EFFECT OFLOCUST BEAN WASTE ASH ON CEMENT-MODIFIED BLACK COTTON SOIL

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CERTIFICATION

The thesis titled "Effect of Locust Bean Waste Ash On Cement - Modified Black Cotton Soil" by Baba Salawu meets the regulations governing the award of the degree of Master of Science (M. Sc) in Civil Engineering Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

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DECLARATION

I hereby declare that this thesis titled "Effect of Locust Bean Waste Ash on Cement- Modified Back Cotton Soil"is a product of my research effort under the supervision of Professor K. J. Osinubi. It has not been presented in any previous application for a higher degree. All quotations and their sources are specifically acknowledged by means of references

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DEDICATION

To my late father, late step mother (may their souls rest in peace), my mother and beloved wife as well as all my loved ones, who stayed by me through thick and thin; to the hopeless and downtroddenwhom i ask not to give up in there quest to be useful in the society some day.

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ABSTRACT

Black cotton soil classified as an A-7-6 (24) soil on AASHTO classification collected from new Marte area of Borno state was modified with up to 4% cement and LBWA up to 8% by weight of the soil. The effect of locust bean waste ash (LBWA) on the cement modified soil was studied with respect to particle size distribution , Atterberg limits, compaction characteristics and shear strength parameters using three 3 compactive efforts namely, British Standard light (BSl), West African Standard (WAS), and British Standard heavy (BSh). Statistical analysis was then carried out on results obtained from the test conducted to determine the significant difference (i.e., $p < 0.05$) in the various soil - cement mixes using a two – way analysis of variance (ANOVA) with the Microsoft Excel Analysis Tool Pack Software. Analyses of the results of the soil-cement mixtures considered indicate increase in particle sizes, increase in the liquid limit and decrease in the plastic limit with corresponding increase in plasticity index, increase in maximum dry density (MDD) with increase in optimum moisture content (OMC) as well decrease in cohesion with increasing angle of internal friction all with higher locust bean waste ash content. The result also showed that the modified soil met the requirement of the Nigerian General Specification of not more than 35% passing No. 200 sieve when used as a sub grade material in road construction. An optimal blend of 4% cement / 8% LBWA is recommended for the modification of black cotton soil.

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CHAPTER ONE

INTRODUCTION

1.1 Preamble

Geotechnical engineers are often faced with the problem of constructing road beds on soil which do not have adequate strength to support the wheel loads imposed upon them either in construction or during the service life of the pavement. It is sometimes necessary to treat these soils, termed expansive soils to give a stable sub-grade or working platforms for the construction of the pavement. Treatment of soil are generally classified into two processes: soil modification or soil stabilization. The purpose of sub-grade modification is to provide a working platform for construction equipment, while sub-grade stabilization is meant to increase the strength and durability of the soil.

1.1.1 Black cotton soil

Expansive soil can be found almost any where in the world but they are basically confined to semi arid regions of the tropical /temperate zones. These areas are usually characterized by marked dry and wet seasons with low rainfall, poor drainage and exceedingly great heat. The precipitation is such that the annual evaporation exceeds the precipitation (Chen, 1988).

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 (Ola, 1978). The second group of parent materials are basic igneous rocks found in India, Nigeria and South Western U.S.A (Plait, 1953). Tropical black clays are formed by weathering (Morin, 1971). Black cotton soil shows high shrink – swell characteristic with surface cracks opening

during the dry season which are more than 50 millimetre or more wide and several millimetre deep. The cracks close during the wet season and uneven soil surface is produced by irregular swelling and heaving. Such soils are especially troublesome as pavement sub-grades or under shallow foundation. The amount of potential volume change is dependent on the mineralogical compositions and clay minerals types. This means that the soils which contain more montmorillonite have higher potential volume change than those that have less of the minerals (Ola, 1983).

The ability of black cotton soil to absorb or release water when wet or dry, respectively, gives the soil its low bearing capacity under wet conditions and cracking under dry conditions. When engineering structure is associated with an black cotton, it experiences either settlement or heave depending on the stress level and the swelling pressure. Because of its soft, highly plastic and cohesive nature, mobility of wheeled vehicles, compaction difficulty and non-provision of satisfactory sub-grade support for subsequent pavement construction operations, problems in construction are always encountered. The combined effects of insufficient shear strength of the soil and the development of excessive deformation under the applied wheel loads give rise to these problems.

1.2 Ordinary Portland Cement

Cement can be described as a material with adhesive and cohesive properties which make it capable of binding minerals fragments into a compact whole (Ejeh, 2007). Ordinary Portland Cement is composed of four main oxides(CaO, SiO_2, Al_2O_3 and Fe_2O_3) and the variation in the relative proportions of these four main oxides give rise to different types of cement with some little addition of some other oxide. The oxides composition that form the main compound of ordinary Portland cement are

tricalcium silicate ($3CaO$, SiO_2, C_3S), dicalcium silicate ($2CaO.SiO_2$, C_2S), tricalcium aluminate ($3CaO.\ Al_2O_3$, C_3A) and tetracalcium aluminoferrite ($4CaO.Al_2O_3.Fe_2O_3$, C_4A). . The two calcium silicate (C_2S, C_3S) which are the most stable of these compound, form 70 to 80 percent of constituents of cement and contribute most to the physical properties of the mix.

The degree of fineness or specific surface area of the clinker grinding also contributes highly to the various types of cement. The finer the grinding, the more rapid is the rate of hydration. Ordinary portland cement has a minimum specific surface of 250 cm^2 /g.

Hydration is the chemical combination of cement and water producing a very hard and strong medium for soil particles and is accompanied by the liberation of heat. The rate of hydration depends on the relative properties of silicate and aluminate compound, the cement fineness and the ambient conditions (temperature and moisture).

1.3 Locust Bean Waste Ash

It is commonly accepted today in soil improvement work to examine the effect of local materials considered to be waste or residue and that may be economically viable for construction purpose (Osinubi 2000). One of the local materials been considered is the ash obtained from the combustion of the waste from the locust bean fruit, It has three components namely: the seed commonly used to produce local seasoning for food, the powder and the husk. The husk is the waste product and when burnt in open air will eventually result into locust bean waste ash (LBWA).

The locust bean tree is common in our environment and it grows to about 15 m in height and has dark evergreen pinnate leaves. The fruit is brown, leathering pod about 10 to 30 cm long. The seed are edible but the waste product litter our

environment with corresponding negative environmental impact. The treatment of soil with locust been waste ash could be a viable way to ameliorating this social menace.

1.4 Statement of the Problem

Black cotton soil is an expansive soil characterized by excessive volume change, expansive tendencies and low bearing capacities when wet (Chen, 1988, Nelson and Miller, 1992; Warren and Kirby, 2004). These soils have high clay content and expand when wet and shrink when dry; these cause serious damages to structures founded on these soil. For example it has been estimated that in the United States of America damages to buildings founded on expansive soils are well over 15 billion US dollars.

Also in the north eastern part of Nigeria, where the soil is predominant, it is definite that road and other Civil engineering infrastructure being erected on these soil will pose great challenges to geotechnical engineers, since avoiding it or finding a suitable replacement is not feasible. It therefore becomes necessary for the geotechnical engineer to look for means of improving the geotechnical properties of the soil in-situ, at a cheaper and efficient means.

Locust bean waste ash is the ash obtained from combustion of the waste from the locust bean. The availability of this waste is high and could be beneficially used for the improvement of this troublesome soil and rid the environment of the waste.

1.5 Justification for the Study

The significance of a good soil to a geotechnical engineer cannot be over emphasized, especially in the area of construction, where the stronger the soil the lesser the cost to erect any structure on the soil. For years, geotechnical engineers have

been concerned with improving the characteristics of poor quality soils and have therefore been researching into various methods of doing so. One of such is to use the abundantly available natural waste materials (e.g. locust bean waste ash) in combination with cement to make a poor quality, extensively deposited black cotton soil a better engineering soil. Hence information on the improved workability of such a soil makes this research worthwhile.

1.6 Aim and Objectives of the Study

This study was aimed at establishing the effect of locust bean waste ash on cement modified black cotton soil. This was achieved through the following specific objectives:

a) Determination of the properties of the natural soil.

b) Modification of black cotton soil using known quantities of cement and locust bean waste ash as admixture when compacted with the British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) conpaction energies.

c) Evaluation of the effect of locust bean waste ash on the cement modified black cotton soil using particle size distribution, Atterberg limits, compaction tests and shear strength parameters.

d) Determination of the optimum mix ratio of cement – locust bean waste ash for optimum workability of black cotton soil.

1.7 Scope of Research

The study involved modification of black cotton soil with cement using locust bean waste ash as the admixture. The modification of black cotton soil with cement

served as control and locust bean waste ash was introduced as an admixture. The Atterberg limit, particles size analysis, compaction and shear strength parameters of the soil – cement – LBWA modified samples shall be evalutated to determine the extent of improvement.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil Modification / Stabilization

Generally, geotechnical structures are to be founded on good and sound engineering soil in order for them to attain their design life span. If these structure are founded on soil with low bearing capacity, they are likely to fail either during or after construction, with or without application of wheel load on them. The black cotton soil is an expansive soil with low bearing capacity, has the ability to absorb and dissipate water with subsequent change in volume. Construction of any structure on this type of soil requires either replacement of the soil by importing a better foreign one or by addition of chemical(s) that will improve the desired properties of the soil. But if the construction involves a large area of land like road construction, replacement of soil by importing new materials or avoiding them is impossible and the soil will therefore have to be stabilized in-situ (Osinubi, 1995).

Well built and maintained roads play major role in the development of a nation. Sub-grade soil form the integral part of the road pavement structure as it provides the support to the pavement from beneath. Therefore, the knowledge of properties of sub-grade soil are very important in the design of road pavement as well as other engineering structures. The main function of the sub-grade is to give adequate support to the pavement and for this, the sub-grade should posses sufficient stability under adverse climate and loading condition. If the weak sub-grade is stabilized, the required crust (outer layer) thickness will be less, rutting is restricted resulting in less repair and overall economy. Basically, there are three majors ways of modifying/stabilizing soils for engineering purposes. These are mechanical, geosynthetic and chemical

modification. Modification is restricted to clayey soils of the AASHTO A-4, A-5, A-6, and A-7 (Office of geotechnical Engineering, 2008).

Modification occurs as a result of calcium cations supplied by modifier replacing the cations present on the surface of clay minerals, promoted by the high pH environment of the modifier – water system. Thus altered, the clay surface mineralogy results in plasticity reduction, reduction in moisture holding capacity, swell reduction, improved stability and the ability to construct working platform as benefit (National Lime Association, 2001).

2.1.1 Mechanical modification / stabilization

Mechanical stabilization is the process of altering soil properties by changing the gradation through mixing with other soil, densifying the soil using compactive efforts, or undercutting the existing soil and replacing them with granular material to improve the soil engineering properties of strength, permeability and compressibility. An existing soil may have poor engineering properties perhaps because of excess clay, silt or fine sand. If a suitable soil is located within a reasonable haul distance, blending the soil together could effect an improvement in the existing soil.

A common remedial procedure for wet and soft grade is to cover it with granular materials or to partially remove and replace the wet sub-grade with a granular material to a predetermined depth below the grade line. The compacted granular layers distribute the wheel loads over a wider area and serve as a working platform (Thompson, 1977).

To provide a firm working platform with granular material, the following condition shall be met. (Office of Geotechnical Engineering, 2008):

1. The thickness of the granular material must be sufficient to develop acceptable pressure distribution over the wet soils.
2. The backfill material must be able to withstand the wheel load without rutting.
3. The compaction of the backfill material should be in accordance with the standard specification. Based on experience, 300 to 600 mm granular material should be adequate for sub-grade modification or stabilization.

2.1.2 Chemical Modification / Stabilization

For close to half a decade, the concern of the geotechnical engineer has been to make poor engineering soil much better. This stimulated research into the available chemical or mechanical means of modifying the soil. These chemicals are mainly industrial waste which pose environmental problems. In the absence of organic matter, when a soil contain a certain amount of fines that cause plastic behaviour of the soil, modification is often recommended (Osinubi and Katte, 1997). Modification is a broad term used to describe any technology or operation that is used to improve soil characteristics and as with stabilization, it involves the use of different kinds of agents. These agents include cement, lime, bitumen, fly ash, etc. These chemicals have been used either single or in combination with one another.

Soil modification or stabilization started since the 1960s in Europe and has spread world-wide, since problematic soils are wide-spread. According to Osinubi (1995) cement and lime, mostly used for modification or stabilization, change the water film on the soil particles, modify the clay minerals to some extent and decrease the soil plasticity index. The main purpose of soil modification is to improve the particles size,

plasticity index and durability under adverse moisture and stress conditions (Osinubi, 2002). Traces of the modifying agent(s) are added to the soil mass in appropriate proportions. The modifier and soil must be mixed thoroughly in order to achieve the desired strength and durability. To achieve this goal in the laboratory, the natural soil structure is destroyed by grinding when preparing the soil. In the field however, successful modification depends on the ability of the modifiers to penetrate large lumps of soil which may contain coarse aggregates and to modify the active constituents (Osinubi, 2002). The most appropriate method used for any situation depends on the economics, engineering requirement and the soil characteristics which have to be determined.

There are three primary reasons to chemically stabilize a soil when mechanical stabilization is not adequate namely: a) improve the strength or increase the soil stability b) water proof the soil and c) for dust control.

2.2 Singe Agent Modification

The most widely used single agent for the treatment of cohesive soil with expansive properties are lime and cement because of their effectiveness in improving these expansive properties (Chen, 1988; Hausman, 1990). The reactions involved in using either of the modifier are similar but vary on the quantity of the modifier required for effective modification. About 3 – 4% of lime by dry weight is required for effective modification, while more than that percentage of cement will be required to achieve the same result (Gillot, 1987).

Most soil improve in strength on the addition of cement. According to Lorenzo and Bergado (2006), when the pore water of the soil encounter with cement, hydration of cement occurs rapidly to produces cemetitious compound. These products are

calcium silicate hydrate(CSH) and calcium aluminate hydrate(CAH) which are the major cementious compound, while lime is deposited as a separate crystalline solid phase. These cement particles bind the adjacent cement grain together during hardening and form a hardened skeleton matrix, which enclose unaltered soil particles. Furthermore, the hydration of cement increases pH value of pore water, which is caused by the dissociation of the bivalent calcium ion (Ca^{++}) from the coagulation of soil particles into large size grains. The soil silica and alumina, which are inherently acidic will then be dissolved by the strong bases of cement compound from the clay mineral and amorphrus materials on the surface of clay particles in a manner similar to reaction between a weak acid and strong base. The hydrous silica and alumina will then gradually react with the calcium ions librated from the hydrolysis of cement to form a new insoluble compound (secondary cement product), which harden when cured thereby stabilizing the soil. But if the soil contain organic matter, it can interfere with these hydration reactions of cement, because of the presence of hydroxyl and carboxyl groups in the organic compound (Gillot, 1987).

For effective modification and subsequent stabilization of a soil with cement, the clay grade minerals should not be in excess of 30%. It becomes more difficult to achieve economic stabilization by use of cement due to greater difficulties in pulverizing and mixing (Gillot, 1987).

Recently, the conventional chemicals (cement, lime, bitumen etc,) are being replaced with agriculture waste. Recent researches in the Department of Civil Engineering, Ahmadu Bello University, Zaria have focused on stabilization of both laterite and black cotton soils using bagasse ash (Stephen, 2006, Osinubi and Alhaji, 2005; Osinubi and Eberemu, 2006; Osinubi and Stephen, 2005, 2006a,b, 2007; Osinubi et al, 2007 a,b, 2009; Osinubi and Mustapha, 2009; Ochepo, 2008). Another

agricultural waste (locust bean waste ash) was studied by Akinmade (2008) who checked its effect on the geotechnical properties of black cotton soil. The result obtained showed some favourable improvement on the geotechnical properties, but it was discovered that the ash could not be used as a stand alone stabilizer because of its low calcium oxide content but could serve as an admixture.

2.3 Multiple Agents Modification

The ever increasing cost of industrially produced modifiers indicates an increased cost of pavement construction. This is uneconomical for a developing country like Nigeria because limited resources will have to be unilaterally directed, thus depriving other sectors of the economy of growth. The cost of cement and other chemicals are as well becoming high and it is therefore proper to use locally available materials considered as waste in the society to either substitute these chemicals or complement them in combination with another to improve on the engineering properties of the soil as well as our environment.

Thus, the addition of small amount of other chemicals to soil-cement, soil- lime mixtures might reduce the cost of construction and still give more favourable result than with only cement or lime. A pozzolana or pozzolanic material has served in this purpose. A pozzolana can be described as a siliceous or siliceous-aluminous material which in itself has little or no cementitious value, but in finely divided form and in the presence of moisture chemically reacts with calcium hydroxide at ordinary temperature to form a compound possessing cementitious properties (Abdullahi, 2003). It is essential that pozzolanas be in finely divided state as it is only then that silica can combine with calcium hydroxide liberated by the hydrating Portland cement in the presence of water to form a stable calcium silicate which has cementitous properties.

Such materials are normally employed as admixtures with or a partial replacement for ordinary Portland cement in the manufacture of concrete or concrete products. Also they find employment in conjuction with lime and/or cement in the stabilization of roads, and the preparation of road base materials.

Keogh (2006) reported that when bagasse ash was mixed with Portland cement in concrete, a significant reaction was obtained when the concrete was cured at elevated temperature. Osinubi (1999) reported on appreciable change in both plastic nature and strength properties of soil - lime – cement stabilization of black cotton soil. Similarly, Nicholson et al. (1994) reported that lime- fly ash admixture showed tremendous potential as an economic method for improving the geotechnical properties of tropical Hawaiian soil. Studying the potential of pulverized coal botton ash admixed cement stabilization of black cotton soil, Osinubi (2000) reported that there was a reasonable improvement in the properties of the soil. A combination of other stabilizing agents have also been studied to make use of the abundantly available waste material in the country for the improvement of the extensively deposited black cotton soil and other problematic soils. Osinubi and Medubi (1997) used cement and phosphatic waste admixture, a by-product from the production of super phosphate fertilizer for the improvement of engineering properties of tropical black soil. Their result showed that the engineering properties of the soil appreciably improved.

2.4 Mechanisms of Reactions

2.4.1 Cement

When water is added to cement it hydrates, and produces cementitious compounds independently of the soil. These products are calcium silicate hydrates and calcium aluminate hydrates which are the major cementitious compound, whereas lime

is deposited as a crystalline solid phase. The increase in strength is due to development of cementitious linkage between these hydration products and soil particles. The lime released during the hydration of cement may react with any pozzolanic material (e.g. locus bean waste ash) to form a secondary cementitious material which also contributes to inter particle bonding. Thus a sizeable fraction of the cementitous material formed in the soil –cement is contributed by the soil itself (Ola, 1975).

In soil-cement two stages of reaction have been identified (Ola, 1975; Obeahon, 1993). The primary stage which forms primary cementing substances tobermorite or calcium silicate hydrate responsible for the high initial strength development and the secondary stage which forms secondary cementing substances, the pozzolana responsible for the continued gain in strength with time. The primary reaction is basically the hydration of cement while the secondary reaction is between free lime product of the primary reaction and the unused silica compound of cement.

2.4.2 Lime

In lime stabilization or modification there is a direct hydration to form cementitious compounds.

2.4.2.1 The physical and chemical component to the reaction of lime with clay.

The physical reaction is one of the cation absorption, calcium replaces other ion present knowns as base exchange reaction. This is followed by the flocculation into group of coarse particles which produce an immediate increase in strength.

For the chemical component of the reaction Moh (1962) suggested the chemical reaction in the soil - cement hydration. The addition of lime to soil causes an immediate increase in the pH of the moulding water, due to the partial dissociation of the calcium hydroxide. The calcium ion in turn combines with reactive silica or alumina or both,

present at soil surfaces to form insoluble calcium silicates or aluminates or both which harden on curing to stabilize the soils. The process continues for some months.

