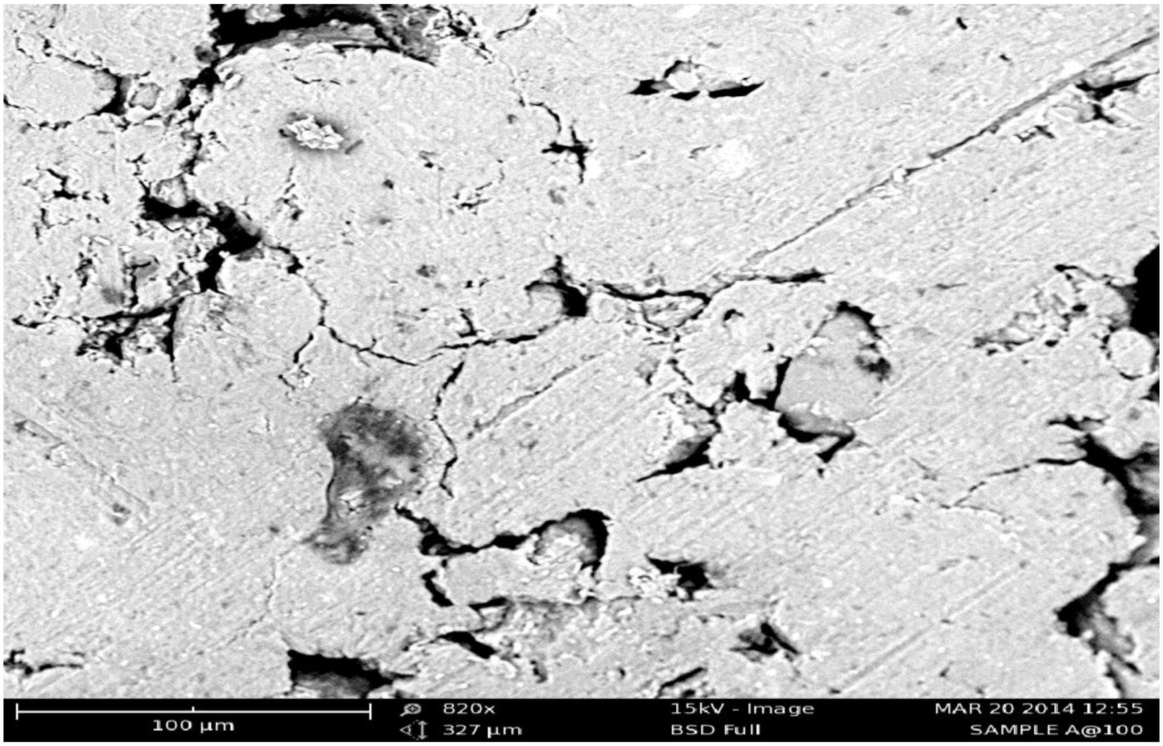

Plate 4.2c: Micrograph of the natural black cotton soil after 28 days curing at 100 µm magnification.

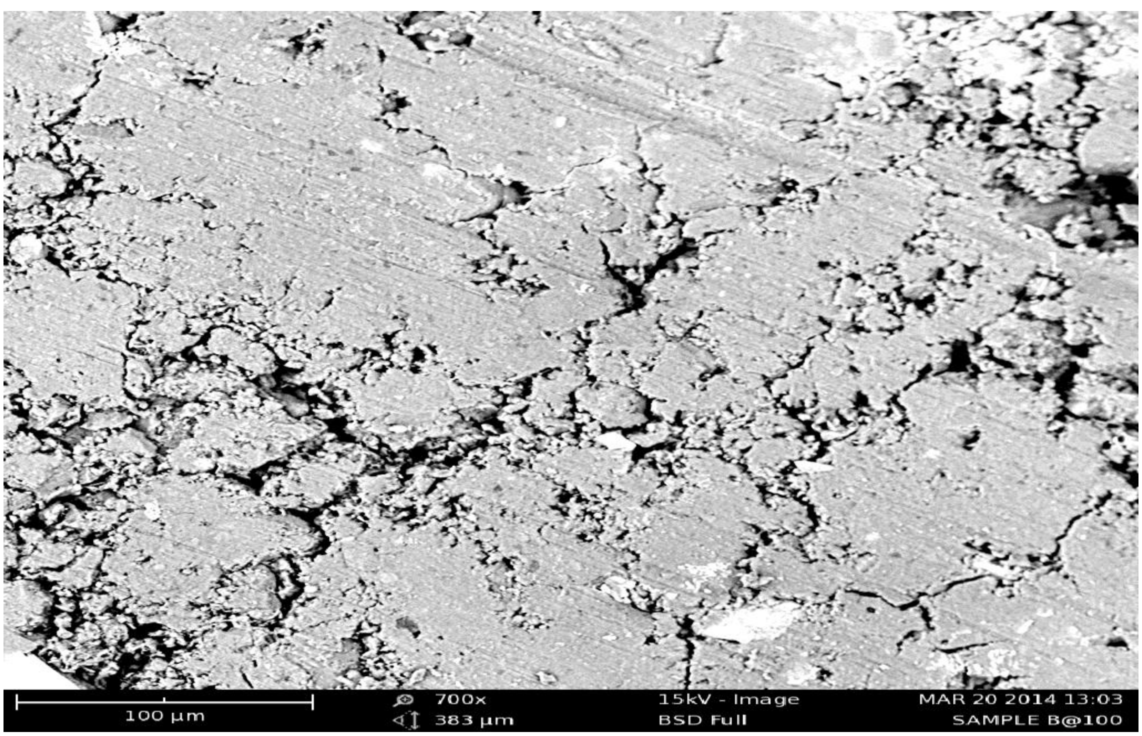

Plate 4.2d: Micrograph of optimally (4 % cement / 6 % IOT) modified black cotton soil after 28 days curing at 100 µm magnification.

4.2.7.2 Energy-dispersive x-ray spectroscopy of specimens

Energy-dispersive x-ray spectroscopy (EDS) identifies the elemental composition of materials imaged in a Scanning Electron Microscope (SEM) for all elements with atomic number greater than that of boron (B) with atomic number 5. Most elements are detected at concentrations of the order of 0.1 %. EDS is used in materials evaluation and identification, contaminants, elemental diffusion profiles and multiple spot analysis of areas from 1 micron to 10 cm in diameter (Neeraj *et al*., 2012).

As the electron beam of the SEM is scanned across the sample surface, it generates X-ray fluorescence from the atoms in its path. The energy of each X-ray photon is characteristic of the element which produced it. The EDS microanalysis system collects the X-rays, sorts and plots them by energy, and automatically identifies and labels the elements responsible for the peaks in this energy distribution. The EDS data are typically compared with either known or computer-generated standards to produce a full quantitative analysis showing the sample composition.

4.2.7.2a 7 days curing period

The results of the EDS elemental analyses of the natural black cotton soil show the usual composition of the alumino silicates minerals as suggested by Reyes et al. (2007). Plate 4.3a - b shows the EDS of the untreated soil after 7 days curing period. It was observed that the untreated soil contains higher amount of silicon content than the modified soil (see Plate4.3c - d). It was also noted that for modified soil, antimony (Sb) with atomic number 51 was the dominant mineral present with low percentage by weight of silicon and aluminum. The decrease in the silicon and aluminum contents could be due to the pozzolanic reaction in which the calcium from cement and IOT reacted with soluble alumina and silica from clay and IOT in the presence of water to produce stable calcium silicate hydrate and calcium aluminates hydrate which enhance long-term strength gain and improvement of the properties of the soil (Neeraj *et al.,* 2012). The decrease in silicon and aluminium contents in the modified soil is an indication that new compounds were formed. The formation of new compounds due to changes in the mineralogical composition could be attributed to the cation ion exchange reaction that may have occurred between low valence element in the additives and the clay structure. This implies an improvement of the workability and shear strength parameters of the modified black cotton soil.

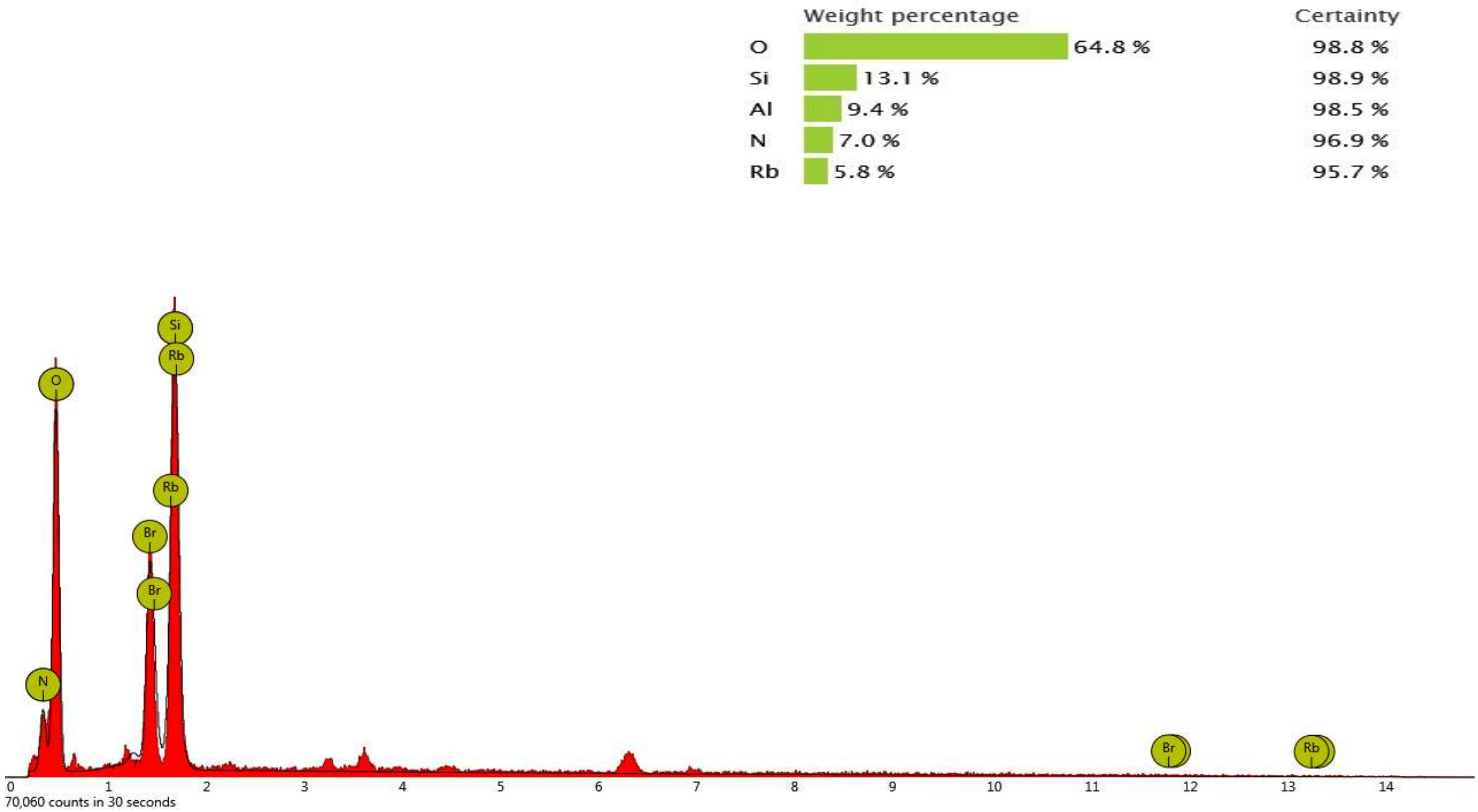

Plate 4.3a: Energy-dispersive x-ray spectroscopy for the natural black cotton soil after 7 days curing period (Point 1)

	Weight percentage	Certainty
O	66.3 %	97.8 %
Si	16.0 %	98.1 %
Al	9.2 %	97.1 %
N	8.5 %	95.1 %

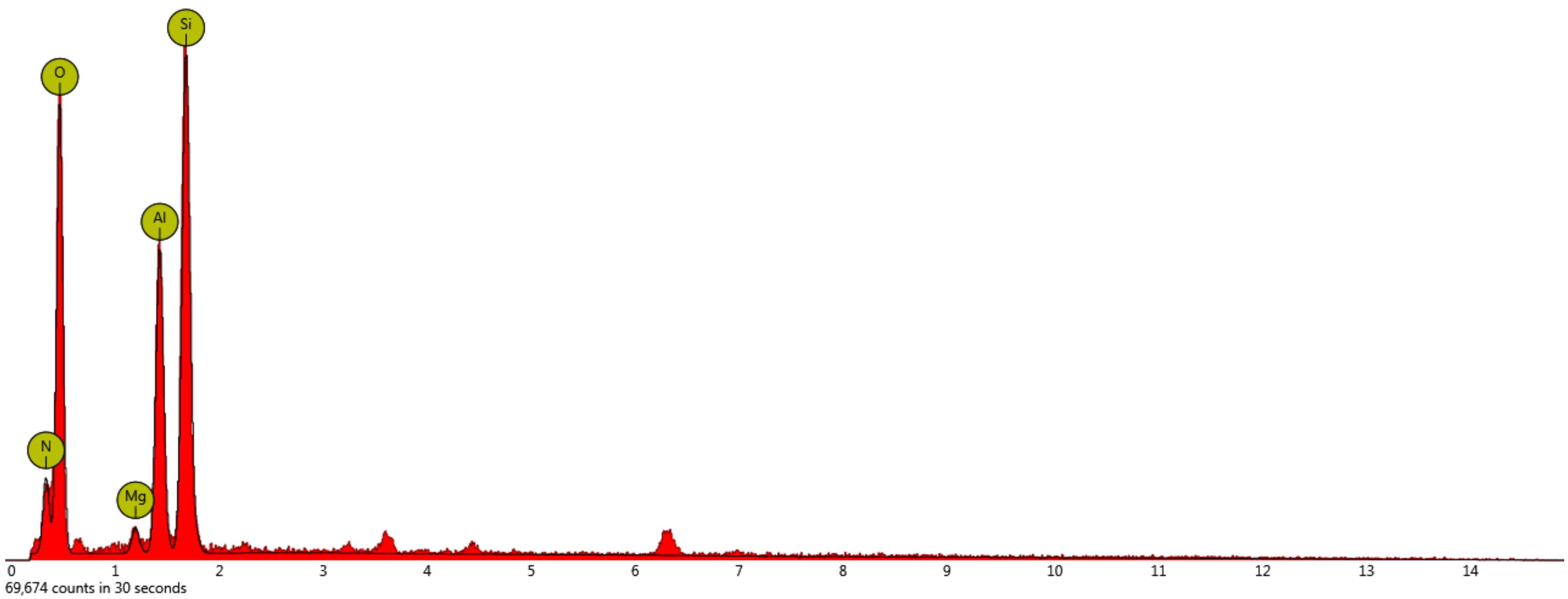

Plate 4.3b: Energy-dispersive x-ray spectroscopy for the natural black cotton soil after 7 days curing period (Point 2).