2.4.3 Admixture Modification Reaction

The addition of cement - locust bean waste ash to the soil causes two basic set of reaction;

(a) Short term reaction

(b) Long term reaction

The immediate effect of introduction of cement or locust bean waste ash is the hydration reaction. Cement hydrates when water is added producing cementitious compounds of the soil. These products are calcium silicates hydrates, calcium alluminate hydrate and hydrated lime. The first two products constitute the major cementitious components whereas the released lime and the locust bean waste ash may cause flocculation and agglomeration of the clay particles caused by ion exchange at the surface of the particles. The results of this short term reactions are to enhance workability and provide an immediate reduction in plasticity, swell and shrinkage.

The long term reactions are accomplished over a period of time that can confirm for weeks, months or years, depending on the rate of chemical breakdown and hydration of silicate and aluminate. This result in binding particles together by the formation of cementitious materials. The long term reaction is pozzolanic reaction. The extent and reaction rate is affected by the fines of the soil which give greater surface area.

2.5 Pozzolana

Pozzolana is a natural or artificial material containing silica in the reactive form. Pozzolana can be described as a siliceous or siliceous-aluminous material which in

itself has little or no cementitious value but will in finely divided form and in the presence of moisture chemically react with calcium hydroxide at ordinary temperature to form a compound possessing cementitious properties (Czermin, 1965, ASTM C618-78). It is essential that pozzolana be in finely divided state as it is only then that silica can combine with calcium hydroxide liberated by the hydrating portland cement in the presence of water to form a stable calcium silicate which has cementitious properties. pozzolanic material most common are volcanic ash, fly ash, burnt clay, opaline shale's etc. the silica in pozzolanas has to be in amorphous form since crystalline form has very low reaction.

Pozzolanas are grouped into two classes namely natural and artificial. Natural pozzolana may further be divided into two main groups. Those derived from volcanic rocks in which the amorphous constituent is glass are produced by fusion. The others are derived from rocks or earth for which the silica constituent contains opal either from precipitation of silica or from the remain of organisms.

Artificial pozzolanas are divided into two main groups; those of organic and of inorganic origins. The most important artificial pozzolanas of organic origin are obtained from calcined spent oil, etc.

Pozzolanas have the characteristics of combining with the free lime liberated during the hydration process of cement to produce stable calcium silicates. Pozzolanas have been found to generally reduce slightly the rate of setting of cement but accelerates the rate of setting time (Lea, 1970; Smith , 1992). The rate of reaction and strength development of lime - pozzolana mixes increases with increase in atmospheric temperature. Pozzolanic mixes usually require much longer time before they achieve their maximum strength values.

Some pozzolanas may possess some undesirable properties because of their angular and porous form, which may require high water content. The activity of natural pozzolanas can be improved by calcinations in the temperature range of 550 - 1100^{o}C. The activity of pozzolanas is assessed by measurement of the pozzolanic activity index (Abdullahi, 2003). This is established by the determination of strength of mixture with a specified replacement of cement by pozzolanas. Assessment of pozzolanicity involves comparison of the quantity of $Ca(OH)_2$ present in a liquid phase in contact with hydrated pozzolanic cement with the quantity of $Ca(OH)_2$ capable of saturating a medium of the same alkalinity. The pozzolanic activity involves fixing of calcium hydroxide by the pozzolana. In this process, the lower the resulting quantity of $Ca(OH)_2$ the higher the pozzolanicity. Pozzolana reacts also with the hydrating tricalcium aluminates. Chemical composition and specific surface of pozzolana also have effect on pozzolanicity.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Black Cotton Soil

The soil sample used for this study was collected at the Chad Basin Development Authority (CBDA) reserved site at New Marte (Latitude $13^{o}27^{I}$N and longitude $13^{o}50^{I}$E) along Maiduguri – Gamboru Road in Borno State. It was collected as disturbed sample at a depth between 0.5 m to 1.5 m after removing the top soil to avoid organic matter. The soil sample were taken, sealed in plastic bags and put in sack for determination of natural moisture contents. The soil samples were then allowed to dry before pulverizing to obtain particle passing sieve BS No. 4. A study of geological and soil maps of Nigeria after Akintola (1982) and Areola (1982), respectively, shows that the parent materials in the study area is basic igneous rock which when weathered formed weakly developed black cotton soil. This location lies within north eastern part of Nigeria extensively covered by black cotton soil.

3.1.2 Locust Bean Waste Ash

The locust bean waste ash (LBWA) used for the study was obtained locally from the burning of the locust bean husks source from Doko, Vunchi and Agaie villages around Bida area in Niger State. The husk of locust bean generated through human activities were collected from dumps in the villages and stockpiled. Smith (1992) as well as Mohammedbhai and Baguant (1990) reported that heat treatment plays a vital role in the production of pozzolanas from agriculture waste. Therefore stockpiled husk of locust bean generated was burnt to ash in open air on a galvanized

iron roofing sheet and cooled before being passed through BS No 200 sieve and kept to be mixed with the soil cement in the appropriate percentages.

The oxide composition of the locust bean ash was determined at the Centre for Energy Research and Training (CERT) A.B.U, Zaria by the method of Energy Dispersive X – Ray Fluorescence (XRF). The specification for pozzolanas are given in Table 3.1.

Table 3.1: 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 C618 - 78)**

3.1.3 Cement

The ordinary Portland cement (OPC) used for the study was purchased in the open market at Samaru market opposite Ahamadu Bello University Zaria, Nigeria.

3.2 Methods

3.2.1 Natural moisture content

The natural moisture content of the soil was determined accordance with test 4a of BS 1377 (1990) part 2. Three weighing containers were cleaned and weighed to the

nearest 0.1g(M_1). The soil sample was then crushed and placed loosely in the container and both the sample and container were weighed together to the nearest 0.01g as M_2. The samples were oven dried at 105 – 110^oC for 24 hours. After 24 hours the weight of dried sample were taken to the nearest 0.01g as M_3. The natural moisture content was calculated as the average of the three dried sample given by eq (3.1)

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

Where

w = Moisture Content (%)

M_1 = Weight of Container (g)

M_2 = Weight of Container plus wet soil (g)

M_3 = Weight of Container plus dried soil (g)

3.2.2 Cation exchange capacity

Ten grammes (10g) of 2mm sieved soil was put into a 100 m^3 plastic beaker about 40ml of Ammonium acetate (1NpH7) were added, stired with a glass rod and left over night. The soil was filtered with light suction using a 55 mm bucher funnel, the soil was leach so that it could fit in a funnel with Ammonium acetate to a volume of 250cm^3. the leachate was tested from the soil to know if it was calcium free, the presences of calcium is indicated by a white precipate or turbidity. The electrolyte was washed out with 150-200ml of isopropyl alcohol.

Chloride was tested for in the leacheate with (0.1 N Ag No_3) till the leacheate become negligible, the soil was allowed to drain thoroughly, then the leached soil was acidified to a volume of 250ml. 50ml of boric acid was measured into 250ml conical flask and a few drop of mixed indicator was added, the acidicidified soil was pour into 500ml flask and the flask was connected to the still, some anti bump and 10ml of 1N.

NaOH was added into the flask, and distilled over the boric acid in the conical flask. 150ml of distill was collected, the NH_4-borate was titrated with a standard acid 0.1N.HCL. The cation exchange capacity was calculated using the formula below.

$$\frac{(\qquad)*\qquad*}{} \tag{3.2}$$

where

B = Blank

NA = Normality of acid

3.2.3 Particle size distribution

The particle size analysis of a soil sample involves determining the percentage by weight of particles within the different size ranges. The test was carried out accordance with BS 1377:1990 part 2. About 200g of the soil sample was weighed and soaked for 24hrs. The sample was washed through BS No. 200 seive to obtain the total percentage of clay size present for hydrometer analysis. The Coarser particles retained was oven dried for 24 hrs and a known weight of solids was passed through a series of standard Sieve reducing progressively. The proportion by weigh of the solid fraction on each sieve was determined. The clay fraction was determined according to BS 1377 (1990).

3.2.4 Specific Gravity

The determination of specific gravity was carried out according to BS 1377 (1990) test 6(B) for fine grained soil. A weighed 50mI density bottle was filled with air dried soil sample and weighed to the nearest 0.01g as M_2. Water was added to the

density bottle contents and the weighed to the nearest 0.01g as M_3. The content was emptied and the bottle filled with water and again weighed to the nearest 0.01g as M_4. The specific gravity of the soil is given by:

$$G_S = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \tag{3.3}$$

Gs = Specific gravity

M_1 = Weigh of density bottle (g)

M_2 = Weigh of density bottle plus dry soil (g)

M_3 = Weigh of density bottle plus soil and water (g)

M_4 = Weigh of density bottle plus water only (g)

3.2.5 Atterberg limits

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

3.2.5.1 Liquid Limit

The soil sample for liquid limit was air dried and about 200 g of the material passing through 425 μm aperture sieve size was thoroughly mixed with water on a flat glass plate to form a homogenous paste. Some of the paste was then placed into the cassangrade apparatus leveled off and a groove made by drawing the grooving tool through the centre along the diameter of the hinger. By turning the crank in an anticlockwise direction at the rate of two revolutions per second, the apparatus with the content were lifted up and dropped on the bottom thereby allowing the parts of the soil to come closer. The number of blows at which the two parts almost touching each other was recorded. A sample of paste was taken for moisture content determination. The

tests were performed for well spaced out moisture content from the drier to the wetter state. A graph of determined moisture content against the number of blows on a semi-logarithmic paper was plotted and the liquid limit deduced as the moisture contents corresponding to 25 blows. The same procedure was also carried out for the treated soil with increment of modifier and admixture.

3.2.5.2 Plastic limit

A portion of the soil / soil - cement LBWA mixes used for the liquid limit test was retained for the determination of plastic Limit. The ball of the soil/soil - admixture was mourded between the palms of the two hands. The moulded sample was rolled on a flat glass surface and subdivided into four equals parts. Each part was rolled between the tips of the finger and glass surface until the thickness of the rolled samples was approximately 3mm and started shearing. The process was repeated for the remaining three part of the rolled sample and the moisture contents were determined. The average of moisture content was taken as the plastic limit. The same procedures were carried out for the treated soil with increments of modifiers and admixture:

3.2.5.3 Plasticity index

The plasticity index of the soil/soil – cement – LBWA mixture is the difference between the liquid limit of the natural/various treated soil and there corresponding plastic index limits. The value of the plasticity index was calculated using;

$$PI = LL - PL \tag{3.4}$$

3.3 Compaction Characteristics

This was done in order to establish the relationship between the maximum dry density (MDD) and optimum moisture content (OMC). The three compaction energies

used were British Standard light (BSL), West African Standard (WAS) and the British Standard heavy (BSH).

3.3.1 Maximum dry density

The compaction test were carried out for the natural soil and treated soils in accordance with Test 3 of BS 1377 (1990) Part 4, using the British Standard light, West African Standard and British Standard heavy.

3kg of the soil/soil cement - LBWA sample were mixed thoroughly with 8% of water (the water is added at 8% for each of the compaction. The saple was then compacted into the 1000 cm^3 (of mass M_l); In three layers of approximately equal mass with each layer receiving 27 blows of 2.5kg rammer falling through a height of 300mm, for the British Standard light compaction; 10 blows of 4.5kg rammer in five layers for West African Standard compaction and 27 blows of 4.5kg rammer in five layers for the British Standard Heavy. The blows were uniformily distributed over the surface of each layer. The collar was then removed and the compaction sample leveled off at the top of mould with a straightedge. The mould and compacted soil was then weighed to the nearest 1g as M_2.

The compacted soil was quickly extruded from the mould and two representative sample from top and bottom were taken for moisture content determination. The soil was then broken up remixed with more water added (8%) in otder to obtain high moisture content and the same procedure was repeated until maximum of five set sample were taken for moisture content determination. The procedure was repeated for the soil using requisite levels of OPC/LBWA blends.

The bulk density in Mg/m^3 was calculated for each compacted layers using.

$$\rho = \frac{m_2 - m_1}{1000} \tag{3.5}$$

The dry density was also calculated using eqn

$$\rho_d = 100\rho/(100+W) \tag{3.6}$$

where

ρ = bulk density of the mix (Mg/m^3)

ρ_d = dry density of the mix (Mg/m^3)

M_1 = Mass of the mould + base

M_2 = Mass of moisture soil + mould

W = Moisture content

The value of dry density obtained from eqn 3.6 were plotted against their respective moisture contents and the maximum dry density (MDD) was deduced as the maximum, point of the resultant curves.

3.3.2 Optimum moisture contents

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

3.4 Shear Strength Parameters

The shear strength test were carried out using the undrained unconsolidated triaxial test procedure in accordance with BS 1377 (1990) Part 7 : Section 8 at maximum dry densities and optimum moisture contents of the various mixes. The modifiers were thoroughly mixed with various soil that filled the triaxial specimen mould manually with a trowel in a sample tray. Water at OMCs obtained above was

added to the mix and further mixed to achieve a uniform colour. The soil - modifier mixes so prepared were compacted in the specimen mould and shaped to required dimension before carrying out the test. Each sample consist of 3 individual cylindrical specimens was subjected to an axial load at 3 confining cell pressure (310, 210 and 100 kN/m^2) respectively. Readings from the dial guage were taken at regular strain intervals until failure occurred. This failure load was recorded as the maximum deviator load; the strain at failure was also recorded.

The maximum deviator stress (δ_f) was determined from the equation:

$$_f = \frac{\quad * \quad (* \qquad)\%}{\quad *} \qquad (\quad . \quad)$$

where

R – Failure load

C_r – Load Ring Constant = 1.47 lb/in^2 (10.13kN/m^2)

 % – Strain

A_0 – Cross sectional area of specimen.

The apparent cohesion (Cu) and angle of internal friction were deduced from failure envelops of plotted Mohr circles constructed from the principal stresses obtained from the Experiments.

3.5 Method of Analysis

In this study two methods of analysis were used:

1. Graphical Method

   Here the values obtained from the various test were plotted in graphical form using Microsoft excel.

2. Two-way analysis of variance (ANOVA) without replication.

In this analysis Microsoft excel analysis tool pack software package was used, the $F_{calculated}$ and the $F_{critical}$ values obtained from the table using degree of freedom were compared t find out if there was any significant effect using a significant level of $\alpha = 5\%$ and $p < 0.005$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Properties of Material Used in the Study

4.1.1 Natural Soil

The result of the test for the identification of the natural soil and the properties revealed that the soil has very high moisture content of 35%, this is attributed to the period of sample collection (during rainy season). The index properties and oxide composition of the black cotton soil are summarized in Tables 4.1 and 4.2, respectively. Based on the American Association of State Highway Transportation Officials (AASHTO, 1986) classification, the soil is classified as an A-7-6 (24) and based on the Unified Soil Classification System (USCS) the soil is a CL soil. The soil is greyish black in colour (from wet to dry) with a liquid limit of 63%, plastic limit of 27% and plasticity index of 36%. Details of test result are shown in Tables A4.1 to A4.4 in the appendix.

Based on the Nigerian General Specification (1997) and the Highway Research Board (1943), suitability limit of 50% passing BS No. 200 sieve, 40% liquid limit and 18% Plasticity Index requirements the soil is found to be unsuitable for direct use as a base course or sub-base course and would therefore require initial modification to improve its workability.

Table 4.1: **Properties of the natural soil.**

Property	Quantity
Percentage passing BS No. 200 sieve, %	80.0
Natural Moisture Content, %	35.0
Liquid limit, %	63.0
Plastic limit, %	27.0
Plasticity index, %	36.0
Linear shrinkage, %	17.0
Specific gravity	2.10
AASHTO classification	A-7-6 (24)
USCS	CL
Maximum Dry Density, Mg/m^3	
British Standard light	1.34
West African Standard	1.45
British Standard heavy	1.53
Optimum Moisture Content, %	
British Standard light	24.0
West African Standard	20.0
British Standard heavy	19.0
Cohesion, kN/m^2	
British Standard light	75
West African Standard	75
British Standard heavy	60.0
Angle of Internal Friction, degree	
British Standard light	18
West African Standard	16
British Standard heavy	14
Colour	Greyish black

Table 4.2 - Oxide composition of black cotton soil

Oxide	Concentration (%)
CaO	-
SiO_2	31.01
Fe_2O_3	4.74
Al_2O_3	16.19
MnO	0.13
Tio_2	1.34

After Stephen 2006.

4.1.2 Additives

The summary of the oxide composition of locust bean waste Ash (LBWA) and ordinary Portland cement (OPC) are shown in Table 4.3. The little amount of calcium oxide (1.08%) present in LBWA to be used for the modification process was

supplement by that of OPC (63%). The higher silicon and aluminimum oxide in LBWA also aided those in OPC to give the necessary requirement for modification.

Table 4.3 Oxide Composition of LBWA and typical OPC

Oxide	*LBWA (%)	**OPC (%)
CaO	1.08	63
SiO_2	55.38	20
Al_2O_3	14.93	6
Fe_2O_3	0.278	3
MnO	0.09	-
Na_2O	0.18	1
K_2O	2.00	-
SO_3		2
P_2O_5	0.23	-
Loss on Ignition	10.63	2

* after Akinmade, 2008 **After Czernin, 1962.

4.2 Cation Exchange Capacity

Some clay undergoes isomorphous substitution, that is, substitution of cation of one kind by another while retaining the same crystal structure. This substitution, along with the dissociation of hydroxyl ions, results in a residual negative charge on the surface of the clay's mineral particles. Positively charged ion (i.e. cations), are therefore adsorbed on its surface. These ions are not strongly held and can be replaced by others present in water. This phenomenon is described as cation exchange. The quantity of exchangeable cation in a soil is termed exchange capacity (Gidigasu, 1976).

When water is added to soil particles, the negative charge on the surface attracts the positive (hydrogen) end of water molecules to form an adsorbed film of water. This adsorbed film of water is thicker than the diameter of particles (in the case of fine – grained soil) which allows the movement of grains across one another. This property improves the plasticity of the soil as the soil can deform plastically without cracking when mixed with varying amount of water. Similarly, this is in agreement with the

findings of Ola, 1983; Osula, 1991; and Osinubi, 1995 that addition of lime caused the flocculation and agglomeration of the clay particles through cation exchange at the surface of the clay particles and the highly plastic nature of lime which cause the plastic limits to increase drastically.

The variation of cation exchange capacity of soil - cement mixture with locust beans waste ash (LBWA) is shown in Figs 4.1a and 4.1b. As can be seen in Fig 4.1a the cation exchange capacity increased with increased LBWA content . The value decreased from 37.5Cmol/kg to a minimum at 2% LBWA content for the natural soil and increased to a value of 46.1 Cmol kg at 0% cement / 8%LBWA.

It could be observed in Figure 4.1b that there is no much variation in cation exchange capacity of the soil as the cement content increase. Though the value decreased from 37.5 Cmol/kg for the natural soil to a value of 19.50 Cmol /kg at 4% cement and 8% LBWA treatment. Detail of the test results are shown in Table A4.2. in the Appendix.

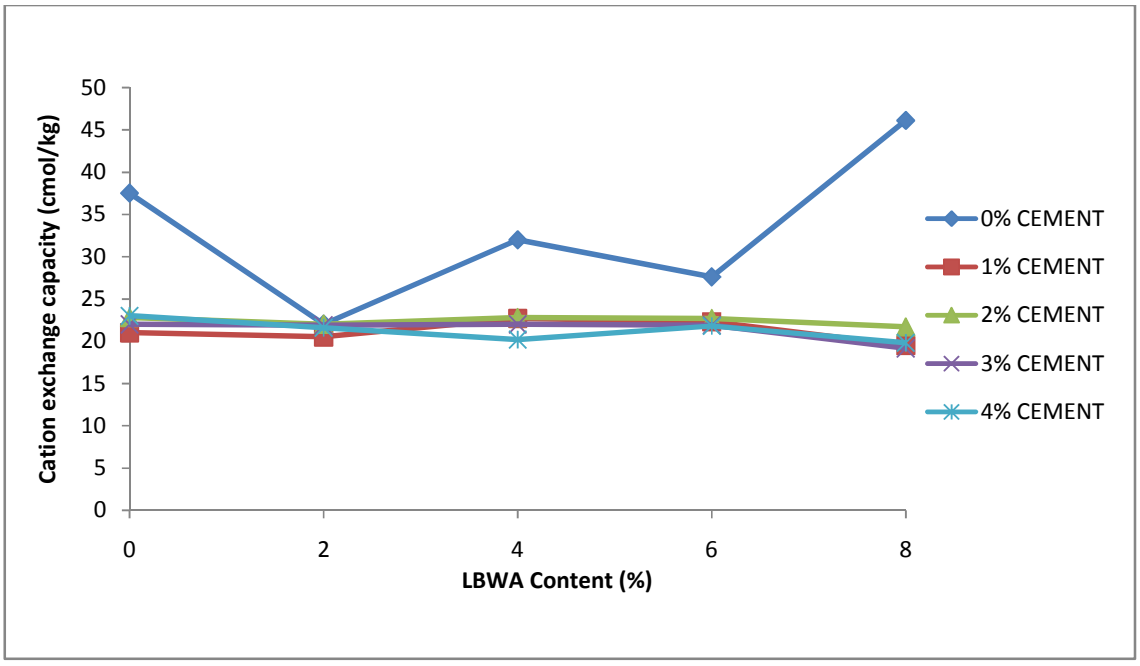

Fig.4.1a - Variation of cation exchange capacity of soil - cement mixtures with LBWA content

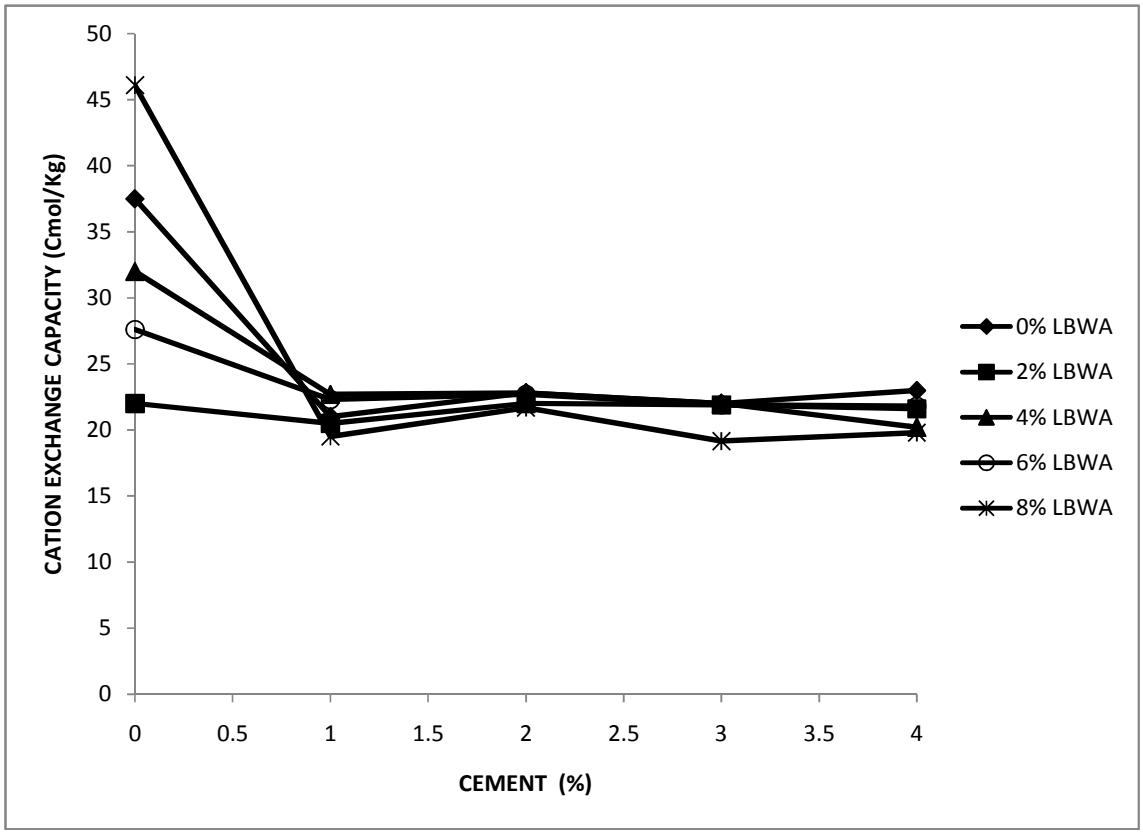

Fig.4.1b - Variation of cation exchange capacity of soil - LBWA mixtures with cement content.

4.3 The particle size distribution

The particle size distribution curve of natural soil and modified soils are shown in Figs 4.2 to 4.17. The curve for the natural soil composed of about 80% fine particles that are less than 0.075mm in diameter.

The variation of particle size with locust bean waste ash content for soil treated with various cement percentages at the three compaction energies, that is British Standard light (BSL), West African Standard (WAS) and British Standard heavy (BSH) respectively shows a tremendous decrease in the amount of fine particles passing BS sieve No.200. The reduction in clay size content was probably due to hydration of cement /LBWA that acted as nucleus to which soil particles adhered. With higher

cement/LBWA content the quantity of free silt and clay progressively reduced and coarse materials was formed in agreement with Osinubi (1995). Details of the test result are shown in Tables A4.3 to A4.4c in the Appendix.

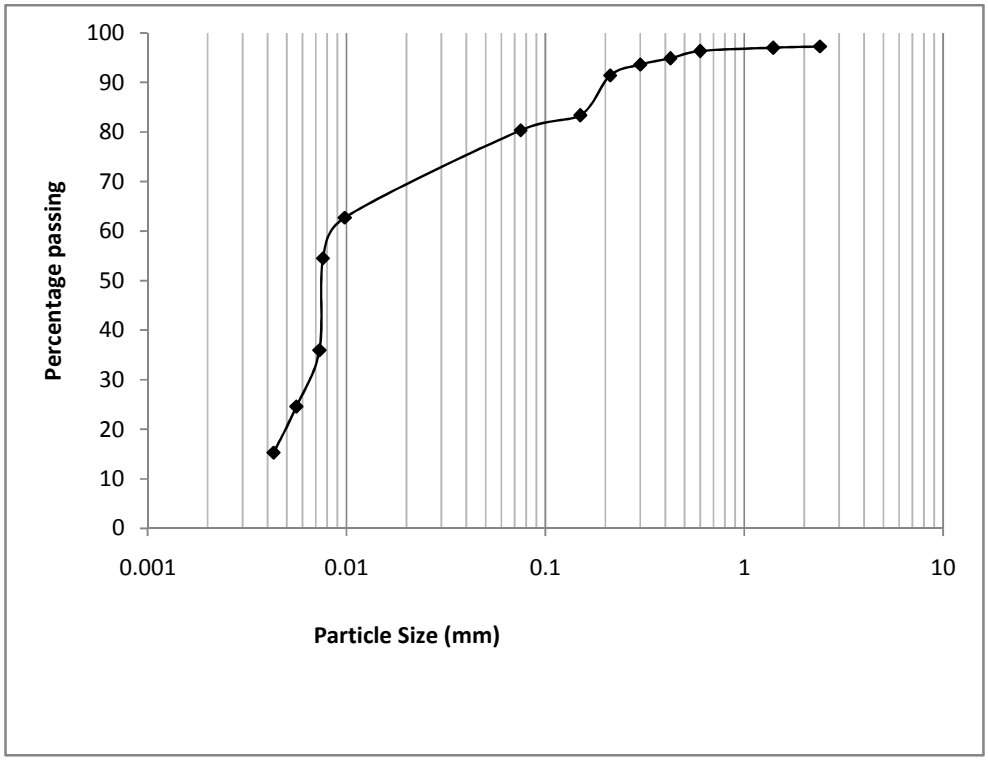

Fig 4.2 - Particle size distribution curve for the natural soil

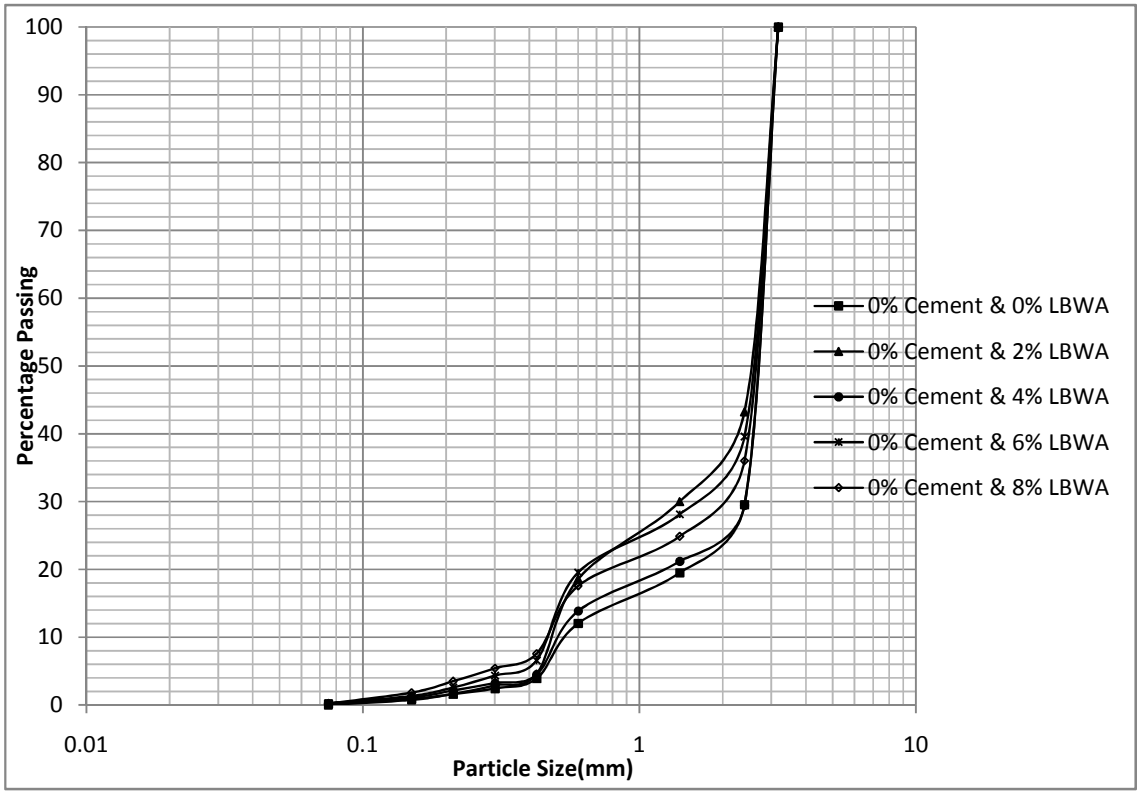

Fig. 4.3 -Particle size distribution curves of soil-0% cement-LBWA mixture (BSL compaction)

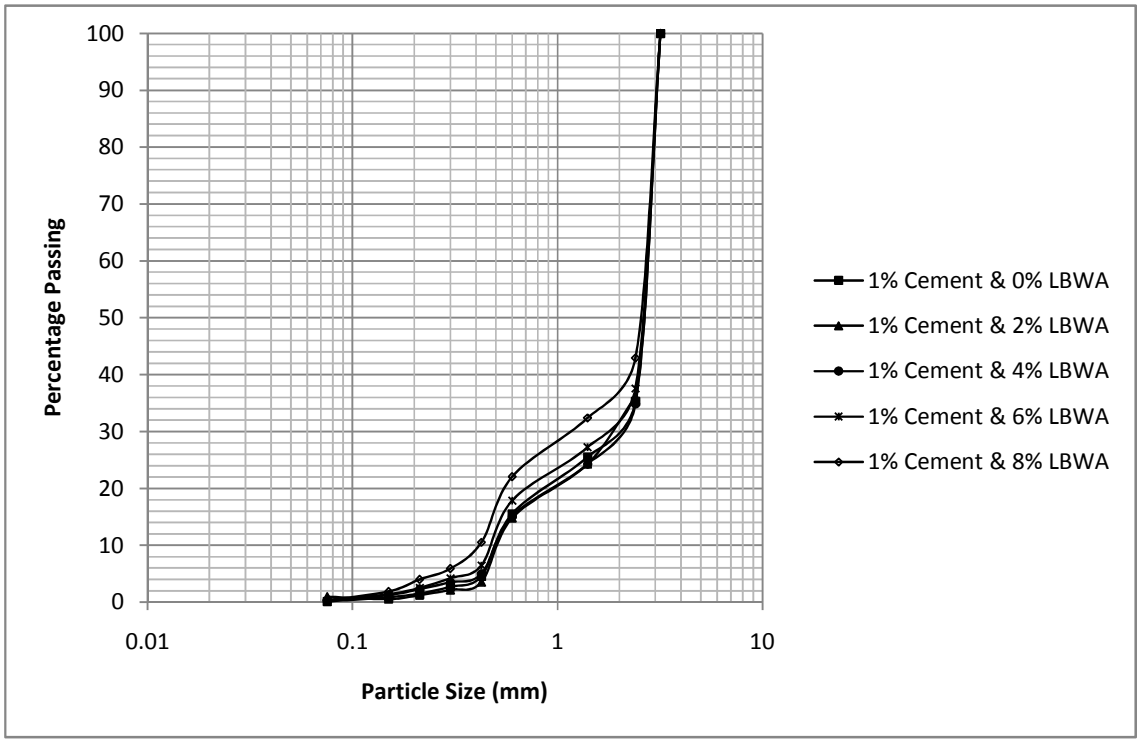

Fig. 4.4 - Particle size distribution curves of soil-1% cement-LBWA mixture (BSL compaction)

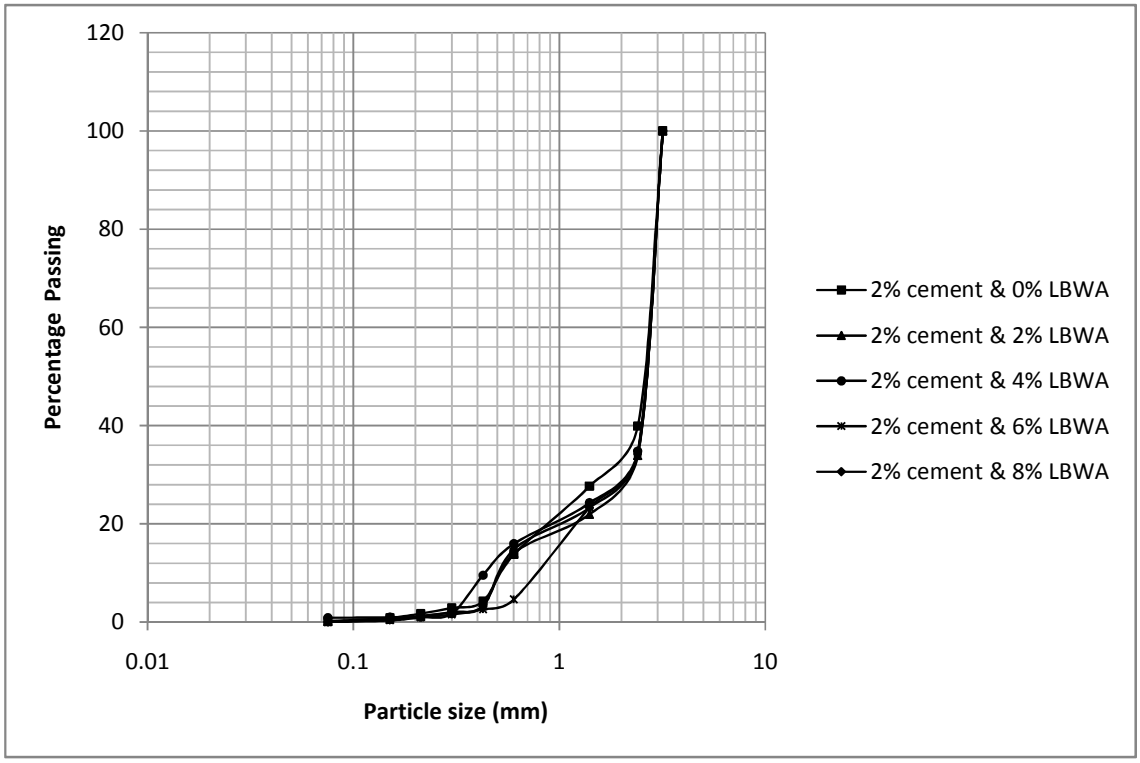

Fig. 4.5 - Particle size distribution curves of soil-2% cement-LBWA mixture (BSL compaction)

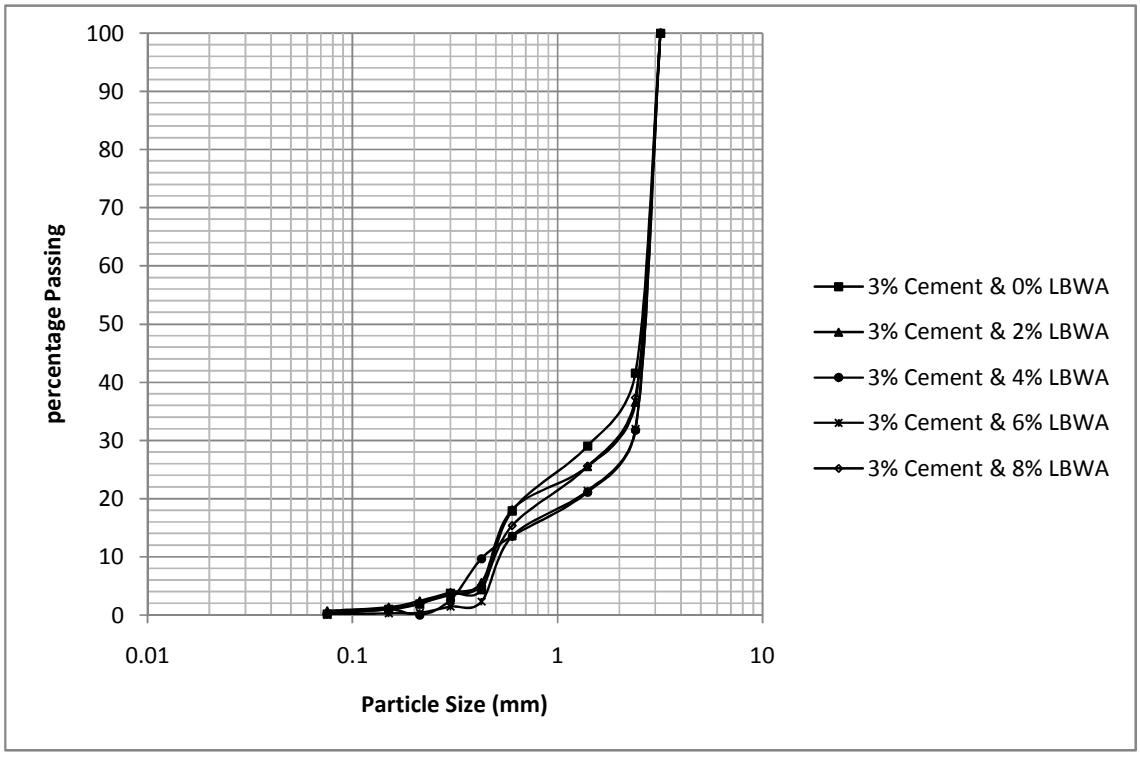

Fig. 4.6 - Particle size distribution curves of soil-3% cement-LBWA mixture (BSLcompaction)