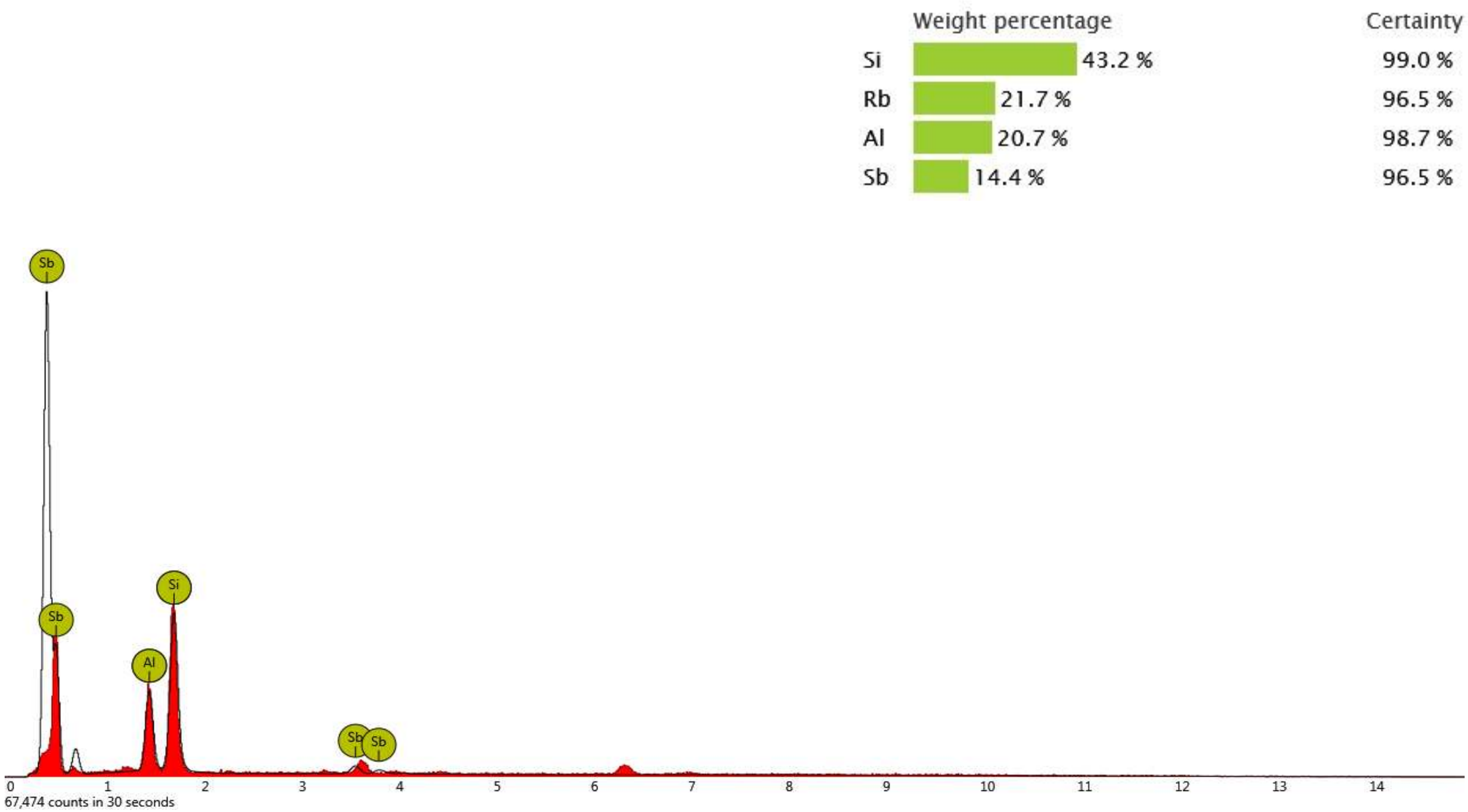

Plate 4.3c: Energy-dispersive x-ray spectroscopy for optimally (4 % cement / 6 % IOT) modified black cotton soil after 7 days curing period (Point 1)

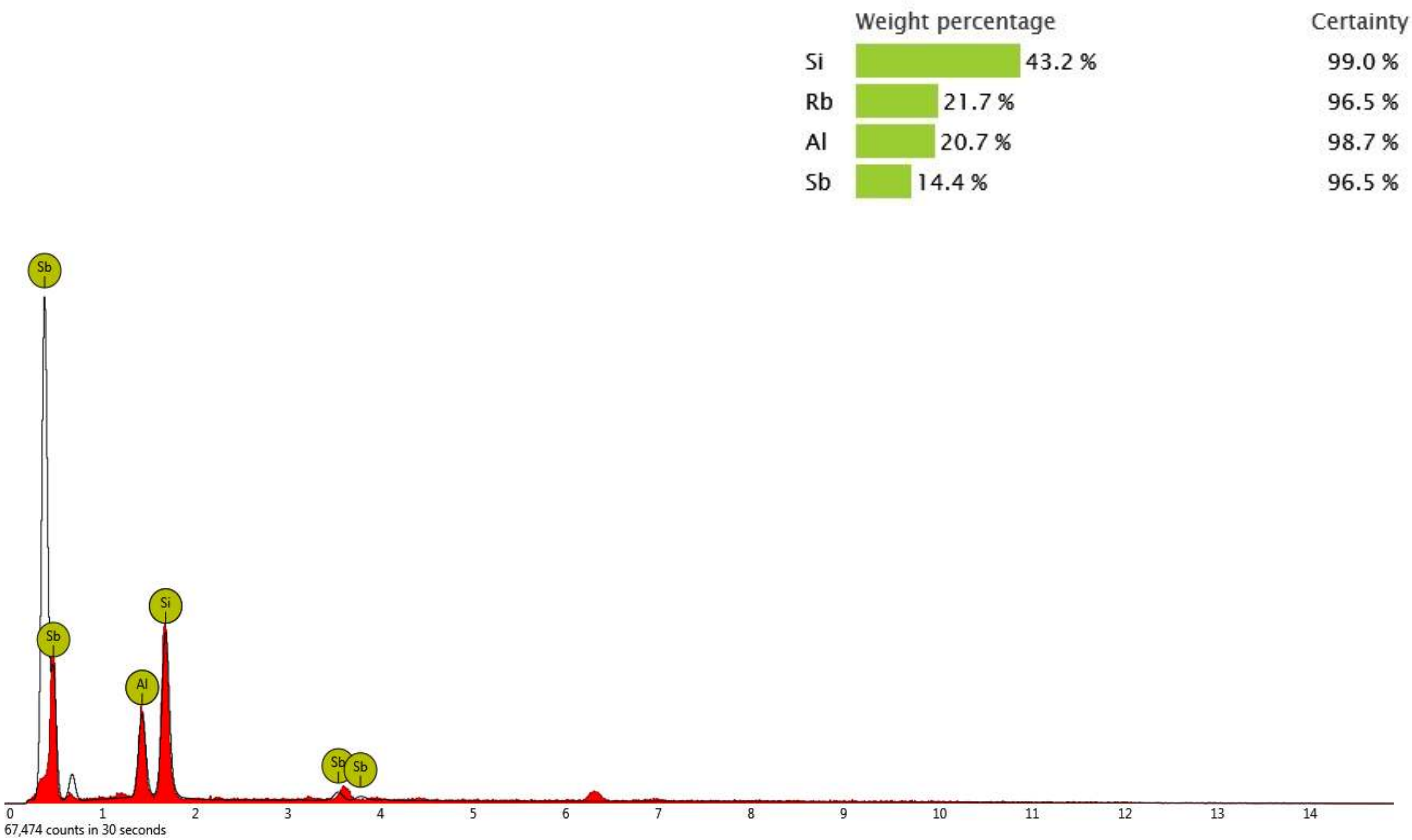

Plate 4.3d: Energy-dispersive x-ray spectroscopy for optimally (4 % cement / 6 % IOT) modified black cotton soil after 7 days curing period (Point 2).

4.2.7.2b. 28 days curing period

The EDS elemental analysis of specimens cured for 28 days is shown on Plate 4.4a- d. The observed trends follow the same pattern as for specimens cured for 7 days.

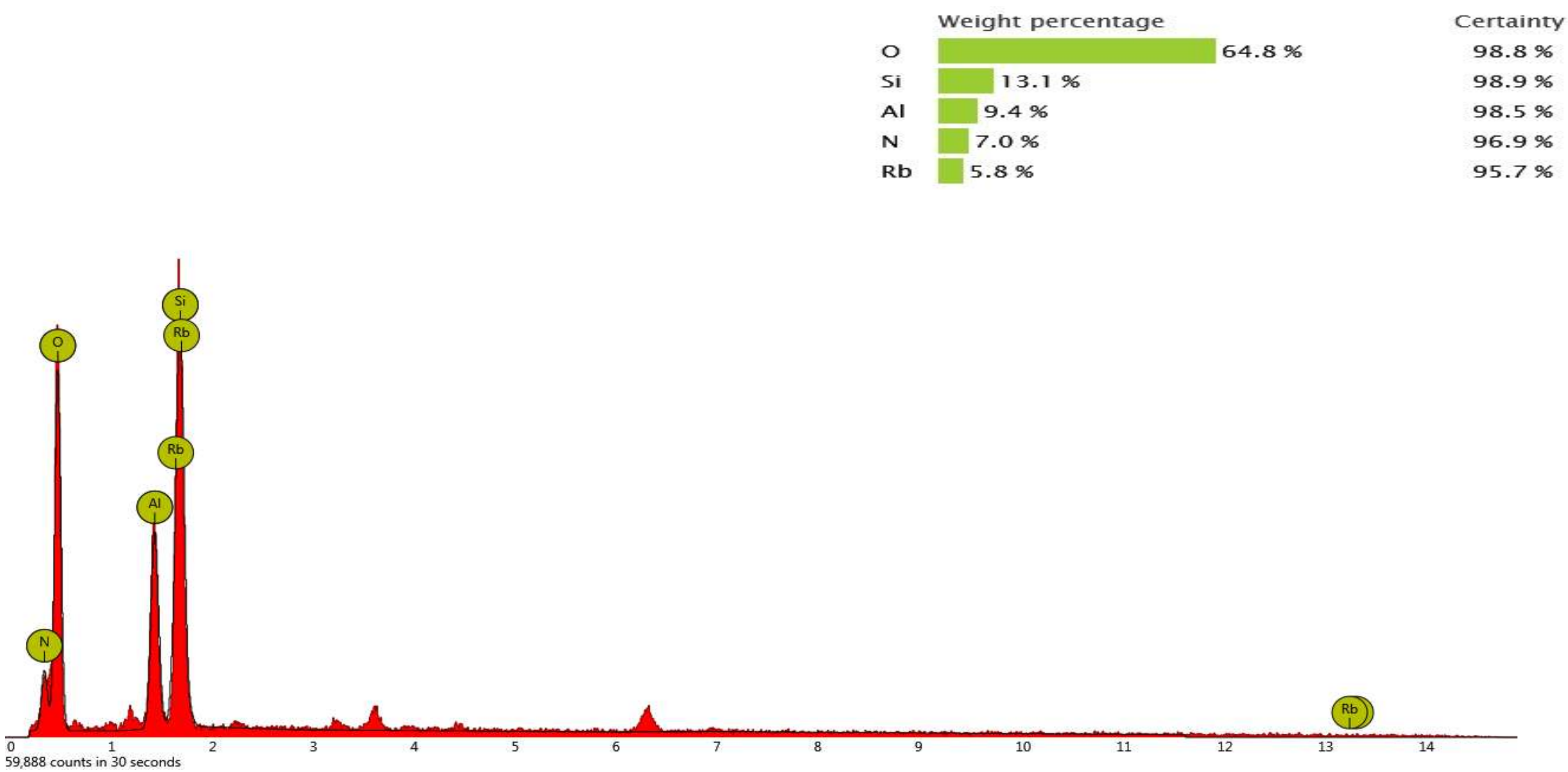

Plate 4.4a: Energy-dispersive x-ray spectroscopy for the natural black cotton soil after 28 days curing period (Point 1)

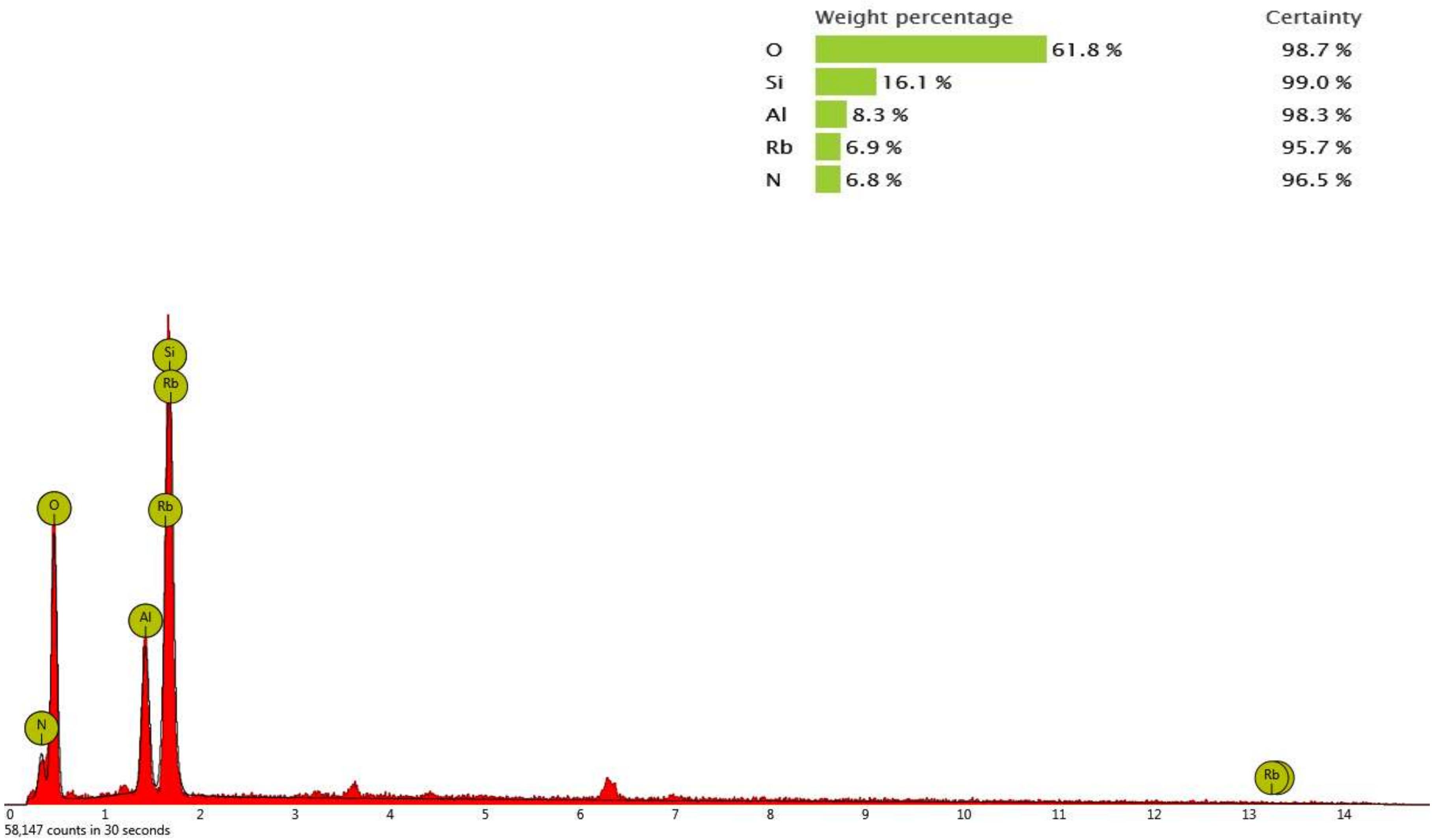

Plate 4.4b: Energy-dispersive x-ray spectroscopy for the natural black cotton soil after 28 days curing period (Point 2)