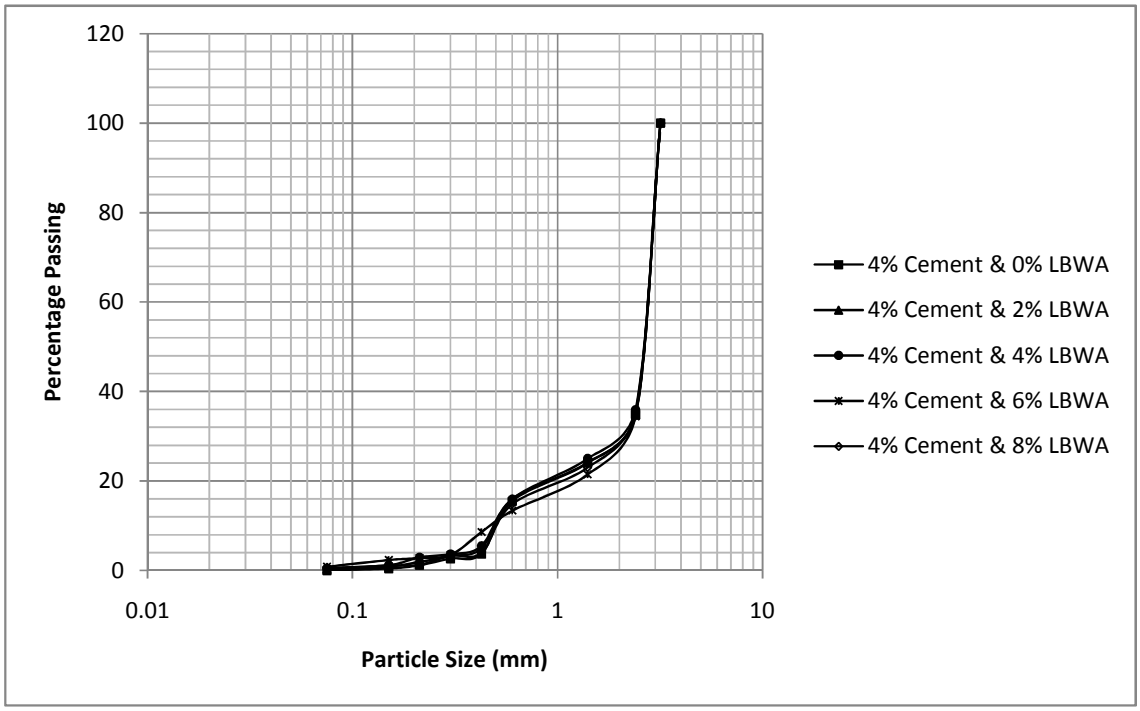

Fig. 4.7 - Particle size distribution curves of soil-4% cement-LBWA mixture (BSL compaction)

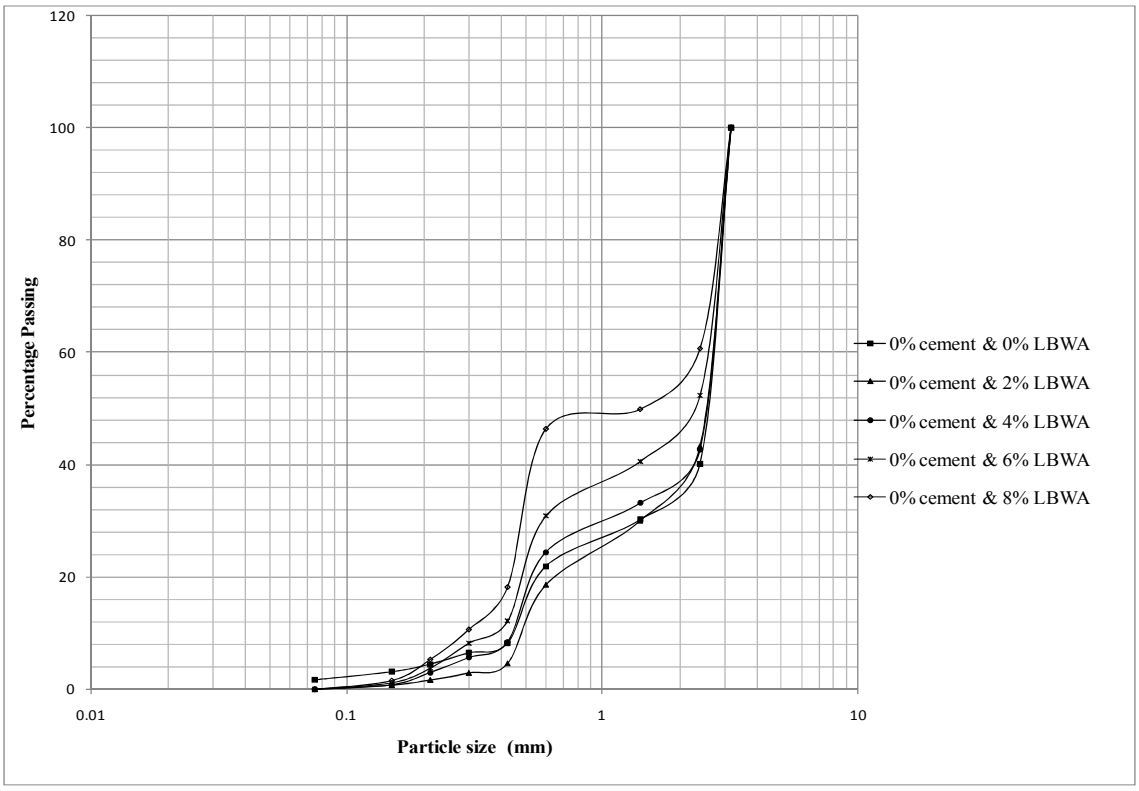

Fig. 4.8 - Particle size distribution curves of soil-0% cement-LBWA mixture (WAS compaction)

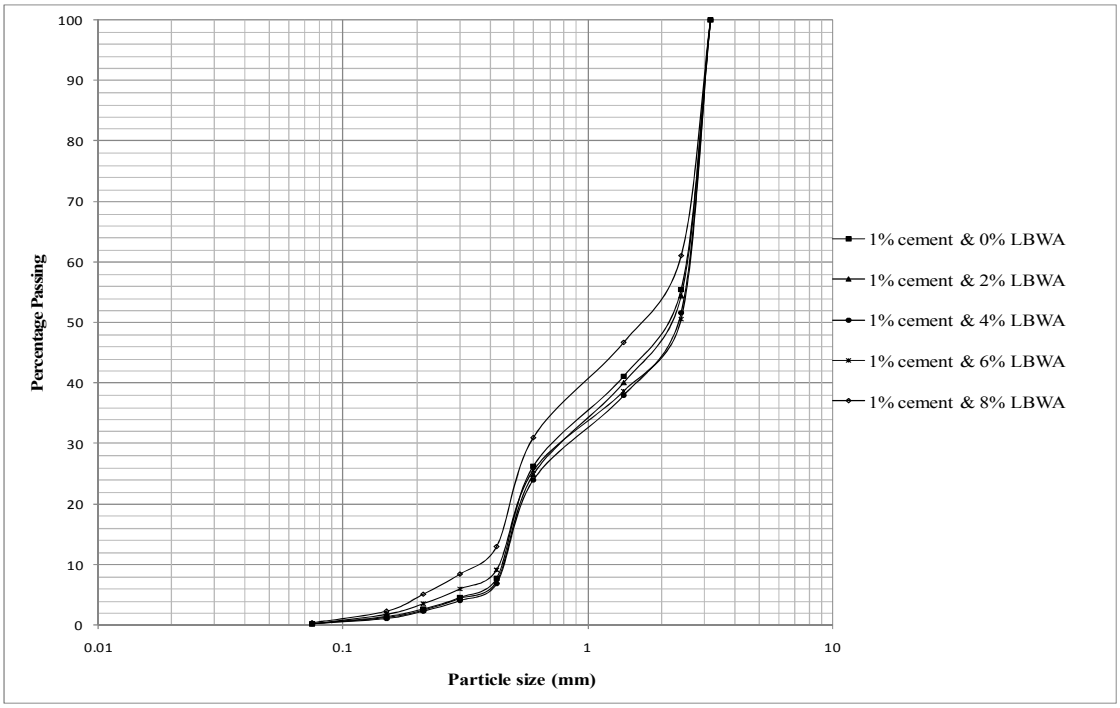

Fig. 4.9 - Particle size distribution curves of soil-1% cement-LBWA mixture (WAS compaction)

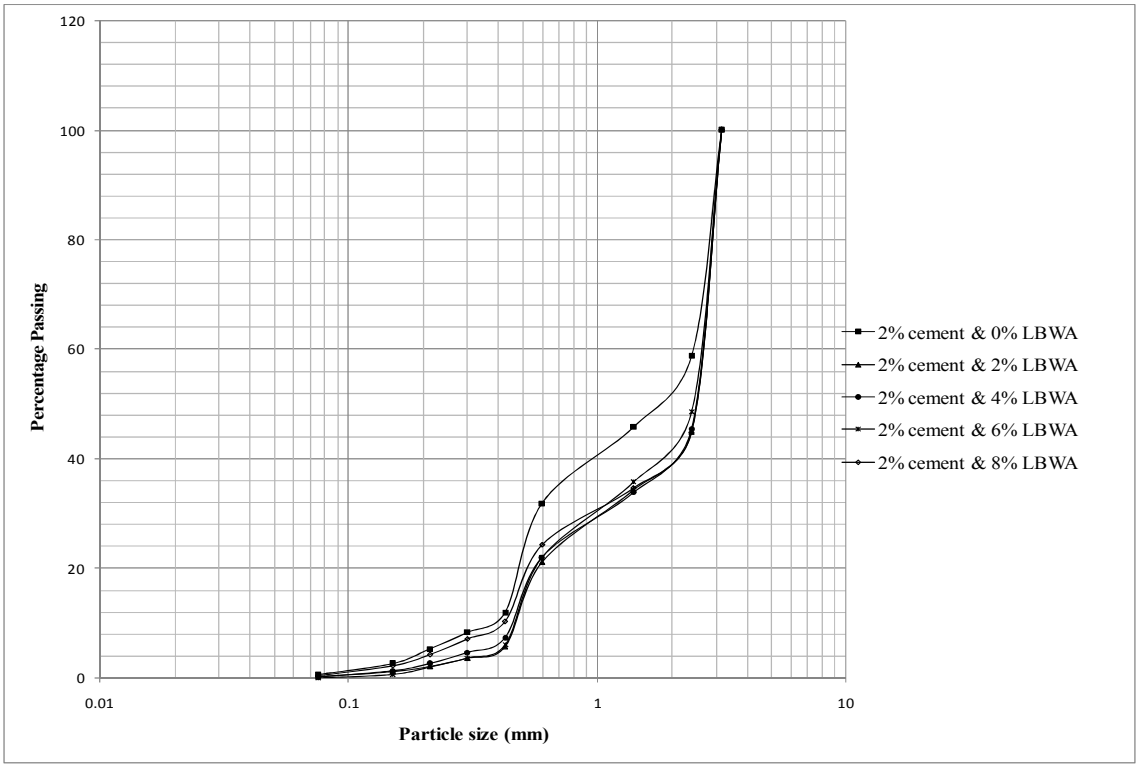

FIG. 4.10 - Particle size distribution curves of soil-2% cement-LBWA mixture (WAS compaction)

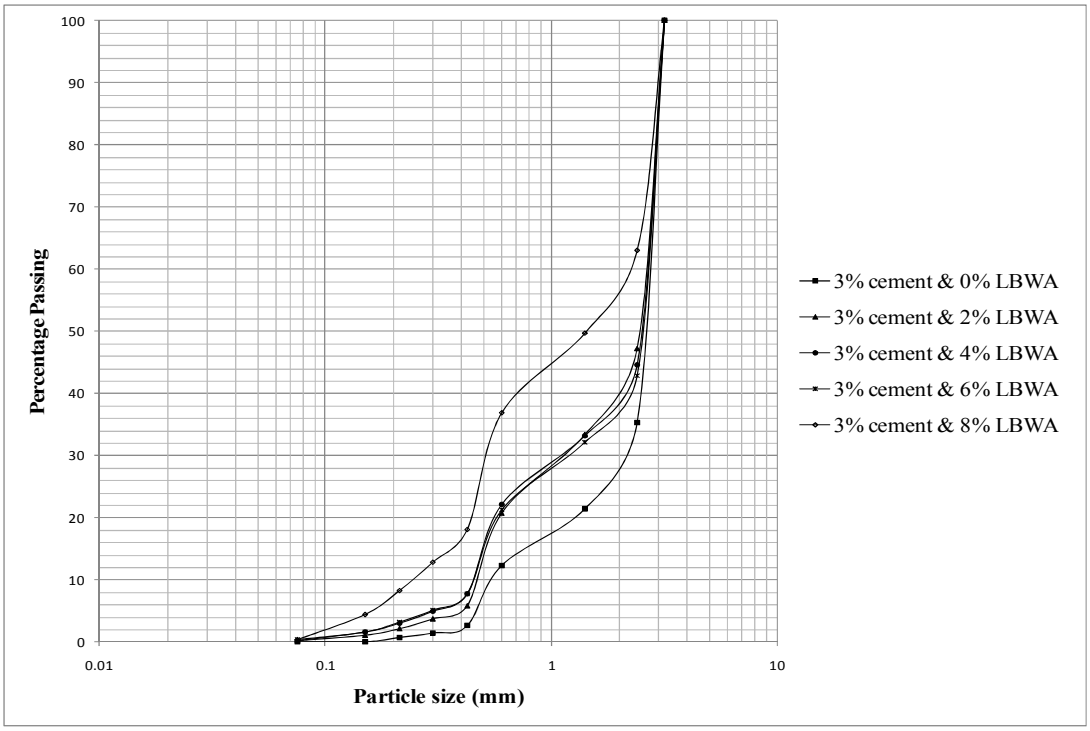

Fig. 4.11 - Particle size distribution curves of soil-3% cement-LBWA mixture (WAS compaction)

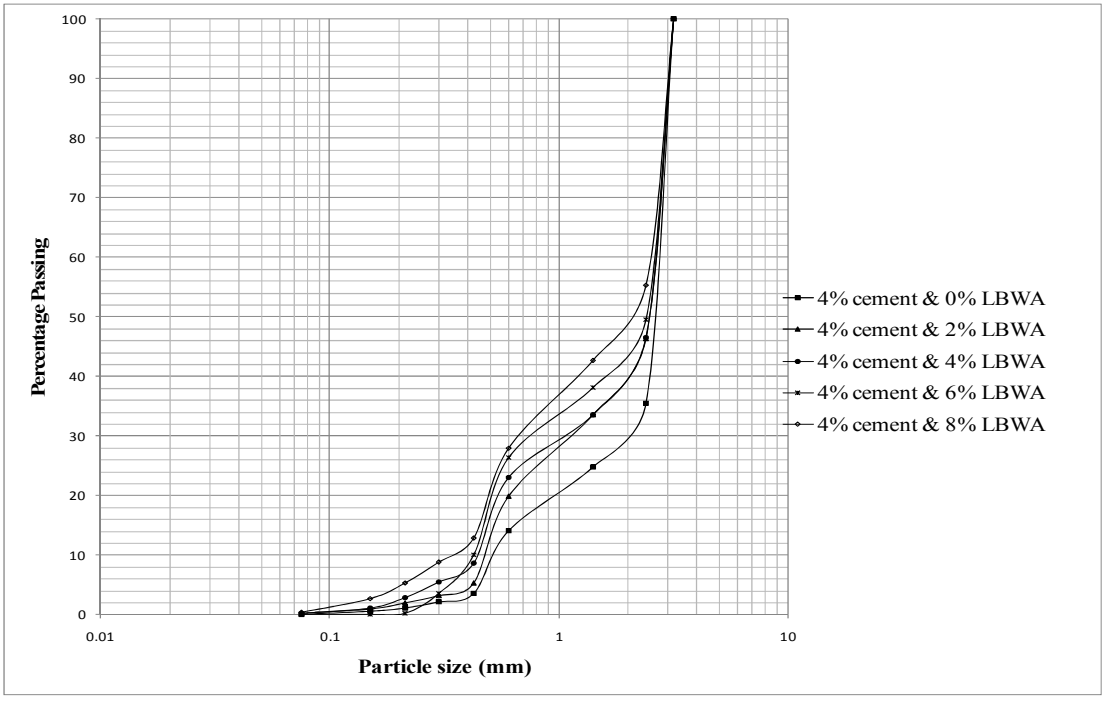

Fig. 4.12 - Particle size distribution curves of soil-4% cement-LBWA mixture (WAS compaction)

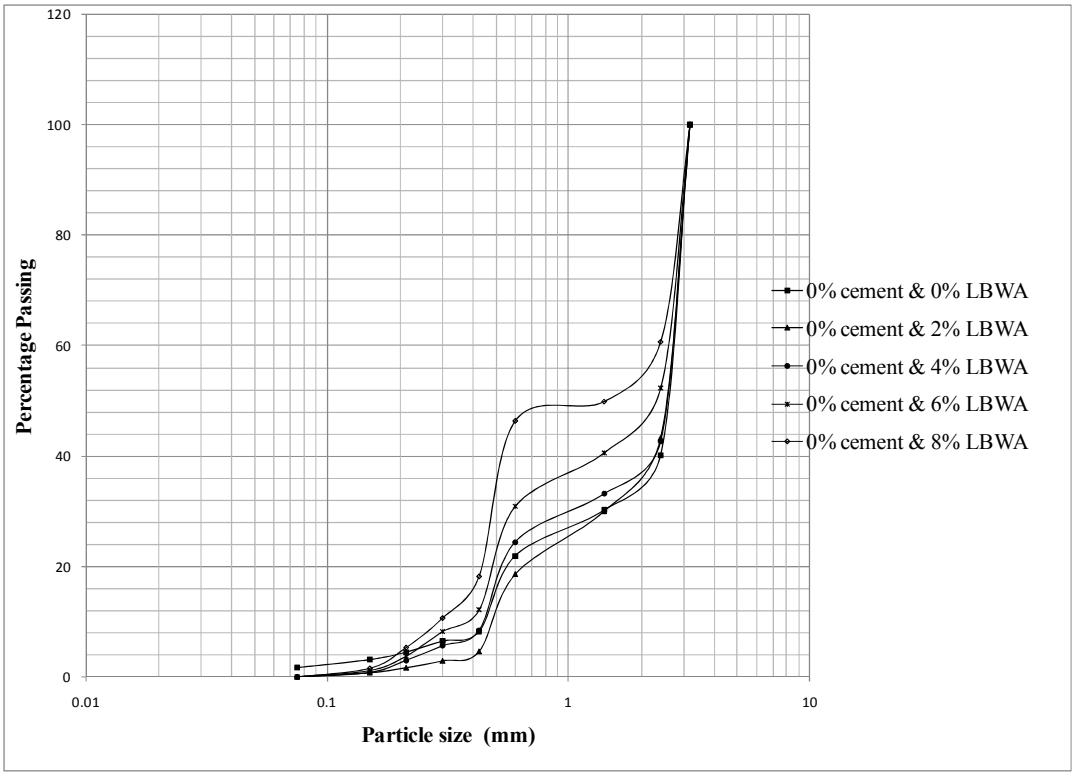

Fig. 4.13 - Particle size distribution curves of soil-0% cement-LBWA mixture (BSH compaction)

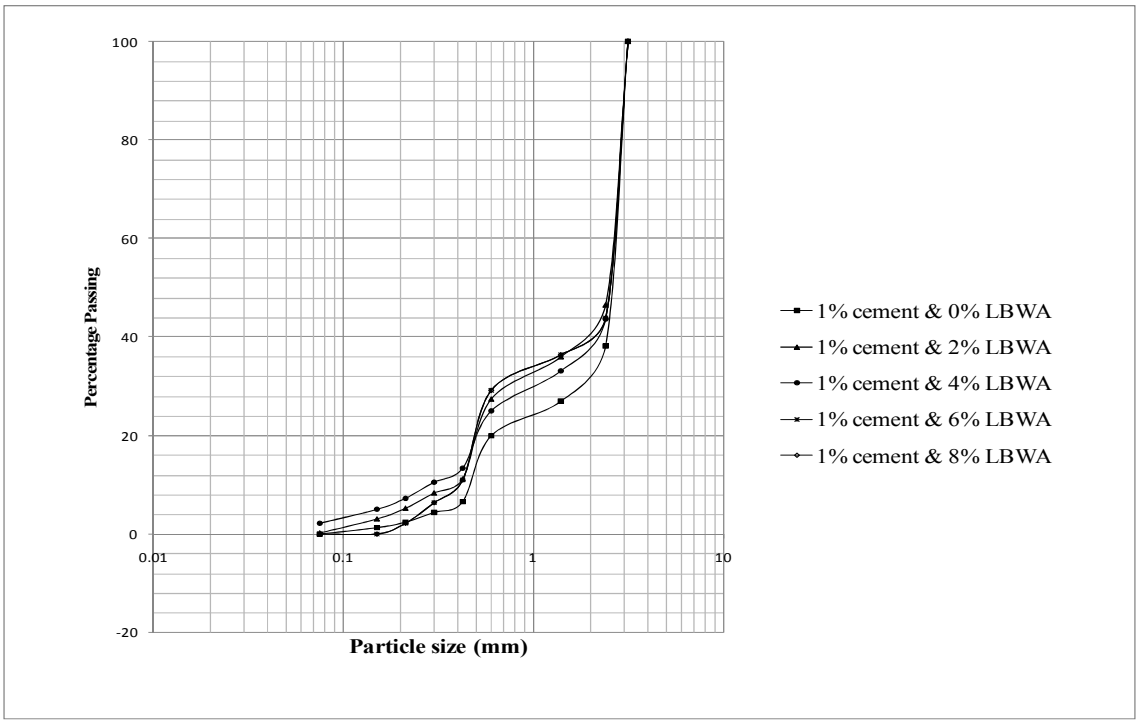

Fig. 4.14 - Particle size distribution curves of soil-1% cement-LBWA mixture (BSH compaction)