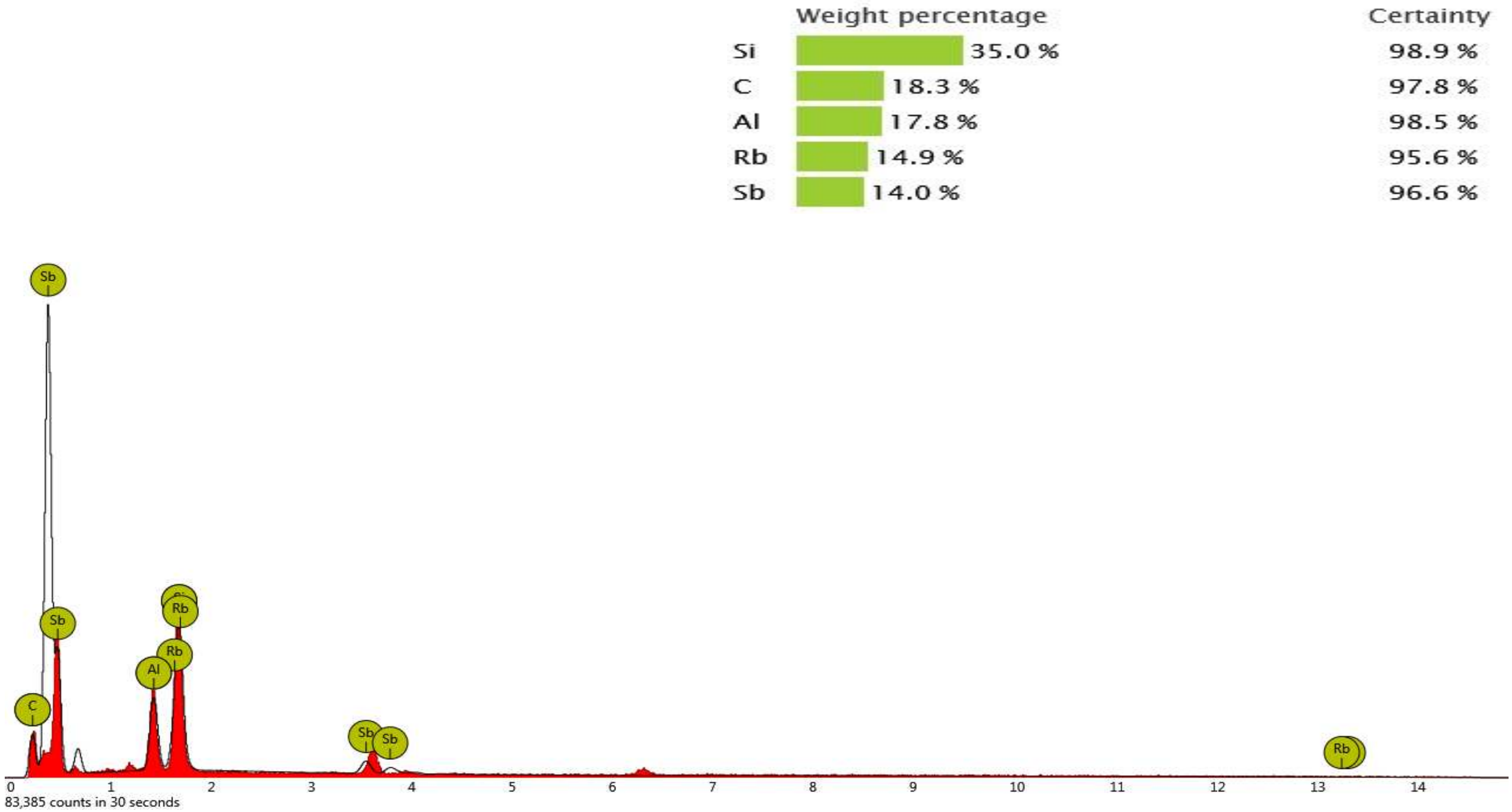

Plate 4.4c: Energy-dispersive x-ray spectroscopy for optimally (4 % cement / 6 % IOT) modified black cotton soil after 28 days curing period (Point 1)

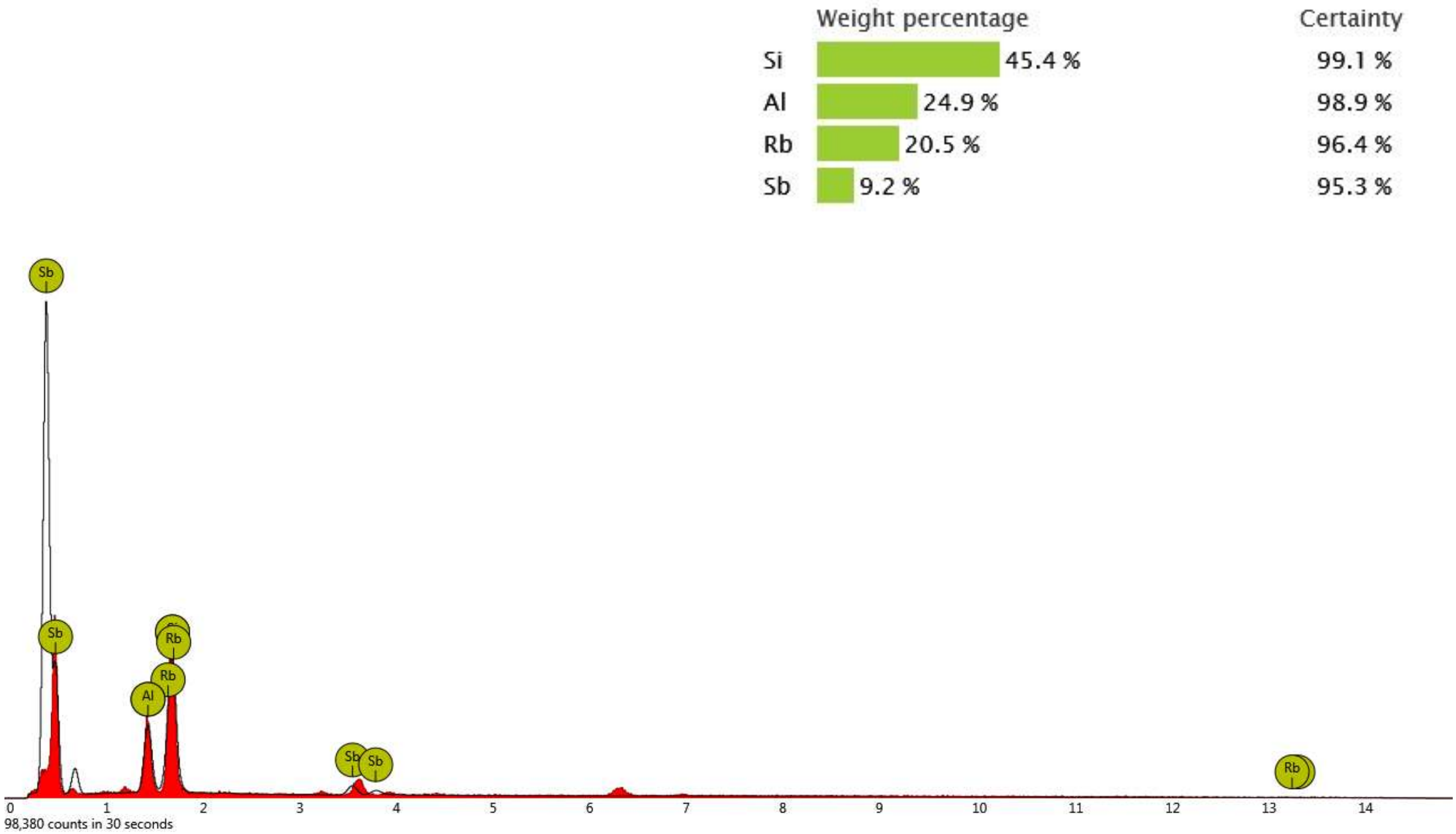

Plate 4.4d: Energy-dispersive x-ray spectroscopy for optimally (4 % cement / 6 % IOT) modified black cotton soil after 28 days curing period(Point2).

4.2.7.3 Fibre metric analysis

The Fibre metric 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 technique could be used to make qualitative and quantitative inferences about unsaturated behaviour of soils such as water retention and water permeability properties, evolution of pore size density functions along different hydro-mechanical paths, macroscopic volume change behaviour, micro and macro scale interactions, and so on (Romero and Simms, 2008).

4.2.7.3a Fibre histogram

The variations of fabrics of the natural black cotton soil and soil - cement mixtures with iron ore tailing content examined with a scanning electron microscope are shown in the histograms presented on Plate 4.5a-b. It was observed that the length of black cotton soil – cement – iron ore tailing mixture fabric decreased from the value of 2.23 µm for the natural soil to a value of 875.16 nm for the modified soil. The decrease in length of soil fabrics could be due to the flocculent nature of IOT and also as a result of cation ion exchange reaction that led to the formation of calcium silicate between the free lime in the cement and the silica in the clay structure. Another possible explanation for the decrease in the soil fabric for the modified soil is the change in particle orientation, or the positions of adjacent particles relative to each other, and texture or appearance of group particles

(Mitchell, 1956). The decrease in fabrics of the soil for the modified sample is an indication of flocculation of the soil particle with cement / IOT treatment.

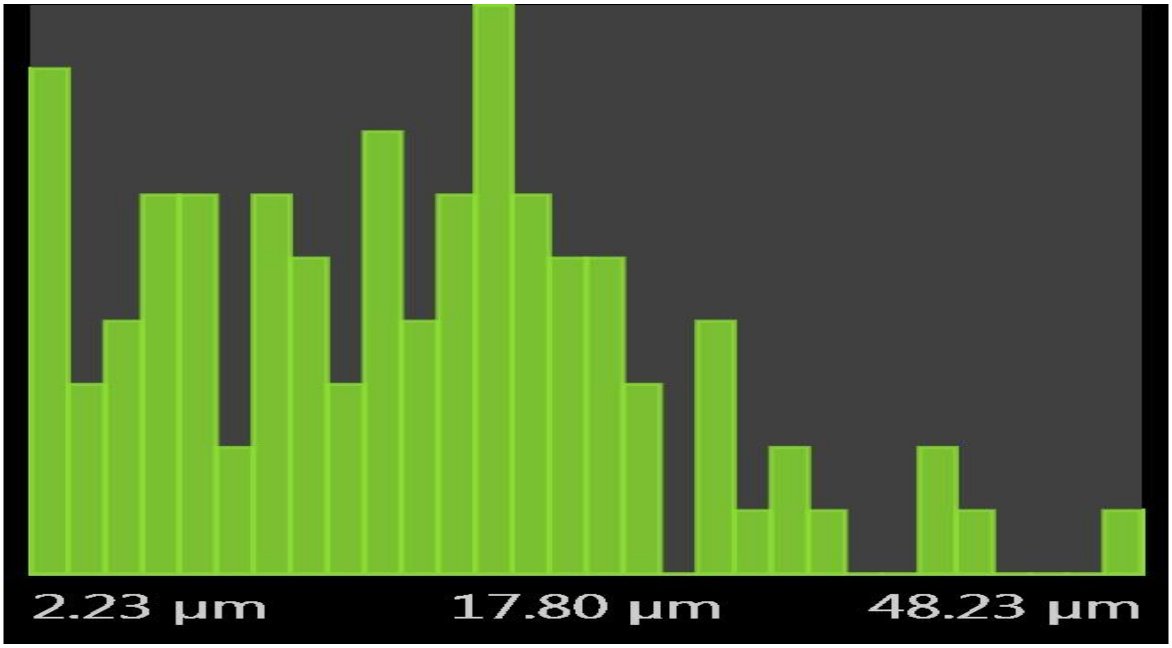

Plate 4.5a: Fibre histogram of the natural black cotton soil.

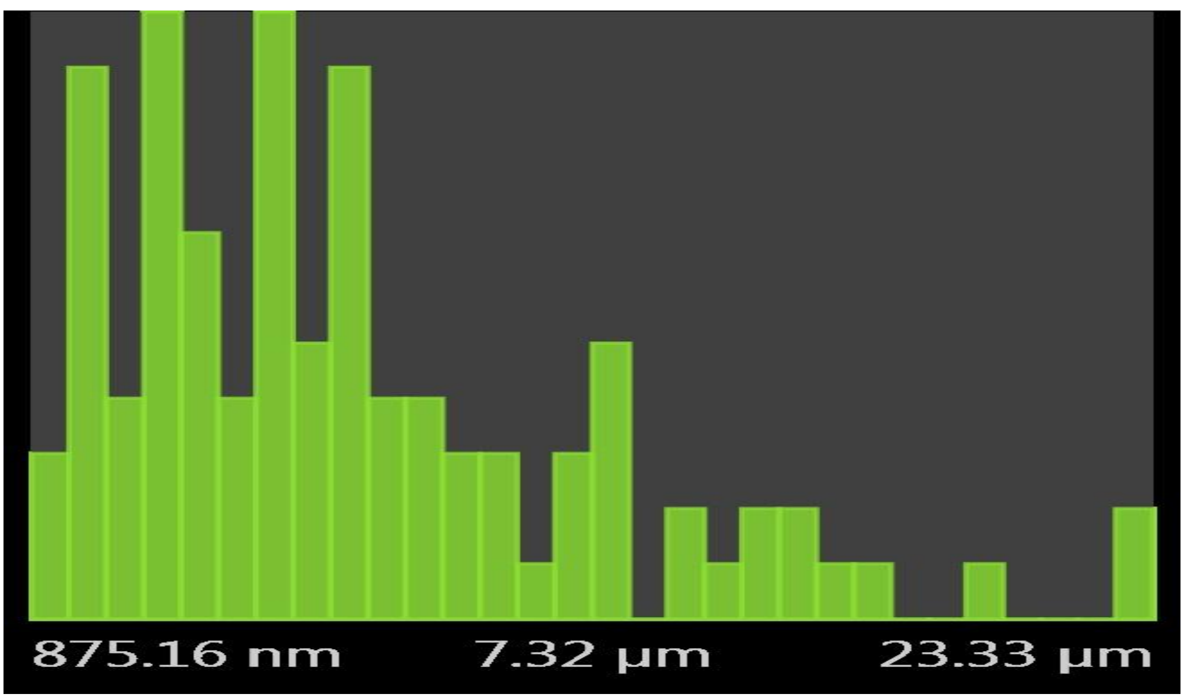

Plate 4.5b: Fibre histogram for the optimally (4 % cement / 6 % IOT) modified black cotton soil.

4.2.7.3b Pore histogram

The variation of surface area of pores of the natural black soil and soil-cement mixtures with iron ore tailing content is shown in Plate 4.6a-b. It was observed that the surface area of pores within soil – cement mixtures considered decreased from the value of 2.75μm^2 for the natural soil to a value of 0.84nm^2 for the modified soil. This technique 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 (see Plate 4.6a-b) . The decrease in pores was the result of the re-arrangement and distribution of particles, particle assemblies and pores and their contacts and connectivity in different soils. Similar behaviour was reported 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).

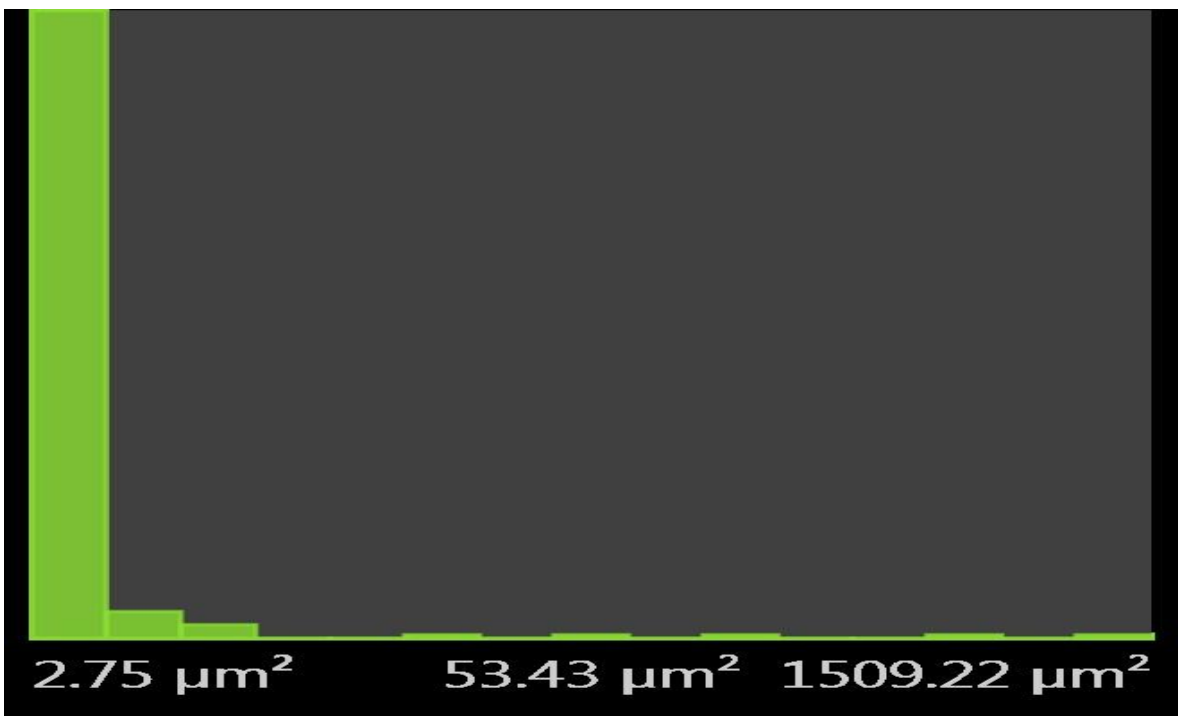

Plate 4.6a: Pore histogram for the natural black cotton soil.

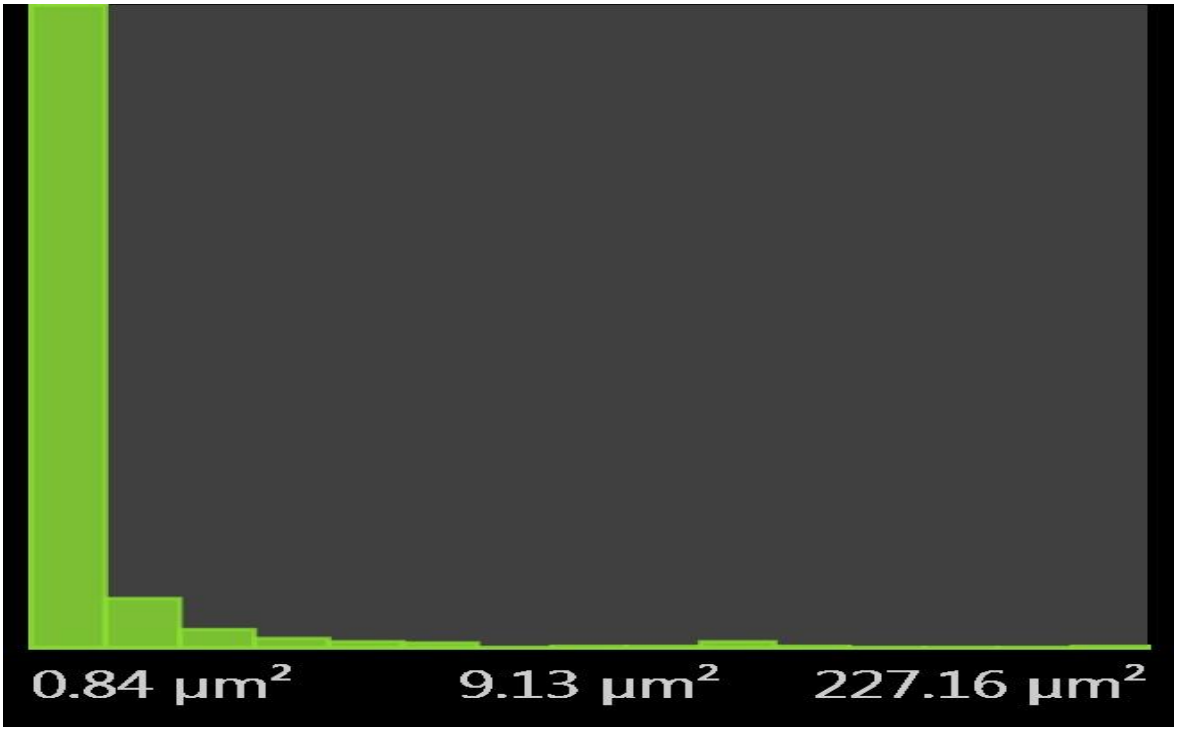

Plate 4.6b: Pore histogram for the optimally (4 % cement / 6 % IOT).modified black cotton soil.

4.3 Leaching Potential of Black Cotton Soil – Cement – Iron Ore Tailing Mixture

4.3.1 Effect of iron ore tailing on pH of soil – cement mixtures

The variation of pH of black cotton soil-cement mixtures with iron ore tailing content is shown in Fig. 4.13a. It was observed that the pH of the black cotton soil – cement-IOT mixtures considered increased from its natural value of 6.24 to 7.04 at 0% cement 10% IOT content. The same trend of increase was observed for 1 and 2% cement content from 7.1 to 7.28 at 1% Cement 0% IOT up to 10 % IOT and 7.33 to 10.70 at 2% Cement 0% IOT up to 10 % IOT content. The increase in pH could be due to alkaline nature of IOT (pH = 9.72) that caused the increase in pH of the acidic black cotton soil – cement mixture. The acid neutralization property may have arisen from the high CEC (24.6 Cmol/kg) of IOT by the solution proton (H^+) which was exchanged with Ca^{2+} ion present in the clay structure. This is in agreement with the findings of Liu and Lal (2012b).

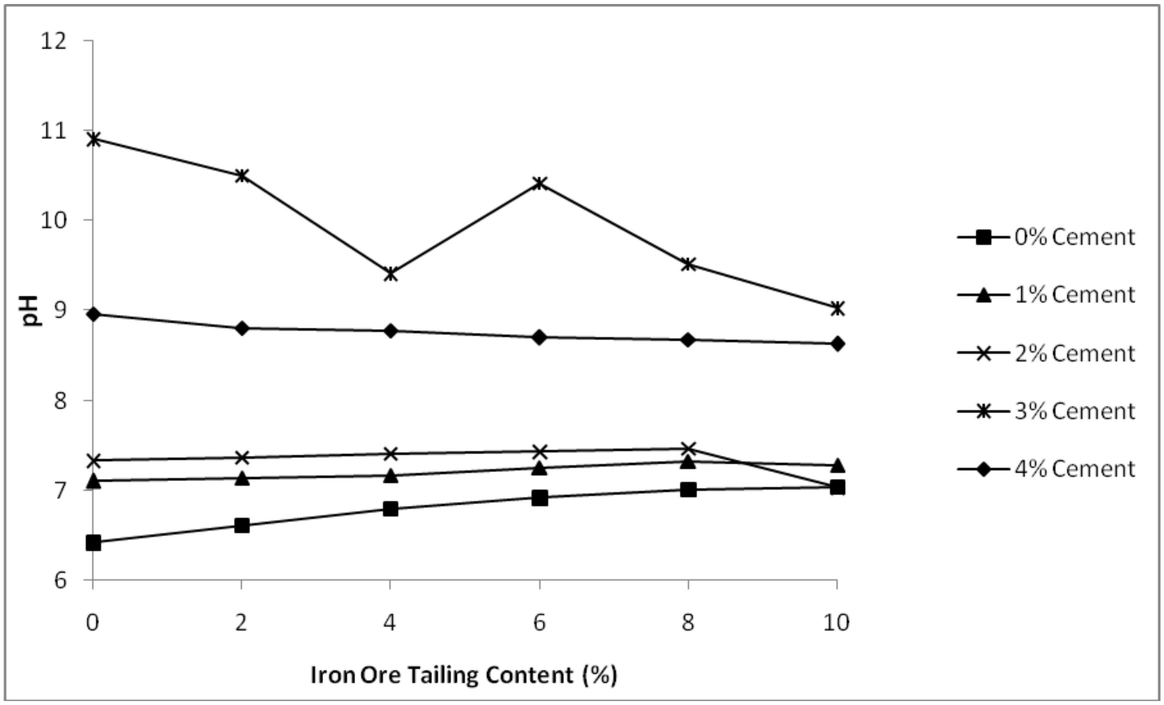

Fig. 4.13a: Variation of pH of black cotton soil - cement mixtures with iron ore tailing content.

The increase in pH of black cotton soil – cement mixture with increase in IOT content could also be as a result of increase in free lime present in the soil with higher IOT treatment that resulted in the higher alkalinity (i.e., pH) of the modified soil (Osinubi,*et al.,* 2010). Amadi (2010a) reported that the increase in pH observed in specimens containing industrial waste may be due to hydroxides which were created by the dissolution of oxides in the waste. A similar finding was reported by Neeraj et al. (2012).

It was also observed that pH decreased from a value of 9.70 at 3 % cement / 0 % IOT to 9.03 at 3 % cement /10 % IOT and 8.96 at 4 % cement / 0 % IOT to 8.63 at 4 % cement /10 % IOT. The decrease is attributed to decrease in the CEC of soil-cement-IOT mixture at higher cement and IOT content. Similar observations were made by Huang and Petrovic (1994), Katz et al. (1996), Liu and Lal (2012a,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 for the optimum blend at 4% cement 6% IOT falls within the permissible range of 6.5-8.5 for drinking water recommended by WHO (2006) and NIS (2007). Detailed test results are shown in Tables A4.13(a) in the Appendix.

4.3.2 Effect of cement content on pH of soil – iron ore tailing mixtures

The effect of cement content on the pH of black cotton soil-cement mixtures with iron ore tailing content is shown in Fig. 4.13b. It was noticed that the pH increases with increase in the cement content from 0% upto 3% cement. 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 modified 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 1, 2, 3 and 4% cement content as shown in Fig4.13b. This implies that the IOT has more pronounced effect on the pH that cement. At 4% cement pH decreases due to decrease in the CEC of the soil-cement-IOT mixtures as earlier discussed.

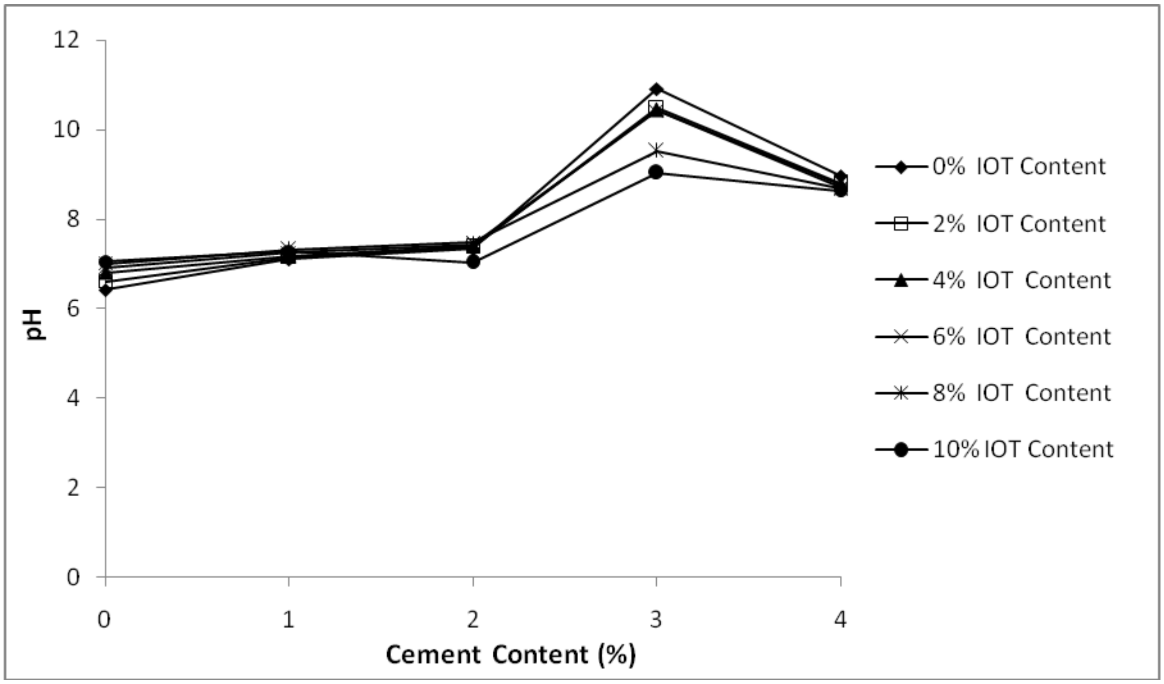

Fig. 4.13b: Variation of pH of black cotton soil - cement mixtures with iron ore tailing content.