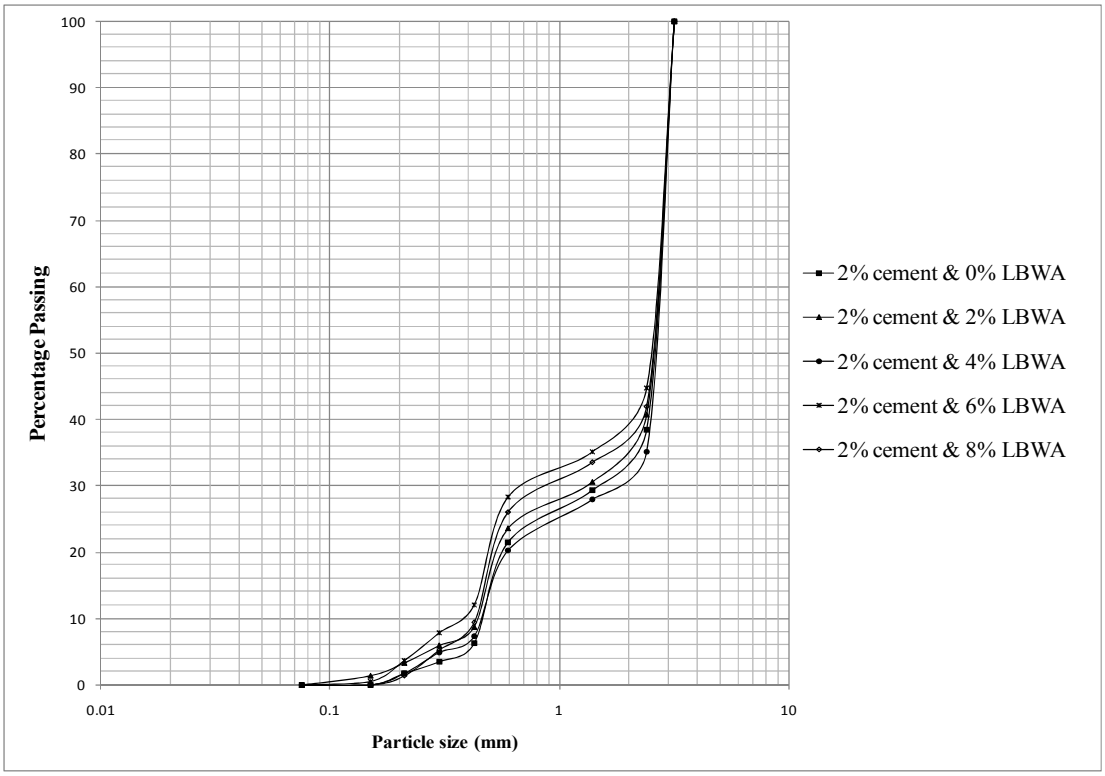

Fig. 4.15 - Particle size distribution curves of soil-2% cement-LBWA mixture (BSH compaction)

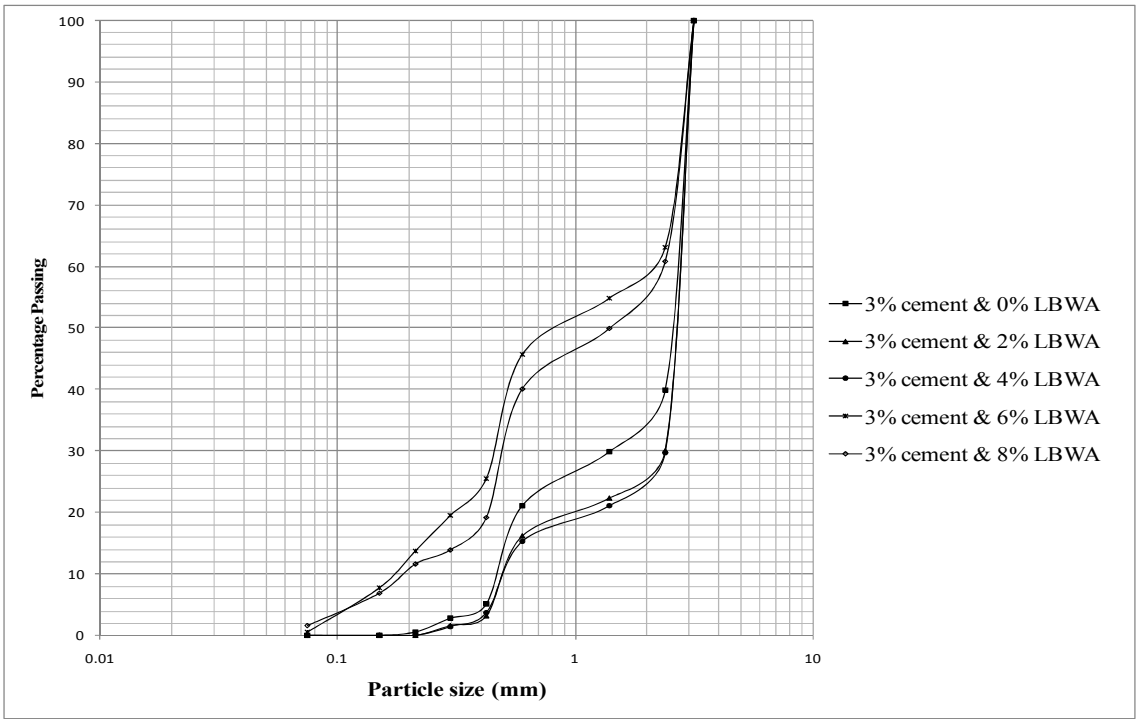

Fig. 4.16 - Particle size distribution curves of soil-3% cement-LBWA mixture (BSH compaction)

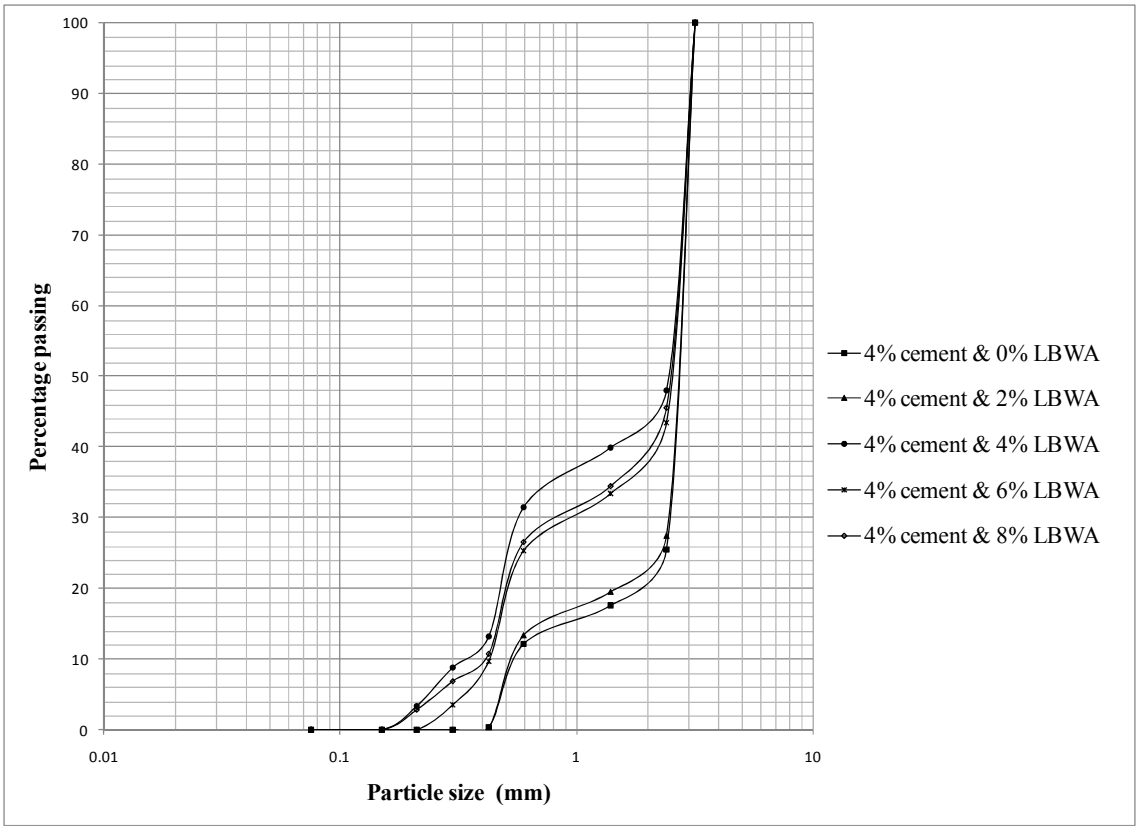

Fig. 4.17 - Particle size distribution curves of soil-4% cement-LBWA mixture (BSH compaction)

4.4 Atterberg Limits

4.4.1 Liquid Limit

The variation of liquid limit of the soil / soil - cement mixture with LBWA is shown in Fig. 4.18. The value of the liquid limit of the soil increased from 63% for the natural soil to a peak value of 79% at 4% OPC and 6% LBWA treatment. The reaction is in conformity with the concept of liquid limit, which is the water content at which the soil transits from plastic to dynamic shear strength. The addition of LBWA and OPC, especially introduces calcium for its strength which caused a decrease in the repulsive force of the soil mixture, thereby requiring more water to take the soil to its dynamic strength (Osinubi, 1995). It is also observed that the value of liquid limit slightly

decreased beyond 6% LBWA content, This reduction may not be unconnected with the agglomeration and flocculation of clay particles.

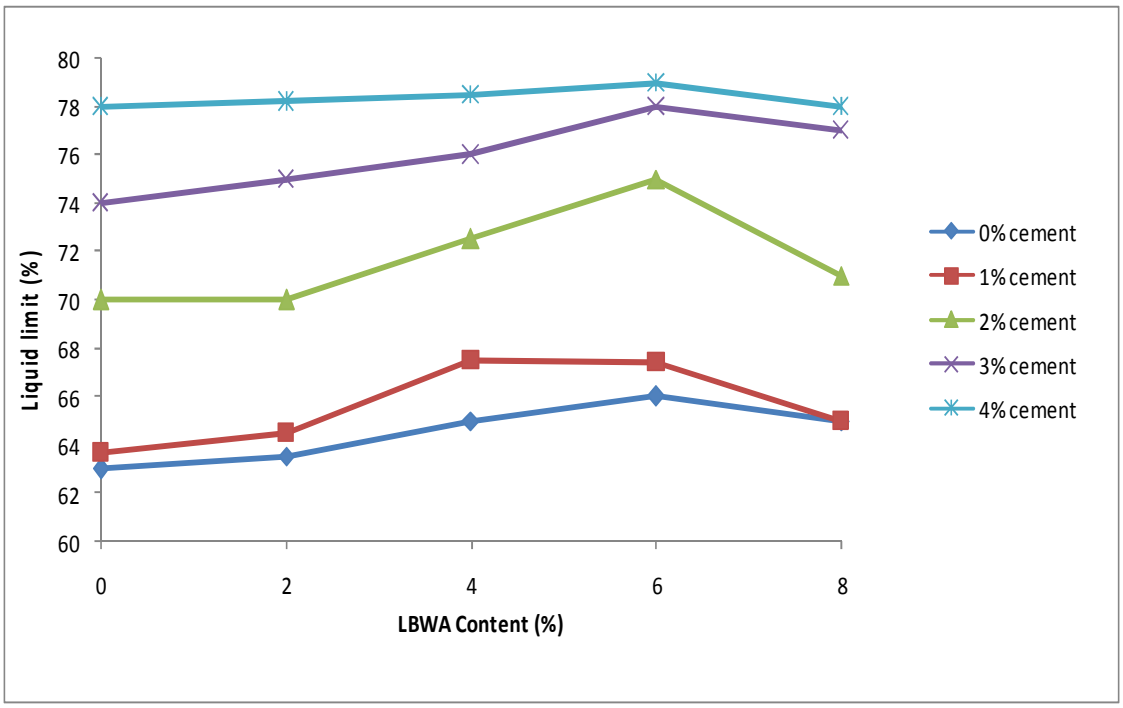

Fig. 4.18: Variation of liquid limit of soil-cement mixtures with LBWA content

A two-way analysis of variance (ANOVA) test on the liquid limit results (see Table 4.4) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 13.33 > F_{crit} = 3.01$ for cement and $F_{cal.} = 275.3 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the liquid limit of black cotton soil was more pronounced than that of cement. Detail of the liquid limit result is shown in Table A4.5 in the Appendix. Details of two-way ANOVA are shown in Table A4.12.

Table 4.4 Two-way analysis of variance for Atterberg limits of soil –cement – LBWA mixtures

Property	Source of variation	d_f	F_{cal}	P-value	F_{crit}	Remarks
Liquid Limit	Cement	4	13.32822	5.77E-05	3.006917	Statistically significant
	LBWA	4	278.3004	1.44E-14	3.006917	More statistically significant
Plastic Limit	Cement	4	8.921137	5.50E-04	3.006917	More statistically significant
	LBWA	4	5.058107	7.91E-03	3.006917	Statistically significant
Plasticity Index	Cement	4	13.15424	6.24E-05	3.006917	Statistically significant
	LBWA	4	32.22352	1.79E-07	3.006917	More statistically significant

d_f – Degree of freedom

4.4.2 Plastic Limit

The variation of plastic limit of the soil /soil - cement mixtures with LBWA content is shown in Fig. 4.19. Generally, the plastic limit decreased with increase in admixture contents, from a value of 26.6% for the natural soil to a minimum value of

24.6% at 4% OPC and 6% LBWA content and thereafter decreased. The decrease in plastic limit is in agreement with the findings reported by Osinubi (1995, 1999) and Peter (1993). The reduction was due to cation exchange reaction whereby the more active and higher valence cat ions (Ca^{2+}) in the admixture replaced the weakly bonded ion in the clay structure thereby leading to flocculation and liberation of water bonded at the outer layers.

A two-way analysis of variance (ANOVA) test on the plastic limit results (see Table 4.4) shows that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 8.92 > F_{crit} = 3.01$ for cement and $F_{cal.} = 5.06 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the plastic limit of black cotton soil was less significant than that of cement. Details of the plastic limit result are shown in Table A4.6 in the Appendix. Details of the ANOVA results are shown in Table A4.13

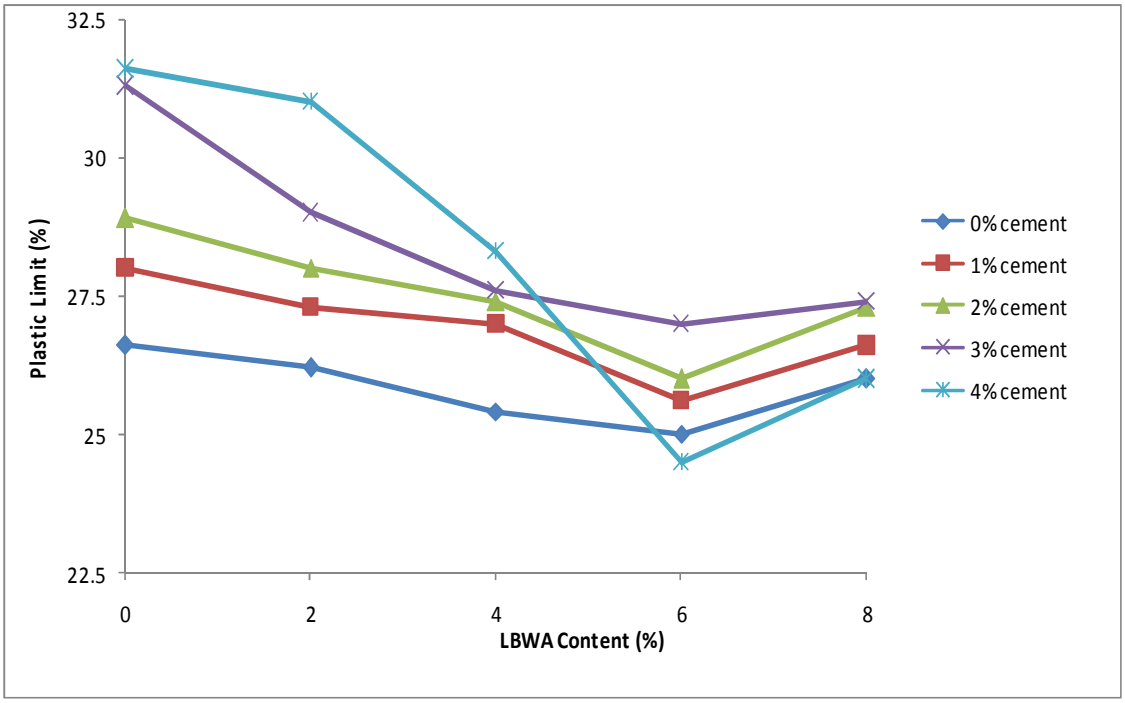

Fig. 4.19: Variation of plastic limit of soil-cement mixtures with LBWA content

4.4.3 Plasticity Index

The variation of the plasticity index of soil – cement mixtures with LBWA content are shown in Fig. 4.20. The increase in liquid limit and decrease in plastic limit were accompanied by a general increase in plasticity index value from a minimum value of 36.4% to a peak value of 54.4% at 4%OPC/6% LBWA treatment. Plasticity index values decreased on further addition of LBWA. This is in conformity with the finding reported by Akinmade, (2008) for LBWA stabilized black cotton soil. The same trend was also reported by Stephen (2005) for baggase ash stabilised black cotton soil.

A two-way analysis of variance (ANOVA) test on the plasticity index results (see Table 4.4) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 13.15 > F_{crit} = 3.01$ for cement and $F_{cal.} = 32.22 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the plasticity index of black cotton soil was more pronounced than that of cement. Details of the plasticity index results are shown in Table A4.7 in the Appendix. Details of ANOVA results are shown in TableA4.14.