4.3.3 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 Fig. 4.13c.The desorption isotherms are all linear in agreement with Shackelford and Daniel (1991) who reported that desorption isotherms can be linear and non-linear.

It was observed that the desorbed values increased with higher IOT content in the range of 0.116mg/l for the natural soil to a peak value of 0.16mg/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 10.552 mg/l at 10 % IOT content. The same trend of increase in the desorbed values of Fe^{2+} was observed for the stepped cement concentrations 1, 2, 3 and 4 % in the ranges 0.032 - 0.068 mg/l at 1% cement / up to 10 % IOT, 0.036 -

0.116 mg/l at 2% cement / up to 10% IOT, 0.084 - 0.112 mg/l at 3 % cement / up to 10 % IOT and 0.224 - 0.508 mg/l at 4 % cement / up to 10% IOT. This implies that more Fe^{2+} was released by the soil – cement mixture with higher IOT content. This trend of increase in the desorbed values may not be unconnected with the increasing pH of the solution (Ijimdiya and Osinubi, 2011).

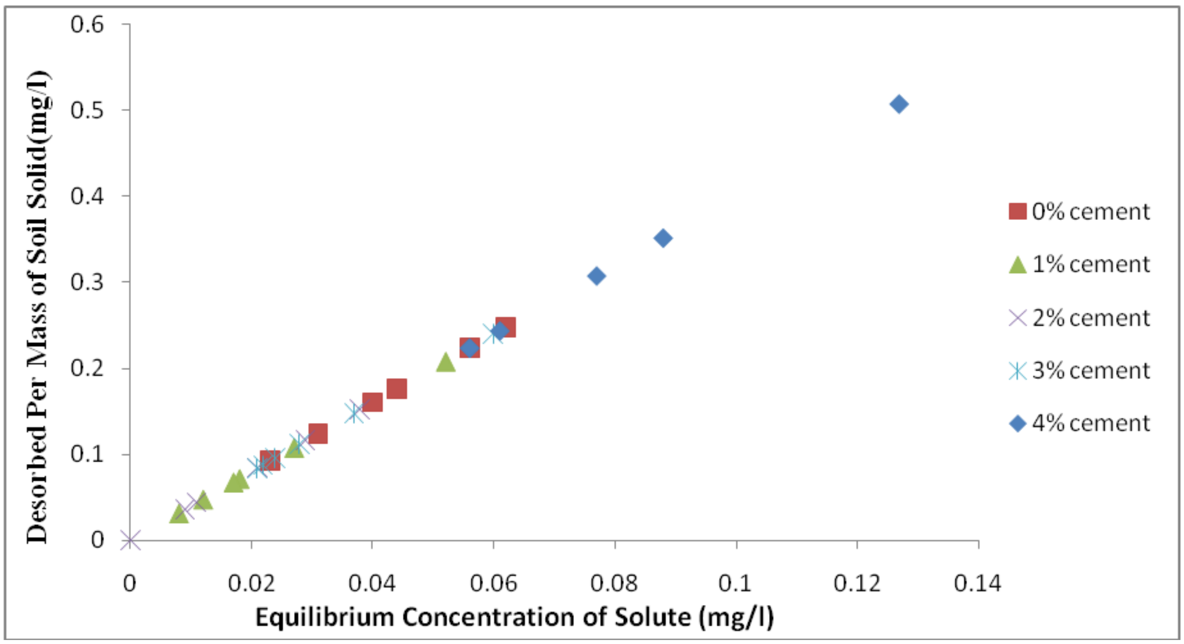

Fig.4.13c Variation of desorption isotherms for Iron (Fe^{2+}) at various cement-Iron ore tailing (IOT) contents.

The possible explanation for the increased desorption capacity of the soil-cement-IOT mixtures with higher IOT content is that the high pH value 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). The desorbed value for the optimum blend at 4 % cement / 6 % IOT 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) in Fig.4.13c

$$y = 4x \qquad (4.5)$$

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 TablesA4.13(b) in the Appendix.

4.3.4 Effect of Iron Ore Tailing on Desorption Isotherm for Iron (Fe^{2+})

The effect of iron ore tailing on the desorption isotherms for iron (Fe^{2+}) in black cotton soil - cement mixtures is shown in Fig. 4.13d.

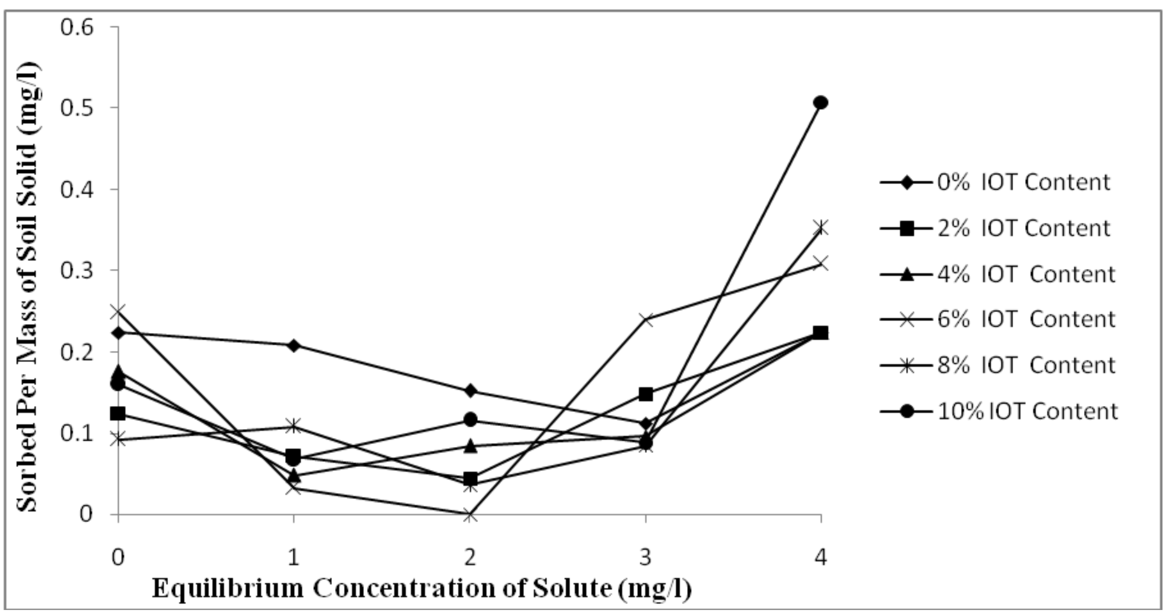

Fig.4.13d Variation of desorption isotherms for Iron (Fe^{2+}) at various cement-Iron ore tailing (IOT) contents.

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+}) in to 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 with increase in cement content from 0 % up to 3 % cement content. At 4 % cement content, a decrease in pH was observed (see Fig. 4.13b) which created a condition for the establishment of attractive electrostatics forces that enhanced the absorption of cation species (Shackelford, 1993; Osinubi and Amadi, 2003) by the soil-cement-iron ore tailing mixes. This implies that absorption of Iron (Fe^{2+}) away from the environment occurred.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Results of preliminary investigations conducted on the natural soil showed that the soil is fine-grained, with a natural moisture content of 19.5 %.The soil belongs to the CH group in the Unified Soil Classification System or A-7-6(22) soil group of the AASHTO soil classification system . The NBRRI classification for the soil is soil of low swell potential with low plasticity. About 74.4 % of the soil particles passed BS No. 200 sieve (0.075µm aperture).The soil is greyish black in colour (from wet to dry states) with a liquid limit of 56 %, plastic limit of 25 % and plasticity index of 31%. The soil has a free swell of about 40%. Results of cation exchange reaction showed a trend of decrease with higher cement and IOT contents.

Result of tests conducted showed that the liquid limit of the soil decreases from 56 to 52.6 % when treated with 0% cement / 0 % IOT up to 10% IOT. The plastic limit also decreased from 25 % to18.18 % when treated with 0 % cement / up to 10 % IOT. The plasticity index increased with higher cement and IOT contents.

The MDD values increased with higher compaction energies and IOT contents. The natural soil recorded MDD values of 1.56,1.64 and 1.68 Mg/m^3 for BSL, WAS and BSH compactions, respectively, increased to 1.66, 1.71 and 1.79 Mg/m^3 l at 0 % cement /10 % IOT treatment. The same trend of increase in MDD was observed for all the cement contents considered. OMC values decreased with higher compactive effort and IOT content. For the natural soil OMC values of 23.5, 20 and 19.3 % for BSL, WAS and BSH compactions, respectively, decreased to 18.5, 17 and 13 % at 0 % cement /10 % IOT treatment. The same trend of decrease in OMCs was observed for all the cement contents considered.

Cohesion values decreased with higher IOT content. For the natural soil cohesion values of 64, 73 and 86 kN/m^2 for BSL, WAS and BSH compactions, respectively, decreased to 44, 64 and 80 kN/m^2 at 0% cement /6 % IOT treatment. The same trend of decrease in cohesion was observed for all the cement contents considered. The values of angle of internal friction increased with higher compactive effort and up to 6 % IOT content. For the natural soil the angle of internal friction increased from 3, 6 and 7^0 for BSL, WAS and BSH compactions, respectively, to 7, 9 and 13^0 at 0 % cement /6 % IOT treatment. The same trend of increase in angle of internal friction was observed for all the cement contents considered.

Microanalysis conducted using scanning electron microscope showed a decrease in the cohesiveness and a change in the fabric orientation of the soil particle. Fibre metric analysis conducted showed a reduction in pore volumes and pore area of the modified soil. These results suggest an improvement in the workability of the modified soil.

Iron ore tailing affect the environment negatively due to its large amounts of toxic contaminants which when use for soil modification releases these contaminants to the environment by leaching. A batch equilibrium test was conducted to determine the leaching potential of iron into the environment results showed that the desorbed values of iron and pH for the optimally modified soil 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, the modified soil did not meet 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. However, a statistical analysis of test results using a two-way analysis of variance showed that cement and iron ore tailing treatment of black cotton soil significantly improved the properties of the natural soil.

5.2 Recommendation

Based on the results of the study carried out 4 % cement / 6 % IOT treatment of black cotton soil when compacted with British Standard heavy energy is recommended for use as a sub-grade material in the construction of lightly trafficked roads.

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APPENDIX

Table A4.1: Natural Moisture Content for Black Cotton Soil

Container No	X1	X2	X3
Mass of Container M1	13.6	12.7	13.2
Mass of Container + Wet Soil M2	45	50.2	45.1
Mass of Container + Dry Soil M3	39.8	44.2	39.9
Mass of Dry Soil (M3-M1) = Ws	26.2	31.5	26.7
Mass of Wet Soil (M2- M1)	31.4	37.5	31.9
Ww = (M2-M1)-(M3-M1)	5.2	6	5.2
Moisture Content W = Ww/Ws	19.85	19.05	19.48
Average Moisture Content W		19.46	

Table A4.2: Specific Gravity of Cement using Kerosene

Flask No.	X1	X2	X3
Mass of Bottle M1	44.5	40.1	37.2
Mass of Bottle + Soil M2	57	53.3	49.7
Mass of Bottle + Soil + Kerosine M3	94.5	90.6	87.2
Mass of Bottle + Kerosine M4	85.4	81	78.1
M4- M1	40.9	40.9	40.9
M3- M2	37.5	37.3	37.5
M2 – M1	12.5	13.2	12.5
(M4 - M1) - (M3 - M2)	3.4	3.6	3.4
Specific Gravity of Kerosine Gk	0.75	0.75	0.75
Gs = (M2-M1) / ((M4-M1)-(M3-M2)) * Gk	2.757353	2.75	2.757353
Average Specific Gravity, Gs		2.75	

Table A4.3: Specific Gravity of Iron Ore Tailing

Flask No.	Y1	Y2	Y3
Mass of Bottle M1	37.2	44.6	26.3
Mass of Bottle + Soil M2	57.6	63.3	50
Mass of Bottle + Soil + Water M3	101	107.1	92.6
Mass of Bottle + Water M4	86.8	94.1	76.1
M4 - M1	49.6	49.5	49.8
M3 – M2	43.4	43.8	42.6
M2 – M1	20.4	18.7	23.7
(M4 - M1) - (M3 - M2)	6.2	5.7	7.2
Gs = (M2-M1) / ((M4-M1)-(M3-M2))	3.29032	3.28070	3.29167
Average Specific Gravity, Gs		3.29	

Table A4.4: Specific Gravity Values for Soil-Cement –IOT Mixes

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	2.46	2.48	2.49	2.52	2.56
2	2.51	2.52	2.53	2.54	2.57
4	2.53	2.54	2.55	2.56	2.57
6	2.54	2.56	2.56	2.57	2.58
8	2.56	2.57	2.58	2.58	2.6
10	2.56	2.57	2.58	2.58	2.61

Table A4.5: Cation Exchange Capacity (Cmol/kg) Test Results for Soil–Cement IOT mixes.