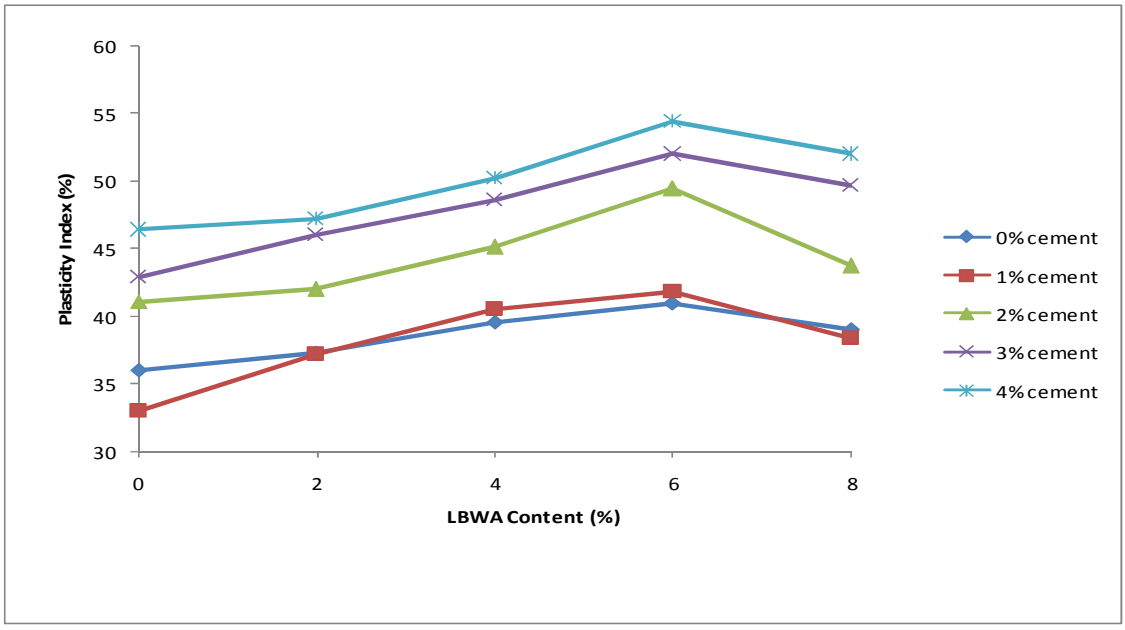

Fig. 4.20: Variation of plasticity index of soil-cement mixtures with LBWA content

4.5 Compaction Characteristics

4.5.1 Maximum Dry Density

The variation of maximum dry density (MDD) (Mg/m^3) of soil- cement with LBWA content for the three compactive efforts are presented in Fig. 4.21 (a - c). Generally MDD values increased with increased admixture contents which are as a result of cement / ash filling the void within the soil.

The MDD for the BSL compaction increased from $1.34Mg/m^3$ for the natural soil to peak value at 4% OPC and 6% LBWA content beyond which it decreased. The reduction may be due to the minimal effect of LBWA (with little calcium) on the workability of the modified soil.

A two-way analysis of variance (ANOVA) test on the MDD (BSL) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 50.75 > F_{crit} = 3.01$ for cement and $F_{cal.} = 207.56 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the MDD BSL of black cotton soil was more pronounced than that of cement. Details of the MDD (BSL) result is shown in Table A4.8a in the Appendix. Details of two-way ANOVA results are shown in Table A4.15a.

The MDD for the WAS compaction also increased from $1.45Mg/m^3$ for the natural soil to a peak value of $1.55Mg/m^3$ at 4% OPC and 6% LBWA content beyond which slight decrease were observed. The increase in MDD values is due to cement – LBWA blend occupying the void within the soil and in addition, the flocculation and agglomeration of the clay particles due primarily to ion exchange (O' Flaherty, 1988). The reduction of the MDD beyond 6% LBWA may be attributed to the presence of large low density aggregate of LBWA replacing the soil with higher specific gravity.

Table 4.5 Two way analysis of variance for compaction characteristics of soil – cement –LBWA mixtures.

Property		Source of variation	d_f	F_{cal}	P-value	F_{crit}	Remarks
BSL	MDD	Cement	4	50.75728	6.82E-09	3.006917	Statistically significant
		LBWA	4	207.6505	1.44E-13	3.006917	More statistically significant
	OMC	Cement	4	37.41058	6.24E-08	3.006917	More statistically significant
		LBWA	4	21.08816	3.23E-06	3.006917	Statistically significant
WAS	MDD	Cement	4	40.88263	3.3E-08	3.006917	More statistically significant
		LBWA	4	29.70892	3.16E-07	3.006917	Statistically significant
	OMC	Cement	4	85.81818	1.34E-10	3.006917	Statistically significant
		LBWA	4	132.000	4.91E-12	3.006917	Statistically significant
BSH	MDD	Cement	4	16.41451	1.61E-05	3.006917	Statistically significant
		LBWA	4	60.66321	1.82E-09	3.006917	More statistically significant
	OMC	Cement	4	75.7222	3.45E-10	3.006917	Statistically significant
		LBWA	4	136.2778	3.83E-12	3.006917	More statistically significant

d_f – Degree of freedom

A two-way analysis of variance (ANOVA) test on the MDD (WAS) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 40.88 > F_{crit} = 3.01$ for cement and $F_{cal.} = 29.71 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the MDD (WAS) of black cotton soil was less significant than that of cement. Details of the MDD (WAS) results are shown in Table A4.8b in the Appendix. Details of two-way ANOVA results are shown in Table A4.15b.

The MDD for the BSH compaction is also in conformity with the other trends observed for the BSL and WAS energy levels. The MDD for BSH increased from 1.53 Mg/m^3 and peaked at 1.62 Mg/m^3 at 4% OPC and 6% LBWA content. The increase in MDD is also due to the cement – LBWA blend filling the voids within the soil matrix and in addition the flocculation and agglomeration of the clay particles due to primarily to ion exchange. Osinubi (1999) reported the similar trend of increase in MDD with increased admixture content up to the peak value of 6% OPC before reduction in the value of MDD at higher admixture content. Akinmade (2008) also reported the same trend of increasing MDD to a peak value before decreasing at higher admixture content where further addition had no significant impact on the MDD values.

A two-way analysis of variance (ANOVA) test on the MDD (BSH) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 16.41 > F_{crit} = 3.01$ for cement and $F_{cal.} = 60.66 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the MDD (BSH) of black cotton soil was more pronounced than that of cement. Details of the MDD (BSH) results are shown in Table A4.8c in the Appendix. Details of two-way ANOVa results are shown in Table A4.15c.

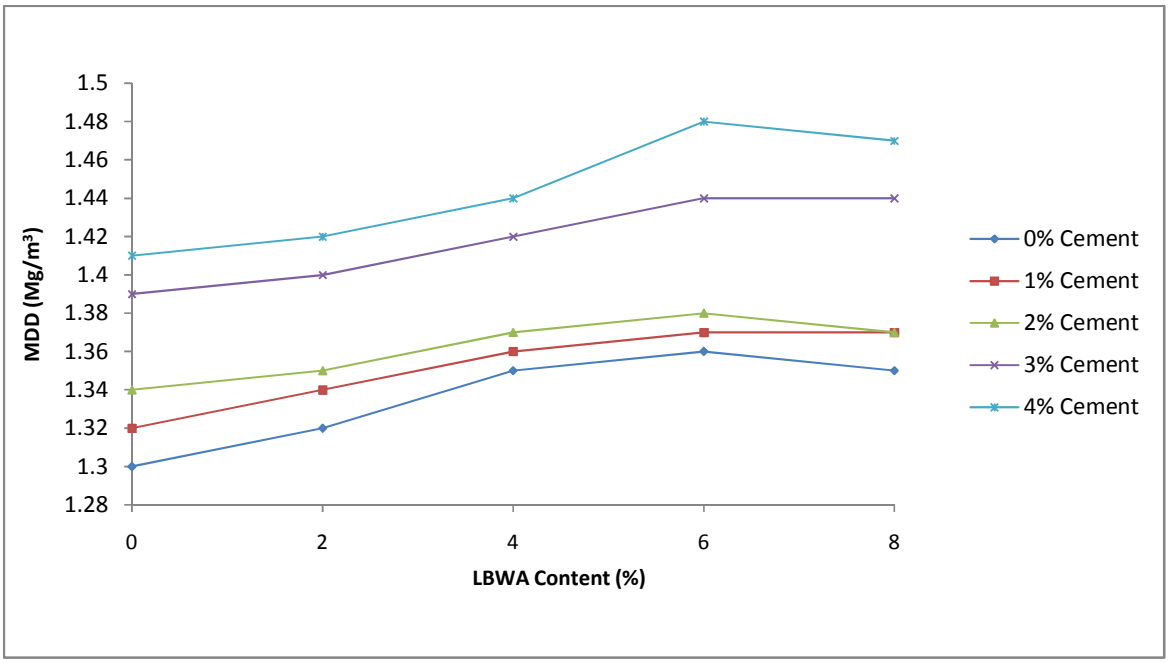

Fig. 4.21a: Variation of maximum dry density of soil-cement mixtures with LBWA content (BSL compaction)

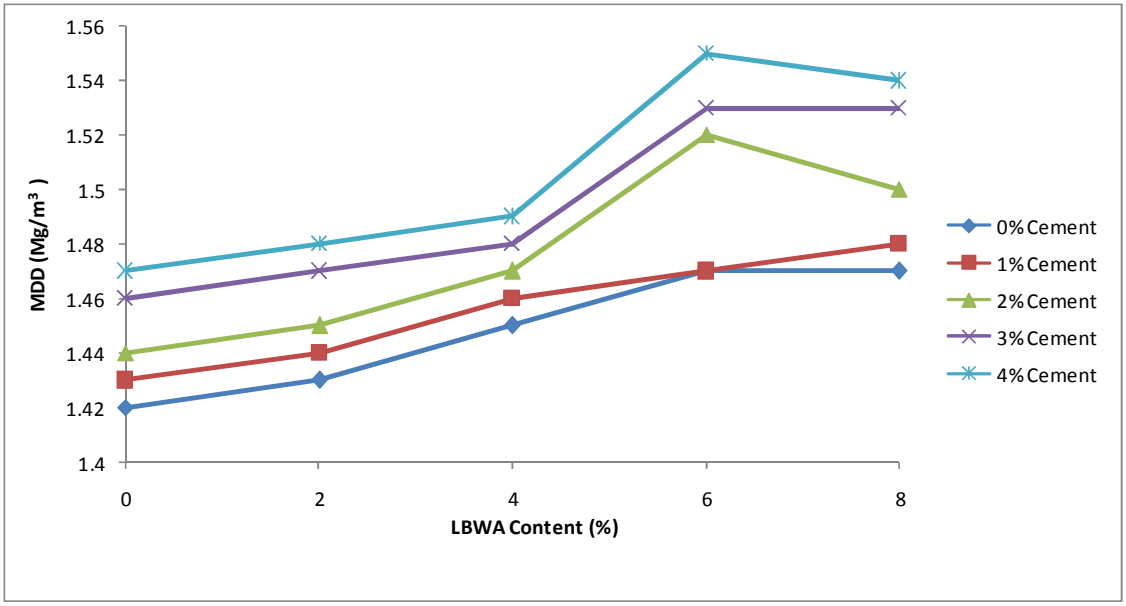

Fig. 4.21b: Variation of maximum dry density of soil-cement mixtures with LBWA content (WAS compaction)

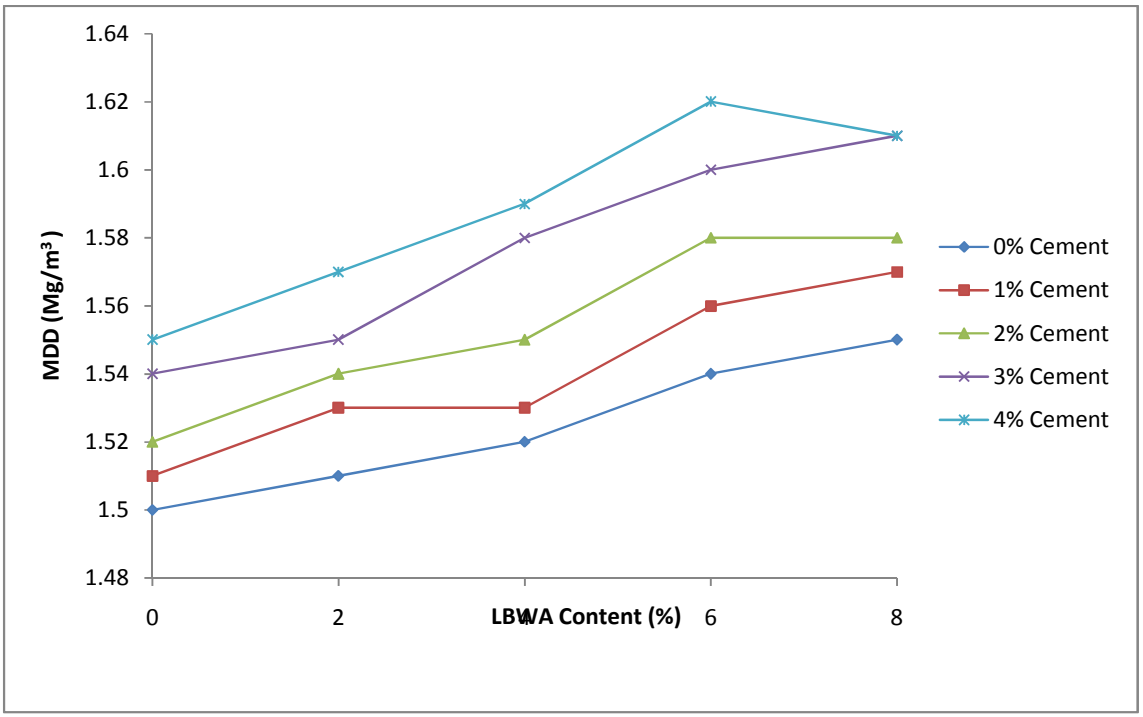

Fig. 4.21c: Variation of maximum dry density of soil-cement mixtures with LBWA content (BSH compaction)

4.5.2 Optimum Moisture Contents

The variation of optimum moisture contents of the soil - cement with LBWA for the BSL, WAS and BSH compactions are presented in Fig. 4.22 (a - c), respectively. It can be observed that OMC increased with higher LBWA content for all the cement contents considered.

The OMC for BSL compaction increased from 24% for the natural soil to 39% at 4% OPC / 6% LBWA treatment beyond which slight decrease was observed. For the WAS the OMC increased from 20% for the natural soil to a peak value of 33% at 4% OPC/6% LBWA treatment beyond which slight decrease was observed. For BSH compaction the OMC also increased from 19% for the natural soil to 30% at 4% OPC/6% LBWA treatment beyond which slight decrease was observed.

The increase in OMC trend with higher admixture content agrees with research works of Osinubi (1999), Stephen (2005), George (2006), Osinubi et al. (2007b), Akinmade (2008), and Ochepo (2008). The explanation offered for this trend is that there was increasing demand for water by various cations and the clay minerals particles to undergo hydration. Another reason could be the increase in surface area caused by higher amount of additives, it implies that apart from water needed for hydration of cement to take place, more water was needed in order to compact the soil – cement mixture. Moreover, it was observed that the OMC decreased with higher compactive efforts because it was easier to break down flocculated aggregate, destroy shear planes and eliminate large pore at higher compactive effort ((Osinubi, 1999).

A two-way analysis of variance (ANOVA) test on the OMC (BSL) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 37.41 > F_{crit} = 3.01$ for cement and $F_{cal.} = 21.09 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the OMC (BSL) of black cotton soil was less significant than that of cement. Details of the OMC (BSL) results are shown in Table A4.9a in the Appendix. Details of two-way ANOVA results are shown in Table A4.16a.

A two-way analysis of variance (ANOVA) test on the OMC (WAS) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 75.72 > F_{crit} = 3.01$ for cement and $F_{cal.} = 136.27 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the MDD (BSH) of black cotton soil was more pronounced than that of cement. Details of the OMC result for the WAS compaction are shown in Table A4.9b in the Appendix. Details of two-way ANOVA are shown in Table A4.16b.

A two-way analysis of variance (ANOVA) test on the OMC (BSH) results (see Table 4.5) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 85.82 > F_{crit} = 3.01$ for cement and $F_{cal.} = 132.0 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the OMC (BSH) of black cotton soil was more pronounced than that of cement. Detail of the OMC (BSH) results are shown in Table A4.9c in the Appendix. Details of two-way ANOVA details are shown in Table A4.16c.

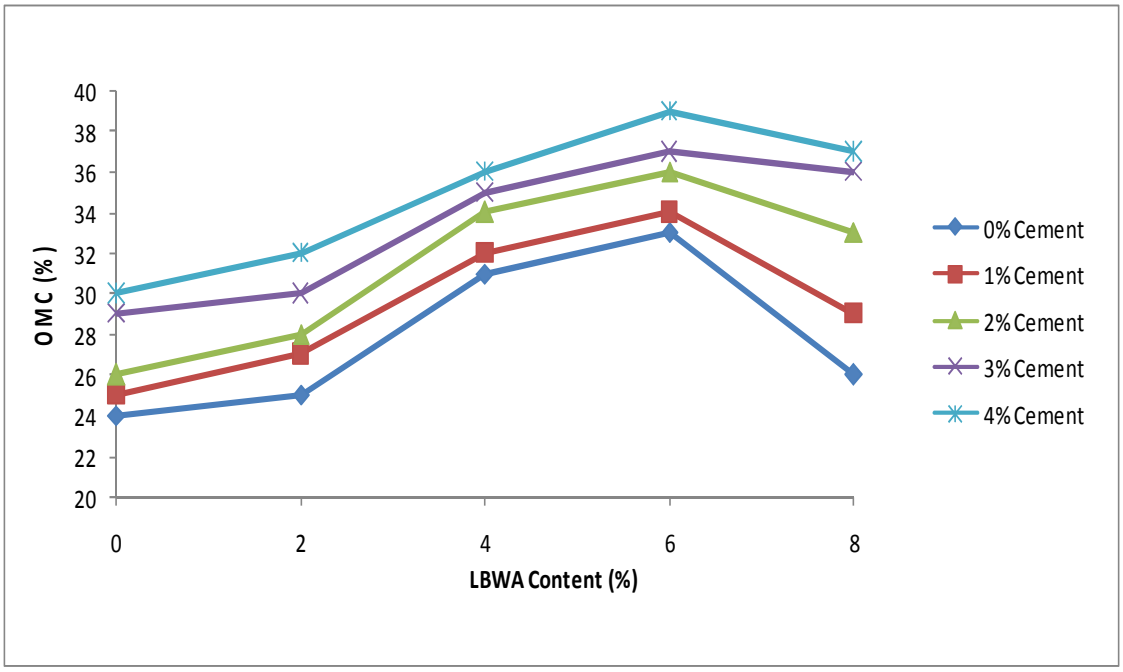

Fig. 4.22a: Variation of optimum moisture content of soil-cement mixtures with LBWA content (BSL compaction)

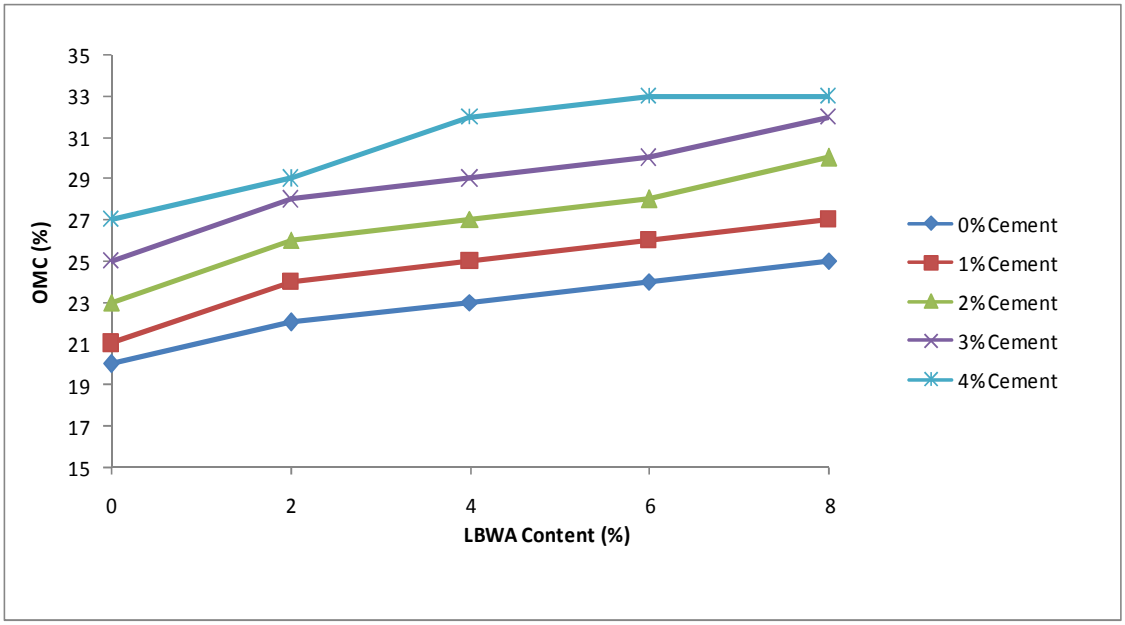

Fig. 4.22b: Variation of optimum moisture content of soil-cement mixtures with LBWA content (WAS compaction)

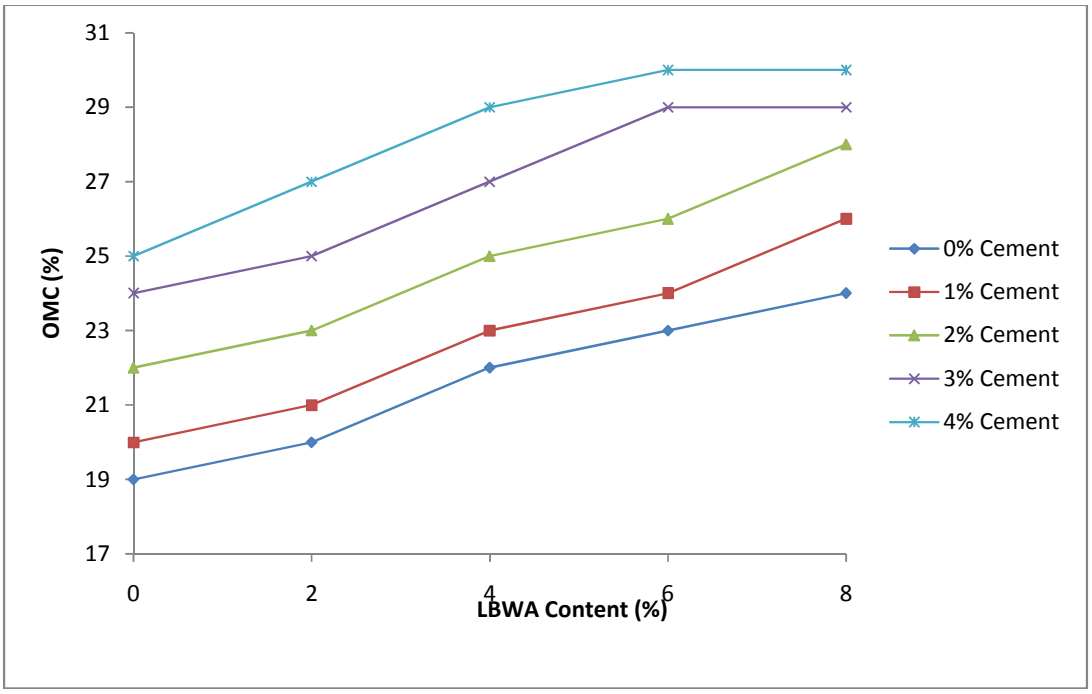

Fig. 4.22c: Variation of optimum moisture content of soil-cement mixtures with LBWA content (BSH compaction)

4.6 Shear Strength Parameters

4.6.1 Cohesion

Variation of cohesion of cement-treated soil with locust bean waste ash for British Standard light energy level is shown in Figure 4.23. The cohesion is seen generally reduced with increase in LBWA content. The reduction in cohesion could be associated with the breaking down of the weak forces holding the clay particles together to form stronger bonds between the clay and OPC/LBWA particles thereby reducing the cohesive nature of the natural soil. For BSL compaction the cohesion reduced from 75kN/m^2 for the natural soil to 20kN/m^2 at 4% OPC / 6% LBWA treatment.

A two-way analysis of variance (ANOVA) test on the cohesion (BSL) results (see Table 4.6) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 84.0 > F_{crit} = 3.01$ for cement and $F_{cal.} = 123.14 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the cohesion (BSL) of black cotton soil was more pronounced than that of cement. Details of the cohesion (BSL) results are shown in Table A4.10a in the Appendix. Details of two-way ANOVA results are shown in Table A4.17a.

Table 4.6 Two-way analysis of variance for shear strength parameters of soil – cement – LBWA mixtures

Property		Source of variation	d_f	F_{cal}	P-value	F_{crit}	Remarks
BSL	Cohesion	Cement	4	84.00325	1.37E-10	3.006917	Statistically significant
		LBWA	4	123.6481	8.14E-12	3.006917	More statistically significant
	Angle of internal Friction	Cement	4	12.80694	7.3E-05	3.006917	More statistically significant
		LBWA	4	9.647102	3.6E-04	3.006917	Statistically significant
WAS	Cohesion	Cement	4	35.56802	8.93E-08	3.006917	Statistically significant
		LBWA	4	53.93681	4.36E-09	3.006917	More Statistically significant
	Angle of internal Friction	Cement	4	42.59874	2.45E-08	3.006917	More Statistically significant
		LBWA	4	3.284179	3.81E-02	3.006917	Statistically significant
BSH	Cohesion	Cement	4	42.23669	2.61E-08	3.006917	Statistically significant
		LBWA	4	48.29806	9.82E-09	3.006917	More statistically significant
	Angle of internal Friction	Cement	4	49.70886	7.95E-09	3.006917	More Statistically significant
		LBWA	4	4.265823	1.54E-02	3.006917	Statistically significant

d_f – Degree of freedom

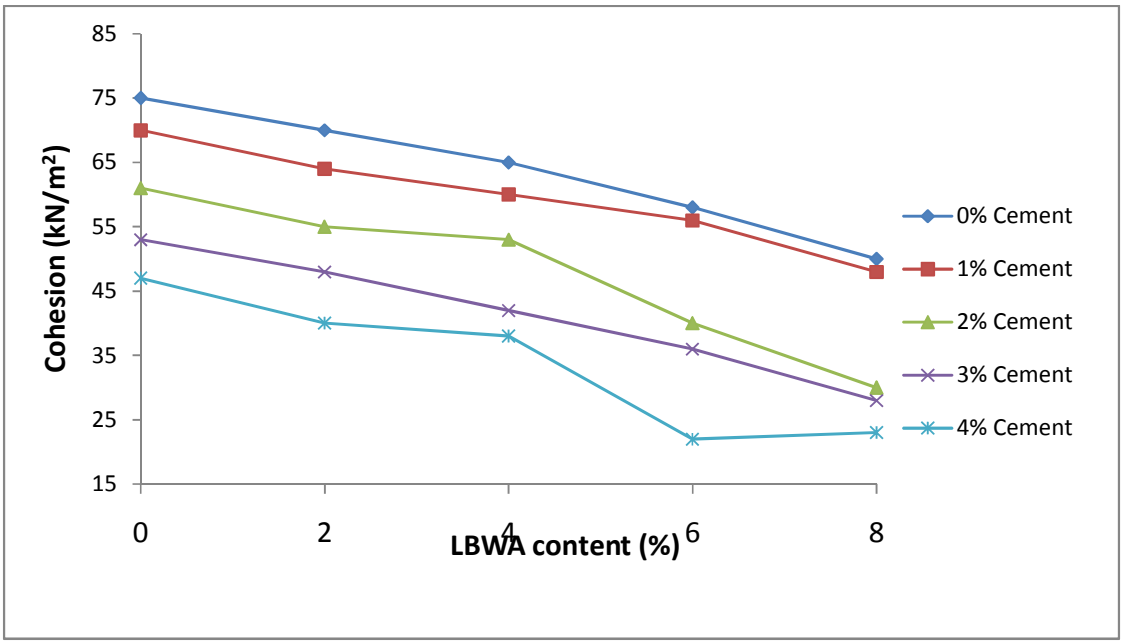

Fig. 4.23 - Variation of cohesion of soil-cement mixtures with LBWA content (BSL compaction).

Similar trends were also observed for the WAS and BSH compactions (see Figs 4.24 and 4.25). For the WAS compaction the cohesion decreased from 70kN/m^2 for natural soil to 15kN/m^2 at 4% OPC/ 6%LBWA treatment. When the BSH compaction was employed the cohesion decreased from 60kN/m^2 for the natural soil to the 20kN/m^2 at 4% OPC/6%LBWA treatment. It is therefore possible that the same process was taking place when the soil was compacted at these energy levels.

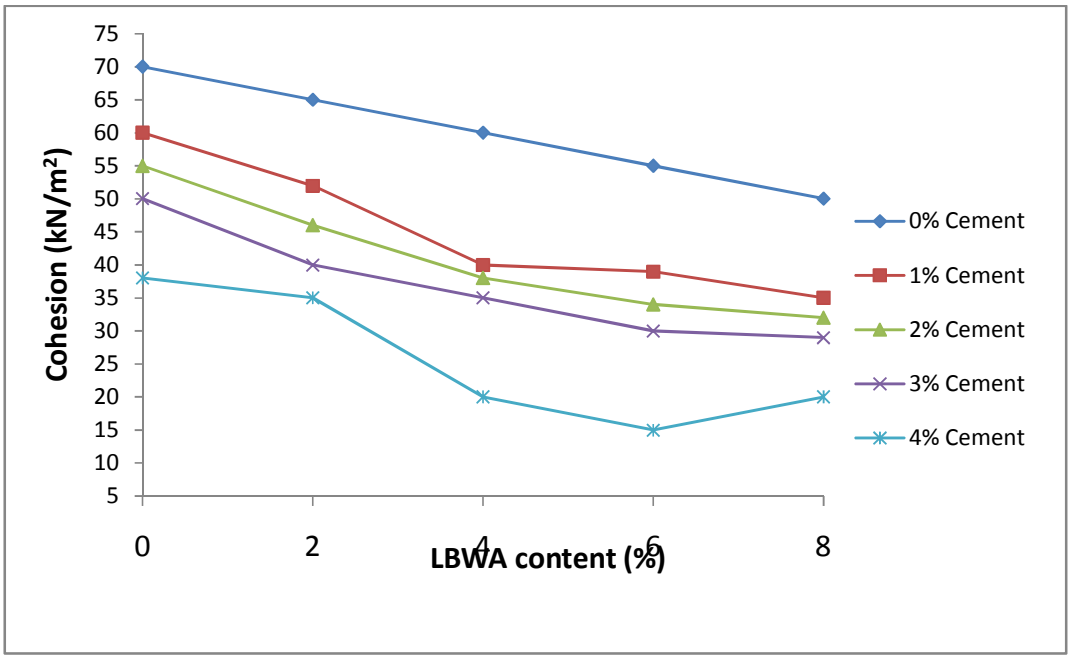

Fig. 4.24 - Variation of cohesion of soil-cement mixtures with LBWA content (WAS compaction)

A two-way analysis of variance (ANOVA) test on the cohesion (WAS) results (see Table 4.6) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 35.52 > F_{crit} = 3.01$ for cement and $F_{cal.} = 53.93 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the cohesion (WAS) of black cotton soil was more pronounced than that of cement. Details of the cohesion (WAS) results are shown in Table A4.10b in the Appendix. Details of two-way ANOVA results are shown in Table A4.17b.

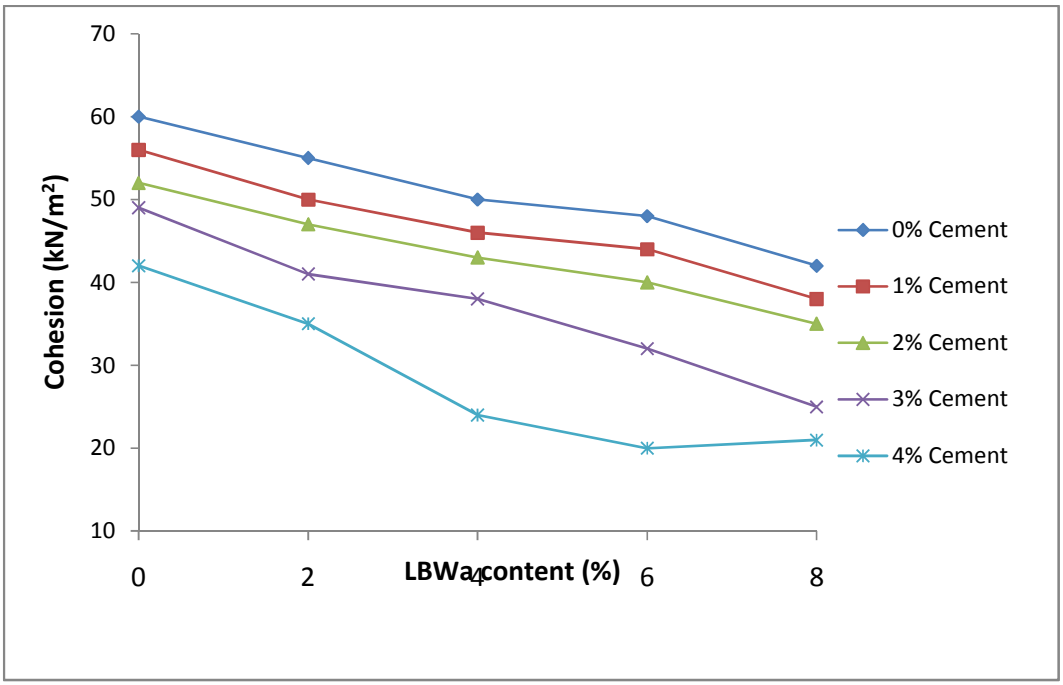

FIG. 4.25 - Variation of cohesion of soil-cement mixtures with LBWA content (BSH compaction)

A two-way analysis of variance (ANOVA) test on the cohesion (BSH) results (see Table 4.6) show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 35.52 > F_{crit} = 3.01$ for cement and $F_{cal.} = 53.93 > F_{crit} = 3.01$ for LBWA.The effect of LBWA on the cohesion (BSH) of black cotton soil was more pronounced than that of cement. Details of the cohesion (BSH) results are shown in Table A4.10c in the Appendix. Details of two-way ANOVA results are shown in Table A4.17c.

4.6.2 Angle of internal friction

The variation of angle of internal friction of soil-cement mixtures with locust bean waste ash content for British standard light, West African standard and British standard heavy energy levels are shown in Figures 4.26 and 4.27. Generally, the angle of internal friction increased for all the OPC / L B WA treatment and the energy levels considered.

For the BSL values of angle of internal friction of the natural soil ranged from 18 to 30^0 when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% OPC and up to 8% LBWA content the value increase from 20 to 30.5^o, 23 to 33^0, 27 to 35.5^0 and 29 to 35^0, respectively.

A two-way analysis of variance (ANOVA) test on the angle of internal friction BSL results show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 12.80 > F_{crit} = 3.01$ for cement and $F_{cal.} = 9.65 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the angle of internal friction BSL of black cotton soil was less significant than that of cement (see Table 4.6). Details of the angle of internal friction (BSL) results are shown in Table A4.11a in the Appendix. Details of two-way ANOVA results are shown in Table A4.18a.

For the WAS value of angle of internal friction of the natural soil ranged from 16 to 420 when treated with up to 8% LBWA content. On treatment with 1, 2, 3, and 4% OPC and UP to 8% LBWA content the values increase from 20 to 42.5^o, 25 to 43^o, 28 to 45^o and 30 to 44.5^o, respectively.

A two-way analysis of variance (ANOVA) test on the angle of internal friction WAS results show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 42.60 > F_{crit} = 3.01$ for cement and $F_{cal.} = 3.28 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the angle of internal friction WAS of black cotton

soil was less significant than that of cement (see Table 4.6). Details of the angle of internal friction (WAS) result are shown in Table A4.11b in the Appendix. Details of two-way ANOVA results are shown in Table A4.18b.

For the BSH values of internal friction of the natural soil ranged from 14 to 38 ^{o} when treated with UP to 8% LBWA content. On treatment with 1,2,3, and 4% OPC and UP to 8% LBWA content the values increased from 16 to 39 ^{o}, 22 to 39.5 ^{o}, 22 to 40 ^{o} and 28 to 40 ^{o} respectively.

A two-way analysis of variance (ANOVA) test on the angle of internal friction BSH results show that the relative effect of cement and LBWA on black cotton soil were statically significant ($F_{cal.} = 49.71 > F_{crit} = 3.01$ for cement and $F_{cal.} = 4.26 > F_{crit} = 3.01$ for LBWA. The effect of LBWA on the angle of internal friction BSH of black cotton soil was less significant than that of cement (see Table 4.6). Details of the angle of internal friction (BSH) results are shown in Table A4.11c in the Appendix. Details of two-way ANOVA details are shown in Table A4.18c.

- The increase in angle of internal friction with higher cement treatment on the natural soil conformed to findings reported by Osula (1991) and Osinubi (1995) . The addition of cement on the natural soil induced a cation exchange between silicate from the clay particle and calcium ion from the free lime which caused flocculation and agglomeration of the clay particles , and this in turn led to the formation of coarser fractions thereby resulting in increase in the angle of internal friction of the soil samples.
- The increase in the angle of internal friction on the cement modified soil with higher LBWA content was as a result of increased particle size and reduced clay fractions of the soil due to flocculation and agglomeration of clay

particles. Increased LBWA provided additional silicate and aluminates which further reacted with calcium ion from free lime to bind clay particles together to form larger particles decreasing the quantity of fine present within the soil sample. (Muazu, 2006)

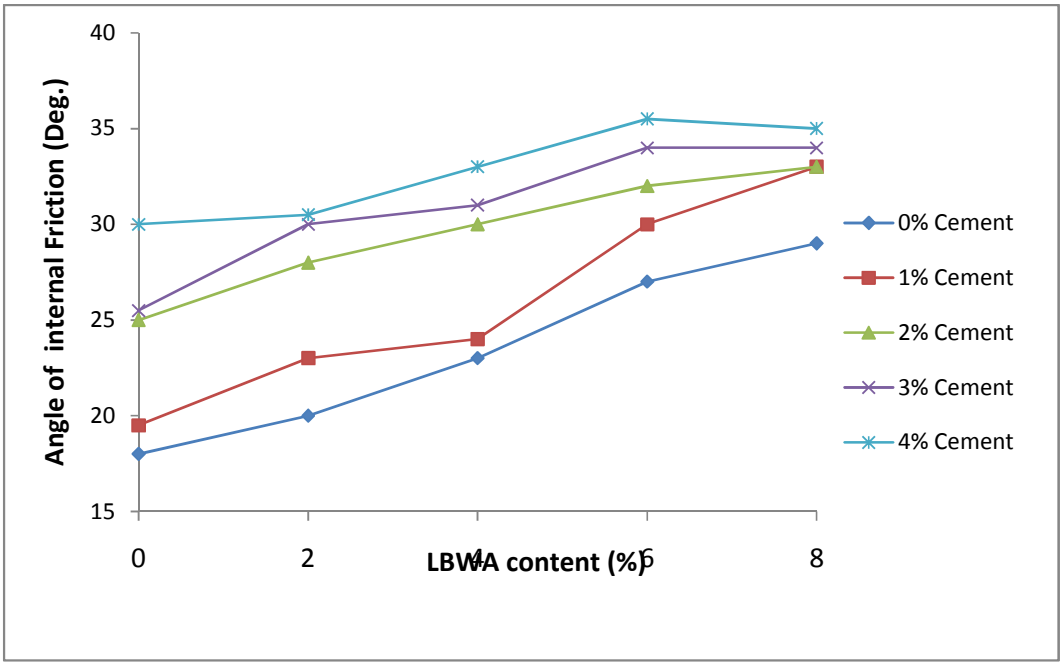

Fig. 4.26 - Variation of angle of internal friction of soil-cement mixtures with LBWA content (BSL compaction)