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	52.52	63	56.6	58	58
2	53.2	58	54	55.5	55
4	54.2	57	54	53	54.5
6	52.2	53.4	53.6	51.5	52
8	50.4	50.2	49	51	52.4
10	50	50.6	34	39.6	50

Table A4.6: Free Swell (%) values for Soil-Cement–IOT mixes

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	40	40.8	42	43	50
2	41	45	43.5	44	50
4	41	46	44	45	50
6	42	47	44	48	50
8	41	48	48	49	50
10	38	45	35	46	47

Table A4.7(a): Wet Sieve Analysis Results for Soil-Cement –IOT mixes

0% CEMENT											
BS S IEVE SIZE	0% IOT % PASSING	BS SIEVE SIZE	2% IOT % PASSING	BS SIEVE SIZE	4% IOT % PASSING	BS SIEVE SIZE	6% IOT % PASSING	BS SIEVE SIZE	8% IOT % PASSING	BS SIEVE SIZE	10% IOT % PASSING
4.76	97.2	4.76	98.35	4.76	99.65	4.76	98	4.76	99.15	4.76	98.65
2.36	96.15	2.36	96.65	2.36	98.05	2.36	96.8	2.36	97.65	2.36	97.5
2	95.55	2	96	2	97.4	2	96.5	2	97.1	2	97.05
0.6	93.5	0.6	93.1	0.6	94.5	0.6	94.4	0.6	95.05	0.6	95.15
0.425	85.75	0.425	85.45	0.425	86.95	0.425	87.2	0.425	88.4	0.425	88.95
0.3	83.45	0.3	82.65	0.3	83.5	0.3	84.8	0.3	86.3	0.3	87.1
0.212	80.85	0.212	78.95	0.212	78.1	0.212	82.2	0.212	83.85	0.212	85.05
0.15	78.45	0.15	75.4	0.15	75.6	0.15	79.7	0.15	81.6	0.15	83.15
0.075	74.2	0.075	74.4	0.075	74.45	0.075	74.9	0.075	76.2	0.075	76.95
0.07437	49.71	0.0625	37.07	0.0633	34.04	0.0732	48.66	0.072	48.41	0.052	47.59
0.0548	47.18	0.0451	35.38	0.0456	31.61	0.056	43.77	0.0551	43.49	0.038	44.31
0.04119	43.81	0.0342	32.86	0.0342	29.18	0.0415	39.72	0.0404	41.03	0.029	41.03
0.03216	38.75	0.0248	29.49	0.0246	27.56	0.032	35.66	0.0311	36.92	0.022	37.74
0.02367	35.38	0.0179	26.12	0.0186	20.26	0.0235	31.61	0.0231	32.82	0.016	34.46
0.01719	32.01	0.0138	16.01	0.0146	8.11	0.0173	27.56	0.0171	28.72	0.012	27.08
0.013	25.27	0.0103	9.267	0.0105	4.86	0.0128	23.51	0.0127	23.79	0.01	11.08
0.01021	12.64	0.0085	7.582	0.0086	4.05	0.0095	18.24	0.0095	17.23	0.009	4.92
0.00844	10.95	0.0064	5.897	0.0065	0.81	0.0082	12.97	0.0082	12.31	0.006	0.00
0.00621	8.42	0.0044	4.212	0.0044	0.00	0.0062	2.43	0.006	5.744	0.004	0.00
0.00438	5.90					0.0044	0.00	0.0043	3.282		

1% 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	99.2	4.76	99.2	4.76	98.9	4.76	98.9	4.76	98.9
2.36	98.3	2.36	98.65	2.36	98.25	2.36	98	2.36	98	2.36	98.35
2	97.85	2	98.3	2	97.85	2	97.5	2	97.55	2	98
0.6	96	0.6	96	0.6	95.95	0.6	95.6	0.6	95.8	0.6	96.15
0.425	89.5	0.425	89.65	0.425	89.15	0.425	89	0.425	90.2	0.425	90.15
0.3	87.8	0.3	87.75	0.3	86.95	0.3	86.9	0.3	88.5	0.3	88.45
0.212	85.95	0.212	85.7	0.212	84.35	0.212	84.4	0.212	86.6	0.212	86.55
0.15	84.15	0.15	83.65	0.15	81.7	0.15	81.8	0.15	84.7	0.15	84.75
0.075	81.15	0.075	80.65	0.075	77.75	0.075	77.2	0.075	80.7	0.075	80.75
0.03693	49.43	0.0298	43.11	0.0202	45.36	0.0266	48.4	0.0507	48.29	0.022	36.83
0.02955	43.57	0.0218	39.79	0.0172	29.69	0.0215	38.6	0.0402	40.92	0.019	19.64
0.02187	40.22	0.0161	35.64	0.0129	23.92	0.0175	26.3	0.0307	37.65	0.014	17.19
0.01645	35.19	0.0116	33.99	0.0091	23.09	0.0129	22.2	0.023	32.74	0.01	12.93
0.01207	31.84	0.0088	29.84	0.0077	20.62	0.0091	22.2	0.0173	27.83	0.008	11.87
0.00884	28.49	0.0071	29.01	0.0054	20.62	0.0075	21.3	0.0125	24.55	0.006	10.64
0.00739	25.97	0.005	28.18	0.0038	20.62	0.0053	21.3	0.0091	22.1	0.004	9.003
0.00541	23.46	0.0037	25.28			0.0038	20.1	0.0075	20.46		
0.00381	22.62							0.0054	19.64		
								0.0039	17.19		

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	98.25	4.76	99.1	4.76	99.5	4.76	99.5	4.76	99.3	4.76	98.85
2.36	96.85	2.36	97.55	2.36	98.25	2.36	98.4	2.36	98.2	2.36	97.9
2	96.2	2	96.7	2	97.85	2	97.9	2	97.8	2	97.4
0.6	93.55	0.6	94	0.6	95.65	0.6	95.6	0.6	95.7	0.6	95.2
0.425	85.6	0.425	86.6	0.425	89	0.425	88.7	0.425	88.75	0.425	88.3
0.3	83.6	0.3	84.55	0.3	86.9	0.3	86.8	0.3	86.7	0.3	86.4
0.212	81.35	0.212	81.9	0.212	84.25	0.212	84.8	0.212	84.55	0.212	84.45
0.15	78.8	0.15	79.35	0.15	81.65	0.15	82.5	0.15	82.35	0.15	82.45
0.075	75.85	0.075	75.25	0.075	77.3	0.075	78.9	0.075	78.65	0.075	78.9
0.0281	49.30	0.0137	48.78	0.0103	43.6	0.0108	40.2	0.0145	43.27	0.056	44.09
0.02229	40.94	0.0112	38.03	0.0085	31.26	0.0086	28.7	0.0119	32.25	0.044	38.37
0.01628	38.44	0.0089	28.11	0.0074	24.27	0.0075	22.2	0.0095	18.78	0.033	35.92
0.01235	31.33	0.0077	22.32	0.0056	16.86	0.0055	17.2	0.0082	12.25	0.025	29.39
0.00944	23.40	0.0058	14.88	0.004	16.04	0.004	17.2	0.006	8.981	0.019	21.23
0.00791	19.22	0.0041	14.88					0.0042	8.981	0.014	15.92
0.00581	15.88									0.01	15.51
0.00411	15.88									0.008	15.51
										0.006	14.7
										0.004	12.25

3% 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	99.15	4.76	97.65	4.76	98.3	4.76	98.5	4.76	98.5	4.76	99.6
2.36	97.85	2.36	95.75	2.36	97.1	2.36	96.8	2.36	97.3	2.36	98.6
2	96.95	2	95.15	2	96.45	2	96.2	2	96.6	2	98
0.6	94.75	0.6	93.4	0.6	94.6	0.6	93.9	0.6	95.35	0.6	96.4
0.425	88.3	0.425	86.6	0.425	88.45	0.425	87.3	0.425	89.2	0.425	89.4
0.3	86.55	0.3	84.65	0.3	86.65	0.3	85.5	0.3	87.1	0.3	87.2
0.212	84.65	0.212	82.55	0.212	84.4	0.212	83.3	0.212	83.6	0.212	84.8
0.15	83.55	0.15	81.4	0.15	83	0.15	82.5	0.15	81.45	0.15	83.6
0.075	80.1	0.075	76.7	0.075	77.8	0.075	76.3	0.075	71.55	0.075	76.45
0.0212	42.69	0.0196	47.01	0.019	48.41	0.0192	47.5	0.0373	46.95	0.019	47.35
0.01678	33.82	0.0166	33.81	0.0161	34.87	0.016	36.8	0.0296	42.46	0.016	37.56
0.01281	26.53	0.013	23.92	0.0127	25.44	0.0129	23.7	0.0222	37.97	0.014	17.96
0.00945	20.72	0.0098	16.49	0.0096	18.87	0.0097	17.2	0.0178	26.13	0.01	8.981
0.00788	18.24	0.0082	13.19	0.0079	16	0.0081	13.5			0.009	5.715
0.00555	17.41	0.0057	12.37	0.0055	12.31	0.0052	13.1			0.006	2.858
0.00397	17.41	0.0041	11.55	0.0041	12.31	0.0041	11.5			0.004	1.633

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	98.2	4.76	96.25	4.76	96.7	4.76	99.6	4.76	98	4.76	98.35
2.36	96.25	2.36	94.55	2.36	95.3	2.36	98.1	2.36	96.4	2.36	97
2	95.55	2	93.85	2	94.6	2	97.5	2	95.7	2	96.35
0.6	93	0.6	91.7	0.6	92.85	0.6	95.3	0.6	93.7	0.6	94.55
0.425	84.75	0.425	84.45	0.425	84.85	0.425	85.9	0.425	86.25	0.425	86.75
0.3	80.5	0.3	80.55	0.3	81.6	0.3	82.9	0.3	82.75	0.3	82.9
0.212	74.65	0.212	74.4	0.212	76.7	0.212	78.4	0.212	77.75	0.212	77
0.15	73.6	0.15	73.35	0.15	76.15	0.15	76.7	0.15	75.5	0.15	76.2
0.075	60.15	0.075	59.9	0.075	63.1	0.075	64.5	0.075	61.75	0.075	60.85
0.05768	41.03	0.0601	37.65	0.0744	47.47	0.0531	46.5	0.0595	36.56	0.078	41.74
0.04305	36.92	0.0443	35.19	0.054	45.83	0.0379	45.3	0.0441	34.53	0.057	39.72
0.0327	33.64	0.0328	33.97	0.04	42.15	0.0283	43.3	0.0324	34.13	0.042	36.48
0.0243	29.13	0.0244	29.46	0.0305	38.88	0.0223	35.9	0.0238	29.66	0.031	35.26
0.01783	25.44	0.0196	14.32	0.0243	29.87	0.0187	19.6	0.0198	11.78	0.024	28.77
0.01287	22.15	0.0144	9.003	0.0194	15.55	0.0139	13.5			0.02	8.106
0.00982	13.13	0.0104	5.729	0.0143	10.64	0.0101	8.98			0.015	1.216
0.00857	4.103	0.0085	4.092	0.0102	7.366	0.0083	7.76				
0.00633	0.821	0.006	4.092	0.0083	7.366	0.0059	7.76				
0.00444	0.41	0.0044	3.683	0.006	5.729	0.0043	6.53				
				0.0043	4.911						

Table A4.7(b): Dry Sieve Results for Soil-Cement– IOT mixes (BSL Compaction)

BS SIEVE SIZE	0% CEMENT						1% 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	26.6	20.3	34.9	31.75	56.85	47.45	61.6	63.3	56.85	69.35	76.35	59.7
2.36	11.95	8.85	15.5	13.6	25.7	18.65	27.55	26.35	26.2	34.75	37.35	27.5
2	9.9	7.1	12.65	11.55	20.7	14.55	21.65	19.95	20.3	27.1	29.4	22.55
0.6	6	4.5	8.05	8.35	12.3	8.55	11.95	11.85	11.1	13.9	15.05	13.6
0.425	2.75	1.6	3.55	4.55	6.25	4.8	5.6	5.8	4.9	5.4	6.95	6.55
0.3	2.2	1.2	2.7	4	5.4	4.2	4.65	4.8	4	4.3	5.8	5.5
0.212	1.75	0.85	1.95	3.4	4.7	3.65	3.95	3.95	3.25	3.4	4.95	4.5
0.15	1.25	0.55	1.2	2.85	4.15	3.15	3.45	3.4	2.7	2.8	4.15	3.6
0.075	0.95	0.25	0.4	2.3	3.5	2.6	2.9	2.6	1.95	1.85	3.15	2.2

BS SIEVE SIZE	2% CEMENT						3% 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	67.35	62.2	67.4	64.95	73.35	83.65	73.55	78.8	77.45	76.1	86.75	86.8
2.36	29.5	25.65	31.15	25.9	33.2	44.75	38.3	41.4	42.85	38.1	48	50.95
2	22.65	19.85	24.8	19.35	25.15	35	30.7	32.25	34.15	30.05	37.25	41
0.6	11.5	10.95	13.9	10.45	12.75	16.05	15	14.1	17.5	15.55	17.5	22.5
0.42	5.25	5.25	6.75	5.5	5.85	6.15	5.65	5.45	7.25	7.4	8.05	10.9
0.3	4.45	4.4	5.75	4.8	5.1	5.15	4.7	4.55	5.95	6.4	7	9.55
0.21	3.8	3.65	4.85	4.15	4.5	4.55	4	3.9	4.9	5.55	6.15	8.4
0.15	3.3	3.05	4.15	3.55	4.1	4.05	3.35	3.45	4	4.9	5.5	7.45
0.07	2.75	2.3	3.25	2.6	3.3	3.1	2.7	2.8	2.8	3.85	4.35	5.8

BS SIEVE SIZE	4% CEMENT					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	75.5	82.15	86.95	89.5	95.35	98
2.36	41.8	39.95	44.45	52.55	69.75	73.7
2	33.45	30.6	34.15	41.6	60.7	65.15
0.6	16.65	14	15.3	17.95	36.5	39.2
0.425	5.8	5.7	6.35	6.35	9.5	7.7
0.3	4.55	4.85	5.6	5.45	7.4	4.7
0.212	3.7	4.2	5.05	4.9	6.1	3.35
0.15	3.05	3.7	4.7	4.4	5.25	2.75
0.075	2.3	3.1	4.15	3.75	4.2	1.95

Table A4.7(c): Dry Sieve Results for Soil-Cement– IOT mixes (WAS Compaction)

BS SIEVE SIZE	0% CEMENT						1% 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	52.15	33.75	53.9	43	74.65	64.1	77.2	65	71.3	70.6	71.15	67.3
2.36	22.9	14.05	21.05	14.9	42.5	33.05	38.55	33.5	33.55	34.85	37.5	31.1
2	18.3	11.3	16.2	11.55	34.3	26.95	30.3	26.35	26.05	26.55	30.1	24.4
0.6	9.95	6.8	8.35	6.6	18.2	14.3	15.25	13.55	13.6	11.9	15.7	13.2
0.425	4.45	2.9	3.5	3.2	7	7.1	7.15	5.25	5.9	4.75	6.35	5.7
0.3	3.7	2.4	2.9	2.75	5.8	6.2	6.25	3.95	4.7	3.9	5.15	4.5
0.212	3.1	1.85	2.4	2.3	5	5.5	5.55	3	3.7	3.3	4.15	3.6
0.15	2.5	1.45	1.9	1.9	4.2	4.9	4.85	2.25	3	2.95	3.35	2.7
0.075	2.1	1	1.35	1.55	3.5	4.2	4.35	1.25	2	2.2	2.25	1.2

BS SIEVE SIZE	2% CEMENT						3% 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	79.25	80.4	76.95	86.25	86.2	89	75.5	83.25	90.6	89.85	93.85	91.4
2.36	39.95	37.6	34.4	49.85	55.9	54.9	38.25	46.8	56.2	55.05	68.8	59.15
2	29.95	27.2	26.45	39.4	47.45	45.85	30.3	37.7	46.5	46.2	61.35	50.1
0.6	12.1	11.25	12.6	17.05	23.6	23.55	14.15	18.1	23.5	24.25	36.2	28.7
0.425	3.8	4.85	5.35	5.5	5.2	6.8	5.8	5.35	6	8.25	8.9	9.65
0.3	3	4.25	4.45	4.65	3.7	5.45	5.05	4.1	4.5	6.7	6.85	7.65
0.212	2.35	3.75	3.7	4.05	2.9	4.75	4.5	3.35	3.55	5.7	5.7	6.4
0.15	1.85	3.3	3.05	3.55	2.35	4.15	4.05	2.7	2.85	4.95	4.95	5.55
0.075	1.25	2.75	2.35	2.85	1.65	3.35	3.55	1.95	1.95	3.9	4.1	4.1

BS SIEVE SIZE	4% CEMENT					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	85.7	93.9	92.4	94.2	96.15	99.25
2.36	52.65	59.3	61.4	59.75	64.3	74.6
2	42.05	49.35	52.65	49.35	54.55	66.2
0.6	18.4	24.85	27.6	25.1	28.45	41.1
0.425	5.55	7.65	5.1	5.9	6.3	9.05
0.3	4.4	6.35	3.45	4.4	4.55	5.7
0.212	3.65	5.55	2.6	3.5	3.65	4
0.15	3.1	5.05	2.1	2.95	3.1	3.25
0.075	2.5	4.3	1.55	2.3	2.25	2.15

Table A4.7(d): Dry Sieve Results for Soil-Cement– IOT mixes (BSH Compaction)

BS SIEVE SIZE	0% CEMENT						1% 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	62.6	30.2	64.6	80.3	86.35	88.05	82.95	90.25	89.7	81.6	92.55	85.25
2.36	32.75	12.6	27.9	40.45	55.3	57.75	46.7	58.2	54.95	48.7	66.2	49.45
2	26.8	10.45	20.7	31.1	47.2	50.15	37.05	47.8	45.75	41.1	57.95	39.05
0.6	14.95	7.7	9.95	14.3	27.65	30.35	18.55	22.65	20.5	20.5	35.1	16.7
0.425	7	4	3.8	5.25	7.85	9	8.3	6.15	6.3	4.8	8	4.7
0.3	6	3.4	3.2	4.6	5.85	6.8	6.95	4.6	4.95	3.35	5.45	3.7
0.212	5.25	2.8	2.7	4.15	4.7	5.45	5.95	3.5	3.95	2.45	3.95	2.95
0.15	4.65	2.3	2.3	3.85	4.05	4.6	5.1	2.6	3.25	1.8	3.1	2.45
0.075	4.2	1.85	1.85	3.4	3.3	3.7	4.25	1.8	2.2	0.95	1.9	1.65

BS SIEVE SIZE	2% CEMENT						3% 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	87.75	86.95	90.05	86.55	96.2	95.75	89.1	89.95	94.25	96.05	97.25	97.15
2.36	54.45	53.45	58.65	52.6	71.65	64.05	55.7	57	66.9	72.05	72.45	71.45
2	44.85	44.05	50.7	44.05	63.7	55.75	47.3	48.4	58.65	63.8	64.15	63.6
0.6	21.9	21.3	27.65	21.3	41.1	34.3	25.8	26.35	34.9	39.65	40.3	42.15
0.425	6.1	6.2	5.95	5.65	11.65	9.6	6.5	7.05	8.1	10.5	11.65	13.15
0.3	4.85	5	4.05	4.45	7.75	6.8	4.9	5.35	5.55	7.25	8.65	9.65
0.212	4.1	4.25	3	3.75	5.6	5.15	3.95	4.3	4.1	5.5	6.8	7.45
0.15	3.6	3.8	2.4	3.25	4.6	4.25	3.4	3.7	3.3	4.55	5.85	6.1
0.075	3.1	3.2	1.75	2.6	3.45	2.9	2.9	3.05	2.4	3.45	4.65	4.3

BS SIEVE SIZE	4% CEMENT					
	0% IOT % PASSING	2% IOT % PASSING	4% IOT % PASSING	6% IOT % PASSING	8% IOT % PASSING	10% IOT % PASSING
4.76	90.4	91.4	97.55	97.85	99	99.5
2.36	60.35	58.65	72.75	77	77.75	81.45
2	51.25	50.45	64.6	69.85	70.35	74.15
0.6	27.9	27.75	39.15	45.85	46.75	50.35
0.425	6.45	8.05	8.5	11.55	14.25	16.1
0.3	4.7	6.4	5.55	7.35	9.35	11
0.212	3.75	5.45	4	5.05	6.35	7.55
0.15	3.3	4.85	3.25	4	4.8	5.7
0.075	2.9	4.25	2.5	3.05	3	3.55

Table A4.8(a): Liquid Limit (%) Test Results for Soil–Cement –IOT mixes

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	56	55.5	55.8	53.4	50.5
2	54.2	54	55.2	53	50.3
4	54	53.6	54.5	52	50.1
6	53.8	52.8	54	49.8	49.4
8	52.8	52.5	53.5	47	49
10	52.6	52	53.1	46.4	48.1

Table A4.8(b): Plastic Limit (%) Test Results for Soil–Cement –IOT mixes

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	25	22.22	18.18	20	18.18
2	23.1	20.5	18.2	18.25	17.14
4	22.22	20	18.18	16.67	12.5
6	21.11	18.18	17.8	14	11.86
8	20	17.14	16.7	11	11.1
10	18.18	16	15.38	9	9.09

Table A4.8(c): Plasticity Index (%) Test Results for Soil–Cement –IOT mixes

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	31	33.28	37.62	33.4	32.32
2	31.1	33.5	37	34.75	33.16
4	31.78	33.6	36.32	35.33	37.6
6	32.69	34.62	36.2	35.8	37.54
8	32.8	35.36	36.8	36	37.9
10	34.42	36	37.72	37.4	39.01

Table A4.8(d):Linear Shrinkage (%) Test Results for Soil–Cement –IOT mixes

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	16.32283	15.9055	14.48031	10.68504	7.496063
2	16.45669	16.2598	14.22047	11.22047	7.314961
4	16.38583	15.6535	13.3937	10.40157	7.220472
6	15.73228	14.5307	13.51969	9.779528	7.244094
8	15.29921	13.4566	13.08661	8.511811	6.866142
10	15.09449	13.4126	12.80315	8.464567	7.149606

Table A4.9 (a): Maximum Dry Density (kN/m^3) Test Results for Soil–Cement–IOT mixes (BSL Compaction)

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	1.56	1.582	1.53	1.55	1.56
2	1.57	1.59	1.57	1.56	1.562
4	1.62	1.62	1.58	1.6	1.6
6	1.63	1.64	1.61	1.61	1.63
8	1.64	1.64	1.62	1.614	1.66
10	1.66	1.66	1.64	1.63	1.68

Table A4.9 (b): Maximum Dry Density (kN/m^3) Test Results for Soil–Cement–IOT Mixes (WAS Compaction)

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	1.64	1.6	1.58	1.65	1.63
2	1.66	1.65	1.63	1.66	1.68
4	1.67	1.67	1.63	1.68	1.687
6	1.687	1.68	1.67	1.69	1.69
8	1.69	1.68	1.745	1.72	1.76
10	1.71	1.69	1.765	1.74	1.77

Table A4.9 (c): Maximum Dry Density (kN/m^3) Test Results for Soil–Cement–IOT Mixes (BSH Compaction)

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	1.68	1.73	1.69	1.754	1.74
2	1.73	1.8	1.77	1.77	1.78
4	1.75	1.81	1.78	1.779	1.81
6	1.78	1.83	1.8	1.795	1.82
8	1.77	1.84	1.87	1.83	1.89
10	1.79	1.85	1.874	1.84	1.9

Table A4.10 (a): Optimum Moisture Content (%) Tests Results for Soil–Cement–IOT Mixes (BSL Compaction)

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	23.5	21.2	22.6	22	21.8
2	20.5	20.8	22.4	21.5	21.4
4	20.2	20.5	22.2	21.4	21
6	19	20	22	21.3	20.5
8	19.5	20.3	20.8	21.2	18.5
10	18.5	20.2	19	21	16

Table A4.10 (b): Optimum Moisture Content (%) Tests Results for Soil–Cement–IOT Mixes (WAS Compaction).

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	20	20.5	21.7	20.4	20.8
2	19.8	19.8	21.5	20	18.7
4	17.5	19.5	21.2	18.4	18
6	17.7	19.4	19.5	17.8	17.5
8	17	19.2	17.7	18.4	17
10	17	19	17.5	17.4	15

Table A4.10 (c): Optimum Moisture Content (%) Tests Results for Soil–Cement–IOT Mixes (BSH Compaction).

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	19.3	17.8	17.8	16.8	16.7
2	18	16	17.4	16.5	16.5
4	16.6	15.5	16.8	16.4	14.6
6	13.7	14.4	16	16.2	14.5
8	13.3	14	13	14.6	12.2
10	13	15	14	14.5	12.6

Table A4.11 (a): Cohesion (kN/m^2) Tests Results for Soil–Cement–IOT Mixes (BSL Compaction).

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	64	80	72	93	88
2	62	77	59	84	85
4	61	74	52	73	80
6	44	42	48	70	70
8	55	67	70	78	141
10	67	73	102	85	210

Table A4.11 (b): Cohesion (kN/m^2) Tests Results for Soil–Cement–IOT Mixes (WAS Compaction)

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	73	90	88	110	120
2	72	89	70	107	117
4	71	79	66	105	114
6	64	66	58	96	99
8	74	76	147	126	149
10	76	100	155	180	237

Table A4.11 (c): Cohesion (kN/m^2) Tests Results for Soil–Cement–IOT Mixes (BSH Compaction)

IOT CONTENT(%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	86	156	136	188	190
2	84	154	132	165	186
4	82	145	130	160	185
6	80	134	120	108	154
8	140	110	190	192	285
10	144	172	277	208	300

Table A4.12 (a): Angle of Internal Friction (deg.) Tests Results for Soil–Cement–IOT Mixes (BSL Compaction)

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	3	5	3.5	3.5	3
2	3.8	6	5	7.4	5
4	4	7	6	7.8	5.5
6	7	10	9	9	8.5
8	4.5	5.4	5	8	4
10	4	5	3.5	4.5	3.5

Table A4.12 (b): Angle of Internal Friction (deg.) Tests Results for Soil–Cement–IOT Mixes (WAS Compaction)

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	6.3	7	5	7	6
2	6.4	9	6.2	10	11
4	6.5	11	7.5	14	12
6	9	15	12	15	16.5
8	6	11	6	10	12.5
10	5.3	8	5	7	8.3

Table A4.12 (c): Angle of Internal Friction (deg.) Tests Results for Soil–Cement–IOT Mixes (BSH Compaction).

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	6.8	10	7.5	11	8.5
2	7	12	9	12	13
4	7.5	14	12	16	16
6	13	17	13	17	17.8
8	8.4	15	12	14	15.5
10	8	14	7	10	11.5

Table A4.13(a) : pH Test Results for Soil–Cement IOT Mixes

IOT CONTENT(%)	CEMENT CONTENT(%)				
	0	1	2	3	4
0	6.42	7.1	7.33	10.91	8.96
2	6.61	7.14	7.37	10.5	8.81
4	6.8	7.17	7.41	9.41	8.78
6	6.92	7.25	7.43	10.42	8.7
8	7.01	7.32	7.47	9.52	8.68
10	7.04	7.28	7.03	9.03	8.63

Table A4.13(b): Desorption isotherms for Iron (Fe^{2+}) Test Results for Soil–Cement IOT Mixes

IOT CONTENT (%)	CEMENT CONTENT (%)				
	0	1	2	3	4
0	0.116	0.208	0.152	0.112	0.224
2	0.124	0.072	0.044	0.148	0.224
4	0.176	0.048	0.084	0.096	0.244
6	0.248	0.032	0	0.24	0.308
8	0.092	0.108	0.036	0.084	0.352
10	0.16	0.068	0.116	0.088	0.508

Table A4.14: Analysis of Variance for Specific Gravity of Soil-Cement -IOT Mixes

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	SUMMARY	Count	Sum	Average	Variance
0% IOT	5	12.51	2.50244	0.00147	0%CEMENT	6	15.163	2.5272	0.00138
2% IOT	5	12.67	2.534	0.00053	1%CEMENT	6	15.24	2.54	0.00124
4% IOT	5	12.75	2.55	0.00025	2%CEMENT	6	15.29	2.5483	0.001177
6% IOT	5	12.81	2.562	0.00022	3%CEMENT	6	15.35	2.5583	0.000577
8% IOT	5	12.89	2.578	0.00022	4%CEMENT	6	15.49	2.5817	0.000377
10% IOT	5	12.9	2.58016	0.00034					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.021742	5	0.004348	43.35574	4.652E-10	2.71089
CEMENT	0.010143	4	0.002536	25.28288	1.408E-07	2.866081
Error	0.002006	20	0.0001			
Total	0.033891	29				

Table A4.15: Analysis of Variance for cation Exchange capacity of Soil-Cement –IOT Mixes

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	288.12	57.624	14.07088	0%CEMENT	6	312.52	52.08667	2.621067
2% IOT	5	275.7	55.14	3.348	1%CEMENT	6	332.2	55.36667	24.23067
4% IOT	5	272.7	54.54	2.208	2%CEMENT	6	301.2	50.2	69.056
6% IOT	5	262.7	52.54	0.838	3%CEMENT	6	308.6	51.43333	40.46667
8% IOT	5	253	50.6	1.54	4%CEMENT	6	321.9	53.65	7.815
10% IOT	5	224.2	44.84	57.848					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	498.3	5	99.66033	8.952385	0.0001366	2.711
CEMENT	96.77	4	24.19155	2.173102	0.10911462	2.866
Error	222.6	20	11.13227			
Total	817.7	29				

Table A4.16: Analysis of Variance for Free Swell of Soil-Cement –IOT Mixes

SUMMARY	Count	Sum	Average	Variance	SUMMARY	Count	Sum	Average	Variance
0% IOT	5	215.8	43.16	15.928	0% CEMENT	6	243	40.5	1.9
2% IOT	5	223.5	44.7	10.95	1% CEMENT	6	271.8	45.3	6.22
4% IOT	5	226	45.2	10.7	2% CEMENT	6	256.5	42.75	18.375
6% IOT	5	231	46.2	10.2	3% CEMENT	6	275	45.83333	5.366667
8% IOT	5	236	47.2	12.7	4% CEMENT	6	297	49.5	1.5
10% IOT	5	211	42.2	28.7					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	86.68167	5	17.33633	4.327232	0.007859	2.71089
CEMENT	276.5853	4	69.14633	17.25926	2.86E-06	2.866081
Error	80.12667	20	4.006333			
Total	443.3937	29				

Table A4.17 (a): Analysis of Variance for Liquid Limit of Soil-Cement –IOT Mixes

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	271.2	54.24	5.453	0% CEMENT	6	323.4	53.9	1.484
2% IOT	5	266.7	53.34	3.498	1% CEMENT	6	320.4	53.4	1.588
4% IOT	5	264.2	52.84	3.223	2% CEMENT	6	326.1	54.35	1.051
6% IOT	5	259.8	51.96	4.868	3% CEMENT	6	301.6	50.267	9.22667
8% IOT	5	254.8	50.96	7.933	4% CEMENT	6	297.4	49.567	0.83867
10% IOT	5	252.2	50.44	8.993					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	52.53767	5	10.50753	11.41875	2.617E-05	2.71089
CEMENT	117.468	4	29.367	31.91371	2.005E-08	2.866081
Error	18.404	20	0.9202			
Total	188.4097	29				

Table A4.17 (b): Analysis of Variance for Plastic Limit of Soil-Cement –IOT Mixes

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	103.58	20.716	8.49748	0%CEMENT	6	129.6	21.6017	5.73817
2% IOT	5	97.19	19.438	5.69072	1%CEMENT	6	114.0	19.0067	5.35002
4% IOT	5	89.57	17.914	13.4557	2%CEMENT	6	104.4	17.4067	1.31738
6% IOT	5	82.95	16.59	13.3759	3%CEMENT	6	88.92	14.82	18.2314
8% IOT	5	75.94	15.188	15.8757	4%CEMENT	6	79.87	13.3117	12.7673
10% IOT	5	67.65	13.53	17.8451					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	178.8234	5	35.764677	18.725723	6.23E-07	2.7108898
CEMENT	260.764	4	65.190988	34.132795	1.13E-08	2.8660814
Error	38.19845	20	1.9099223			
Total	477.7858	29				

Table A4.17(c): Analysis of Variance for Plasticity Index of Soil-Cement –IOT Mixes

SUMMARY	Count	Sum	Average	Variance	SUMMARY	Count	Sum	Average	Variance
0% IOT	5	167.12	33.424	6.84908	0%CEMENT	6	193.2	32.215	1.96071
2% IOT	5	169.51	33.902	4.72002	1% CEMENT	6	206.3	34.39333	1.246827
4% IOT	5	174.63	34.926	5.22808	2% CEMENT	6	221.6	36.94333	0.405187
6% IOT	5	176.85	35.37	3.3319	3% CEMENT	6	212.6	35.44667	1.786867
8% IOT	5	178.86	35.772	3.65992	4% CEMENT	6	217.5	36.255	7.76391
10% IOT	5	184.55	36.91	3.0836					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	40.3	5	8.0604	6.31812	0.0011344	2.711
CEMENT	81.98	4	20.494	16.0639	4.899E-06	2.866
Error	25.52	20	1.2758			
Total	147.8	29				

Table A4.17(d): Analysis of Variance for Linear shrinkage of Soil-Cement –IOT Mixes

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	64.9	12.978	14.331	0% CEMENT	6	95.3	15.882	0.3521
2% IOT	5	65.5	13.094	14.877	1% CEMENT	6	89.2	14.87	1.5709
4% IOT	5	63.1	12.611	14.515	2% CEMENT	6	81.5	13.584	0.4212
6% IOT	5	60.8	12.161	12.516	3% CEMENT	6	59.1	9.8438	1.3189
8% IOT	5	57.2	11.444	12.792	4% CEMENT	6	43.3	7.2152	0.0432
10% IOT	5	56.9	11.385	11.588					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	13.87086	5	2.774173	11.90453	1.95E-05	2.71089
CEMENT	317.8081	4	79.45203	340.9445	4.32E-18	2.866081
Error	4.660701	20	0.233035			
Total	336.3397	29				

Table A4.18(a): Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –IOT Mixes (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	SUMMARY	Count	Sum	Average	Variance
0% IOT	5	7.782	1.556	0.0004	0% CEMENT	6	9.68	1.6133	0.0016
2% IOT	5	7.852	1.57	0.0001	1% CEMENT	6	9.732	1.622	0.0009
4% IOT	5	8.02	1.604	0.0003	2% CEMENT	6	9.55	1.5917	0.0016
6% IOT	5	8.12	1.624	0.0002	3% CEMENT	6	9.564	1.594	0.001
8% IOT	5	8.174	1.635	0.0003	4% CEMENT	6	9.692	1.6153	0.0025
10% IOT	5	8.27	1.654	0.0004					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	0.035897	5	0.007179	63.72189	1.3495E-11	2.71089
CEMENT	0.00443	4	0.001107	9.829586	0.00014482	2.866081
Error	0.002253	20	0.000113			
Total	0.04258	29				

Table A4.18(b): Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –IOT Mixes (WAS Compaction).

SUMMARY	Count	Sum	Average	Variance	SUMMARY	Count	Sum	Average	Variance
0% IOT	5	8.1	1.62	0.0008	0%CEMENT	6	10.057	1.6762	0.0006
2% IOT	5	8.28	1.656	0.0003	1%CEMENT	6	9.97	1.6617	0.0011
4% IOT	5	8.337	1.6674	0.0005	2%CEMENT	6	10.02	1.67	0.0052
6% IOT	5	8.417	1.6834	7E-05	3%CEMENT	6	10.14	1.69	0.0012
8% IOT	5	8.595	1.719	0.0012	4%CEMENT	6	10.217	1.7028	0.0028
10% IOT	5	8.675	1.735	0.0012					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	0.04446	5	0.00889	17.6890	9.807E-07	2.71089
CEMENT	0.00643	4	0.00160	3.19898	0.034869	2.866081
Error	0.01005	20	0.00050			
Total	0.06094	29				

Table A4.18 (c): Analysis of Variance for Maximum Dry Density Test Results for Soil–Cement –IOT Mixes (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	8.594	1.7188	0.001	0%CEMENT	6	10.5	1.75	0.00164
2% IOT	5	8.85	1.77	0.0007	1%CEMENT	6	10.86	1.81	0.00188
4% IOT	5	8.929	1.7858	0.0006	2%CEMENT	6	10.784	1.79733	0.00475
6% IOT	5	9.025	1.805	0.0004	3%CEMENT	6	10.768	1.79467	0.00116
8% IOT	5	9.2	1.84	0.0021	4%CEMENT	6	10.94	1.82333	0.00387
10% IOT	5	9.254	1.8508	0.0017					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	0.058773	5	0.011755	30.51371	1.05E-08	2.71089
CEMENT	0.01835	4	0.004587	11.90849	4.112E-05	2.866081
Error	0.007705	20	0.000385			
Total	0.084828	29				

Table A4.19(a): Analysis of Variance for Optimum Moisture Content Tests Results for Soil–Cement –IOT Mixes (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	111.1	22.22	0.762	0%CEMENT	6	121.2	20.2	3.16
2% IOT	5	106.6	21.32	0.537	1%CEMENT	6	123	20.5	0.192
4% IOT	5	105.3	21.06	0.618	2%CEMENT	6	129	21.5	1.9
6% IOT	5	102.8	20.56	1.343	3%CEMENT	6	128.4	21.4	0.116
8% IOT	5	100.3	20.06	1.163	4%CEMENT	6	119.2	19.867	4.91867
10% IOT	5	94.7	18.94	3.668					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	31.75467	5	6.350933	6.454638	0.0010052	2.71089
CEMENT	12.68533	4	3.171333	3.223118	0.0339831	2.866081
Error	19.67867	20	0.983933			
Total	64.11867	29				

Table A4.19 (b): Analysis of Variance for Optimum Moisture Content Tests Results for Soil–Cement –IOT Mixes (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	103.4	20.68	0.407	0%CEMENT	6	109	18.1667	1.8827
2% IOT	5	99.8	19.96	1.003	1%CEMENT	6	117.4	19.5667	0.2827
4% IOT	5	94.6	18.92	2.167	2%CEMENT	6	119.1	19.85	3.647
6% IOT	5	91.9	18.38	0.967	3%CEMENT	6	112.4	18.7333	1.4507
8% IOT	5	89.3	17.86	0.898	4%CEMENT	6	107	17.8333	3.6827
10% IOT	5	85.9	17.18	2.062					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	42.867	5	8.5734	14.45605	4.668E-06	2.71089
CEMENT	18.15467	4	4.538667	7.652878	0.0006545	2.866081
Error	11.86133	20	0.593067			
Total	72.883	29				

Table A4.19(c): Analysis of Variance for Optimum Moisture Content Tests Results for Soil–Cement –IOT Mixes (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	88.4	17.68	1.097	0%CEMENT	6	93.9	15.65	7.219
2% IOT	5	84.4	16.88	0.647	1%CEMENT	6	92.7	15.45	1.847
4% IOT	5	79.9	15.98	0.842	2%CEMENT	6	95	15.8333	3.73467
6% IOT	5	74.8	14.96	1.183	3%CEMENT	6	95	15.8333	1.02667
8% IOT	5	67.1	13.42	0.852	4%CEMENT	6	87.1	14.5167	3.54967
10% IOT	5	69.1	13.82	1.012					

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
IOT	71.58	5	14.3163	18.71	6.275E-07	2.711
CEMENT	7.229	4	1.80717	2.3618	0.08789356	2.866
Error	15.3	20	0.76517			
Total	94.11	29				

Table A4.20(a): Analysis of Variance for Cohesion Tests Results for Soil–Cement–IOT Mixes (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	397	79.4	137.8	0% CEMENT	6	353	58.83333	68.56667
2% IOT	5	367	73.4	149.3	1% CEMENT	6	413	68.83333	191.7667
4% IOT	5	340	68	127.5	2% CEMENT	6	403	67.16667	381.7667
6% IOT	5	274	54.8	197.2	3% CEMENT	6	483	80.5	72.3
8% IOT	5	411	82.2	1148.7	4% CEMENT	6	674	112.3333	2907.467
10% IOT	5	537	107.4	3468.3					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	7710.267	5	1542.053	2.965753	0.036679	2.71089
CEMENT	10516.13	4	2629.033	5.056287	0.005565	2.866081
Error	10399.07	20	519.9533			
Total	28625.47	29				

Table A4.20(b): Analysis of Variance for Cohesion Tests Results for Soil–Cement–IOT Mixes (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	481	96.2	350.2	0% CEMENT	6	430	71.66667	17.06667
2% IOT	5	455	91	434.5	1% CEMENT	6	500	83.33333	145.4667
4% IOT	5	435	87	453.5	2% CEMENT	6	584	97.33333	1831.067
6% IOT	5	383	76.6	373.8	3% CEMENT	6	724	120.6667	940.6667
8% IOT	5	572	114.4	1375.3	4% CEMENT	6	836	139.3333	2554.667
10% IOT	5	748	149.6	4117.3					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	17215.07	5	3443.013	6.731472	0.00079	2.71089
CEMENT	18188.8	4	4547.2	8.890279	0.00027	2.866081
Error	10229.6	20	511.48			
Total	45633.47	29				

Table A4.20(c): Analysis of Variance for Cohesion Tests Results for Soil–Cement–IOT Mixes (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	756	151.2	1841.2	0% CEMENT	6	616	102.6667	933.86
2% IOT	5	721	144.2	1512.2	1% CEMENT	6	871	145.1667	455.36
4% IOT	5	702	140.4	1478.3	2% CEMENT	6	985	164.1667	3668.96
6% IOT	5	596	119.2	773.2	3% CEMENT	6	1021	170.1667	1244.16
8% IOT	5	917	183.4	4427.8	4% CEMENT	6	1300	216.6667	3639.06
10% IOT	5	1101	220.2	4468.2					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	32735.77	5	6547.153	7.715514	0.00035	2.71089
CEMENT	41032.2	4	10258.05	12.08863	3.71E-05	2.866081
Error	16971.4	20	848.57			
Total	90739.37	29				

Table A4.21(a): Analysis of Variance for Angle of Internal Friction Results for Soil–Cement–IOT Mixes (BSL Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	18	3.6	0.675	0% CEMENT	6	26.3	4.383333	1.881667
2% IOT	5	27.2	5.44	1.808	1% CEMENT	6	38.4	6.4	3.68
4% IOT	5	30.3	6.06	2.118	2% CEMENT	6	32	5.333333	4.166667
6% IOT	5	43.5	8.7	1.2	3% CEMENT	6	40.2	6.7	4.752
8% IOT	5	26.9	5.38	2.422	4% CEMENT	6	29.5	4.916667	3.941667
10% IOT	5	20.5	4.1	0.425					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	80.64267	5	16.12853	28.12953	2.12E-08	2.71089
CEMENT	23.12467	4	5.781167	10.08284	0.000123	2.866081
Error	11.46733	20	0.573367			
Total	115.2347	29				

Table A4.21(b):Analysis of Variance for Angle of Internal Friction Results for Soil–Cement–IOT Mixes (WAS Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	31.3	6.26	0.688	0% CEMENT	6	39.5	6.583333	1.589667
2% IOT	5	42.6	8.52	4.612	1% CEMENT	6	61	10.16667	8.166667
4% IOT	5	51	10.2	9.825	2% CEMENT	6	41.7	6.95	6.975
6% IOT	5	67.5	13.5	9	3% CEMENT	6	63	10.5	11.5
8% IOT	5	45.5	9.1	8.8	4% CEMENT	6	66.3	11.05	13.155
10% IOT	5	33.6	6.72	2.297					

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
IOT	173.107	5	34.6214	20.4711	3.03E-07	2.71089
CEMENT	107.0633	4	26.76583	15.82622	5.47E-06	2.866081
Error	33.82467	20	1.691233			
Total	313.995	29				

Table A4.21(c): Analysis of Variance for Angle of Internal Friction Results for Soil–Cement–IOT Mixes (BSH Compaction).

SUMMARY	*Count*	*Sum*	*Average*	*Variance*	*SUMMARY*	*Count*	*Sum*	*Average*	*Variance*
0% IOT	5	43.8	8.76	3.013	0% CEMENT	6	50.7	8.45	5.327
2% IOT	5	53	10.6	6.3	1% CEMENT	6	82	13.66667	5.866667
4% IOT	5	65.5	13.1	12.55	2% CEMENT	6	60.5	10.08333	6.641667
6% IOT	5	77.8	15.56	5.568	3% CEMENT	6	80	13.33333	7.866667
8% IOT	5	64.9	12.98	8.352	4% CEMENT	6	82.3	13.71667	11.54167
10% IOT	5	50.5	10.1	7.8					

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
IOT	153.883	5	30.7766	19.03589	5.46E-07	2.71089
CEMENT	141.9967	4	35.49917	21.95689	4.41E-07	2.866081
Error	32.33533	20	1.616767			
Total	328.215	29				