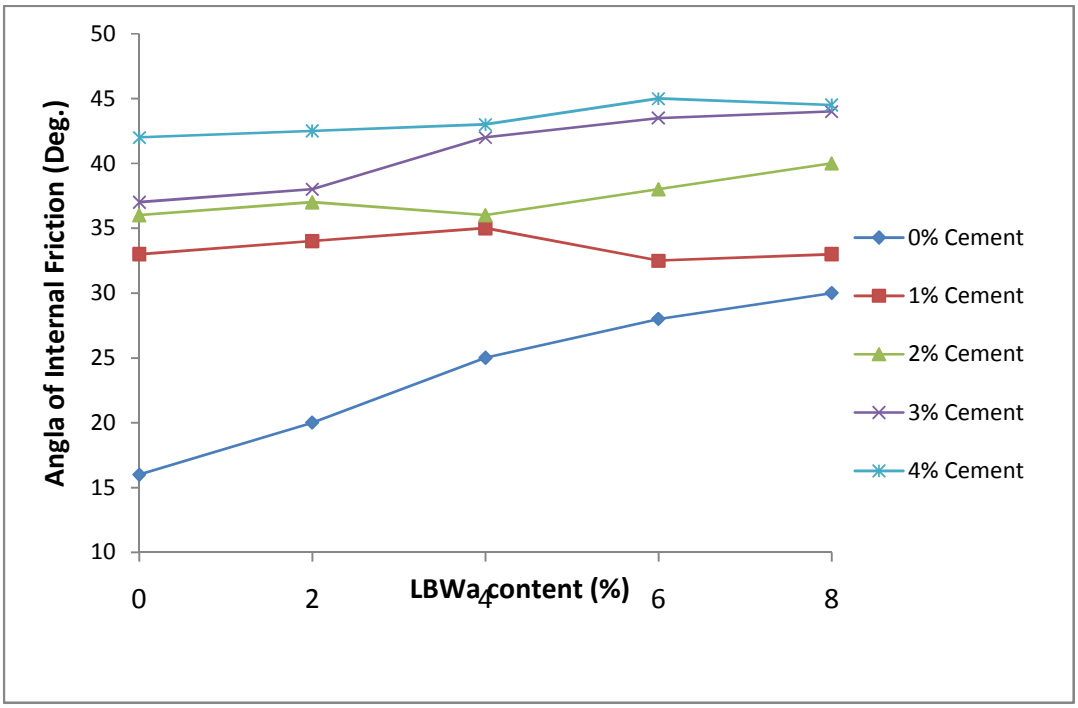

Fig. 4.27 - Variation of Angle of internal friction of soil-cement mixtures with LBWA content (WAS compaction)

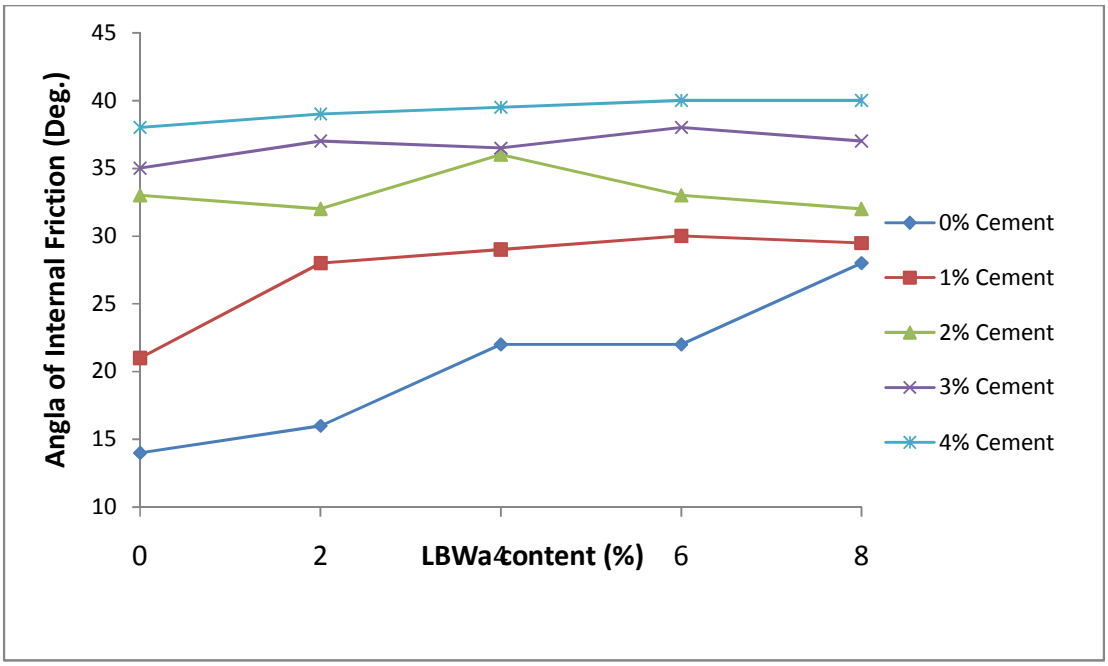

Fig. 4.28 - Variation of angle of internal friction of soil-cement mixtures with LBWA content (BSH compaction)

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The preliminary investigation conducted on the natural black cotton soil collected at the Chad basin Development Authority (CBDA) New Marte, Borno State shows that the soil falls under A-7- 6 (24) classification for AASHTO(1986) and CL using the Unified Soil Classification System (USCS). The natural soil has high moisture content of 35% because it was collected during the rainy season. It has a liquid limit value of 63%, plastic limit of 27% and plasticity index of 36% specific, gravity of 2.01 and the predominant clay mineral is montmorillonite. All these properties indicate that the soil is highly plastic with about 80% of the soil particles passing the BS.No. 200 sieve. The workability of the soil is very low and this makes it unsuitable for geotechnical engineering use.

In an effort to improve the workability of the soil for engineering purpose, the air dried sample were treated with up to 4% OPC to 8% LBWA blend in stepped concentration of 0,2,4,6 and 8% by dry weight of the soil. The test conducted showed that the percentage of particles passing the BS No. 200 seive size tremendously reduced from 80% for the natural soil to almost zero for all the energy levels considered. Also the liquid limit of the natural soil increased from 63 to 79% at 4%OPC / 6% LBWA treatment. The plastic limit however decreased from 26.6% for the natural soil to 24.6% at 4%OPC/6% LBWA treatment. The plasticity index for all the concentration of additive exceeded 12% value prescribed for sub-base and base courses by Nigeria General Specifications (1997).

The MDD increased for soil compacted using British Standard light energy level from 1.30Mg/m^3 for the natural soil to 1.48 Mg/m^3 at 4% OPC / 6%LBWA treatment. For WAS compaction the MDD increased from 1.42 Mg/m^3 for natural soil

to 1.55 Mg/m^3 at 4% OPC / 6% LBWA treatment. For BSH compaction, the value increased from 1.50 Mg/m^3 for the natural soil to 1.62 Mg/m^3 at 4%OPC/6% LBWA treatment. The OMC on the other hand decreased with higher compactive efforts, but increased with high LBWA content. The optimum moisture content values at the natural states increased from 24, 21 and 19% to 39,33 and 30% when compacted using BSL, WAS and BSH energies at 4%OPC/6%LBWA treatment, respectively.

The angle of internal friction for the cement modified soil increase while the cohesion decreased. The angle of internal friction values increased from 18^0,14^0 and 16^0 for the natural soil to 35.5^o,45^o and 40^o at 4%OPC/6% LBWA blend for BSL, WAS and BSH compaction, respectively. The cohesion value decreased from 75, 70 and 60kN/m^2 for natural soil to 22, 15 and 20 kN/m^2 treatment for BSL, WAS and BSH compactions, respectively.

5.2 Recommendation

Based on the results of the investigation of the effect of locust bean waste ash on cement black cotton soil, an optimum of 4% OPC/6% LBWA is recommended for the modification of black cotton soil used in road construction.

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TABLE A4.12:A 2-WAY ANOVA FOR THE VALUES OF LIQUID LIMIT TEST RESULT.

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	348.7	69.74	42.088
Cement 2	5	351.2	70.24	41.113
Cement 3	5	359.5	71.9	31.925
Cement 4	5	365.4	73.08	36.332
Cement 5	5	357	71.4	36.3
LBWA 1	5	322.5	64.5	1.5
LBWA 2	5	329.1	65.82	2.897
LBWA 3	5	358.5	71.7	4.45
LBWA 4	5	380	76	2.5
LBWA 5	5	391.7	78.34	0.178

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	35.4584	4	8.8646	13.32822	5.77E-05	3.006917
LBWAs	740.3904	4	185.0976	278.3004	1.44E-14	3.006917
Error	10.6416	16	0.6651			
Total	786.4904	24				

TABLE A4.13:A 2-WAY ANOVA FOR THE VALUES OF PLASTIC LIMIT TEST RESULT.

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	146.4	29.28	4.607
Cement 2	5	141.5	28.3	3.32
Cement 3	5	135.7	27.14	1.168
Cement 4	5	128.2	25.64	0.868
Cement 5	5	133	26.6	0.38
LBWA 1	5	129.2	25.84	0.408
LBWA 2	5	134.5	26.9	0.79
LBWA 3	5	137.3	27.46	1.178
LBWA 4	5	142.3	28.46	3.088
LBWA 5	5	141.5	28.3	9.29

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	40.7464	4	10.1866	8.921137	0.00055	3.006917
LBWAs	23.1024	4	5.7756	5.058107	0.007906	3.006917
Error	18.2696	16	1.14185			
Total	82.1184	24				

TABLE A4.13:A 2-WAY ANOVA FOR THE VALUES OF PLATICITY INDEX TEST RESULT.

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	*5*	*191.5*	*38.3*	*56.945*
Cement 2	*5*	*209.7*	*41.94*	*22.038*
Cement 3	*5*	*219*	*43.8*	*17.805*
Cement 4	*5*	*238.6*	*47.72*	*36.492*
Cement 5	*5*	*222.8*	*44.56*	*32.693*
LBWA 1	*5*	*183.3*	*36.66*	*34.658*
LBWA 2	*5*	*194.6*	*38.92*	*6.087*
LBWA 3	*5*	*221.3*	*44.26*	*10.633*
LBWA 4	*5*	*233.2*	*46.64*	*14.153*
LBWA 5	*5*	*249.2*	*49.84*	*13.068*

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	*241.0856*	*4*	*60.2714*	*13.15424*	*6.24E-05*	*3.006917*
LBWAs	*590.5816*	*4*	*147.6454*	*32.22362*	*1.79E-07*	*3.006917*
Error	*73.3104*	*16*	*4.5819*			
Total	*904.9776*	*24*				

TABLE A4.15a:A 2-WAY ANOVA FOR THE VALUES OF MDD TEST RESULT (BSL)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	6.76	1.352	0.00217
Cement 2	5	6.83	1.366	0.00178
Cement 3	5	6.94	1.388	0.00157
Cement 4	5	7.03	1.406	0.00268
Cement 5	5	7	1.4	0.0027
LBWA 1	5	6.68	1.336	0.00063
LBWA 2	5	6.76	1.352	0.00047
LBWA 3	5	6.81	1.362	0.00027
LBWA 4	5	7.09	1.418	0.00052
LBWA 5	5	7.22	1.444	0.00093

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	0.010456	4	0.002614	50.75728	6.82E-09	3.006917
LBWAs	0.042776	4	0.010694	207.6505	1.44E-13	3.006917
Error	0.000824	16	5.15E-05			
Total	0.054056	24				

TABLE A 4.15b:A 2-WAY ANOVA FOR VALUES OF MDD TEST RESULT (WAS)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	7.22	1.444	0.00043
Cement 2	5	7.27	1.454	0.00043
Cement 3	5	7.35	1.47	0.00025
Cement 4	5	7.55	1.51	0.00155
Cement 5	5	7.52	1.504	0.00093
LBWA 1	5	7.24	1.448	0.00052
LBWA 2	5	7.28	1.456	0.00043
LBWA 3	5	7.38	1.476	0.00113
LBWA 4	5	7.47	1.494	0.00113
LBWA 5	5	7.54	1.508	0.00157

ANOVA

Source of	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

Variation						
Cements	0.017416	4	0.004354	40.88263	3.3E-08	3.006917
LBWAs	0.012656	4	0.003164	29.70892	3.16E-07	3.006917
Error	0.001704	16	0.000107			
Total	0.031776	24				

TABLE A4.15c:A 2-WAY ANOVA FOR THE VALUES OF MDD TEST RESULT (BSH)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	7.69	1.538	0.00157
Cement 2	5	7.75	1.55	0.00125
Cement 3	5	7.79	1.558	0.00137
Cement 4	5	7.87	1.574	0.00148
Cement 5	5	7.91	1.582	0.00057
LBWA 1	5	7.62	1.524	0.00043
LBWA 2	5	7.7	1.54	0.0006
LBWA 3	5	7.73	1.546	0.00048
LBWA 4	5	7.93	1.586	0.00033
LBWA 5	5	8.03	1.606	0.00013

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	0.006336	4	0.001584	16.41451	1.61E-05	3.006917
LBWAs	0.023416	4	0.005854	60.66321	1.82E-09	3.006917
Error	0.001544	16	9.65E-05			
Total	0.031296	24				

TABLE A4.16a: A 2-WAY ANOVA FOR THE VALUES OF OMC TEST RESULT (BSL)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	134	26.8	6.7
Cement 2	5	142	28.4	7.3

Cement 3	5	168	33.6	4.3
Cement 4	5	181	36.2	6.7
Cement 5	5	163	32.6	24.8
LBWA 1	5	139	27.8	15.7
LBWA 2	5	148	29.6	13.3
LBWA 3	5	158	31.6	22.8
LBWA 4	5	169	33.8	16.7
LBWA 5	5	174	34.8	13.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	297.04	4	74.26	37.41058	6.24E-08	3.006917
LBWAs	167.44	4	41.86	21.08816	3.23E-06	3.006917
Error	31.76	16	1.985			
Total	496.24	24				

TABLE A4.16c:A 2-WAY ANOVA FOR THE VALUES OF OMC TEST RESULT (WAS)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	110	22	6.5
Cement 2	5	116	23.2	8.2
Cement 3	5	126	25.2	8.2
Cement 4	5	132	26.4	9.3
Cement 5	5	136	27.2	5.2
LBWA 1	5	108	21.6	4.3
LBWA 2	5	114	22.8	5.7
LBWA 3	5	124	24.8	5.7
LBWA 4	5	133	26.6	4.3
LBWA 5	5	141	28.2	4.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	94.4	4	23.6	85.81818	1.34E-10	3.006917
LBWAs	145.2	4	36.3	132	4.91E-12	3.006917
Error	4.4	16	0.275			
Total	244	24				

TABLE A4.16b:A 2-WAY ANOVA FOR THE VALUES OF OMC TEST RESULT (BSH)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	116	23.2	8.2
Cement 2	5	129	25.8	8.2
Cement 3	5	136	27.2	12.2
Cement 4	5	141	28.2	12.2
Cement 5	5	146	29.2	9.7
LBWA 1	5	114	22.8	3.7
LBWA 2	5	123	24.6	5.3
LBWA 3	5	134	26.8	6.7
LBWA 4	5	144	28.8	6.7
LBWA 5	5	153	30.6	6.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	109.04	4	27.26	75.72222	3.45E-10	3.006917
LBWAs	196.24	4	49.06	136.2778	3.83E-12	3.006917
Error	5.76	16	0.36			
Total	311.04	24				

TABLE A4.17a:A 2-WAY ANOVA FOR THE VALUES OF COHESION TEST RESULT (BSL)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	306	61.2	134.2
Cement 2	5	277	55.4	144.8
Cement 3	5	258	51.6	132.3
Cement 4	5	212	42.4	222.8
Cement 5	5	179	35.8	152.2

LBWA 1	5	318	63.6	97.3
LBWA 2	5	298	59.6	68.8
LBWA 3	5	239	47.8	157.7
LBWA 4	5	207	41.4	96.8
LBWA 5	5	170	34	121.5

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	2069.84	4	517.46	84.00325	1.57E-10	3.006917
LBWAs	3046.64	4	761.66	123.6461	8.14E-12	3.006917
Error	98.56	16	6.16			
Total	5215.04	24				

TABLE A4.17b:A 2-WAY ANOVA FOR THE VALUES OF COHESION TEST RESULT (WAS)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	273	54.6	140.8
Cement 2	5	238	47.6	135.3
Cement 3	5	193	38.6	204.8
Cement 4		174	34.8	210.2
Cement 5	5	140	28	207.5
LBWA 1	5	300	60	62.5
LBWA 2	5	226	45.2	108.7
LBWA 3	5	194	38.8	170.7
LBWA 4	5	170	34	167.5
LBWA 5	5	128	25.6	104.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	2206.64	4	551.66	35.56802	8.93E-08	3.006917
LBWAs	3346.24	4	836.56	53.93681	4.36E-09	3.006917
Error	248.16	16	15.51			
Total	5801.04	24				

TABLE A4.17c:A 2-WAY ANOVA FOR THE VALUES OF COHESION TEST RESULT (BSH)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	257	51.4	47.8
Cement 2	5	227	45.4	60.3
Cement 3	5	201	40.2	101.2
Cement 4	5	182	36.4	120.8
Cement 5	5	150	30	87.5
LBWA 1	5	255	51	47
LBWA 2	5	234	46.8	45.2
LBWA 3	5	201	40.2	101.2
LBWA 4	5	185	37	82.5
LBWA 5	5	142	28.4	93.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	1349.04	4	337.26	42.23669	2.61E-08	3.006917
LBWAs	1542.64	4	385.66	48.29806	9.82E-09	3.006917
Error	127.76	16	7.985			
Total	3019.44	24				

TABLE A4.18a:A 2-WAY ANOVA FOR THE VALUES OF INTERNRICTION TEST RESULT (BSL)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	117	23.4	21.3
Cement 2	5	129.5	25.9	30.05
Cement 3	5	148	29.6	10.3
Cement 4	5	163.5	32.7	24.45
Cement 5	5	164	32.8	6.325
LBWA 1	5	118	23.6	23.675
LBWA 2	5	140.5	28.1	54.05
LBWA 3	5	141	28.2	19.7
LBWA 4	5	158.5	31.7	11.2
LBWA 5	5	164	32.8	5.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	346.94	4	86.735	12.80694	7.3E-05	3.006917
LBWAs	261.34	4	65.335	9.647102	0.000363	3.006917
Error	108.36	16	6.7725			
Total	716.64	24				

TABLE A4.18b:A 2-WAY ANOVA FOR THE VALUES OF INTERNRICTION TEST RESULT (WAS)

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	102	20.4	30.8
Cement 2	5	137.5	27.5	13.75
Cement 3	5	166	33.2	2.7
Cement 4	5	183.5	36.7	1.2
Cement 5	5	196.5	39.3	0.7
LBWA 1	5	141	28.2	104.7
LBWA 2	5	152	30.4	83.3
LBWA 3	5	163	32.6	49.925
LBWA 4	5	163	32.6	50.8
LBWA 5	5	166.5	33.3	25.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	1149.74	4	287.435	42.59874	2.45E-08	3.006917
LBWAs	88.64	4	22.16	3.284179	0.038093	3.006917
Error	107.96	16	6.7475			
Total	1346.34	24				

TABLE A4.18c:A 2-WAY ANOVA FOR THE VALUES OF INTERNRICTION TEST RESULT (BSH)

I

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Cement 1	5	119	23.8	33.2
Cement 2	5	167.5	33.5	1
Cement 3	5	187	37.4	2.8
Cement 4	5	204.5	40.9	10.3
Cement 5	5	217	43.4	1.675
LBWA 1	5	164	32.8	98.7
LBWA 2	5	171.5	34.3	73.2
LBWA 3	5	181	36.2	51.7
LBWA 4	5	187	37.4	51.925
LBWA 5	5	191.5	38.3	42.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Cements	1178.1	4	294.525	49.70886	7.95E-09	3.006917
LBWAs	101.1	4	25.275	4.265823	0.015424	3.006917
Error	94.8	16	5.925			
Total	1374	24				

APPENDIX

Table A4.1: Test results on natural moisture content

Sample No	Weight M1	Weight M2	Weight M3	Moisture Content w	Average w (%)
1	12	19	17	40	
2	14.0	26	22.6	35	35
3	12.3	16.6	15.6	30	

Table A4.2: Test results for cation exchange capacity of soil -cement – LBWA mixture

CEMENT CONTENT %	LBWA CONTENT %				
	0	1	2	3	4
0	37.5	21.0	22.80	22.0	23.0
2	22	20.50	22	21.90	21.6
4	32	22.70	22.80	22.0	20.20
6	27.6	22.30	22.70	21.90	21.80
8	46.1	19.50	21.70	19.15	19.80

TABLE A4.3 - Particle size analysis for Natural soil

SIEVE SIZE	0% C & 0% LBWA
2.4	97.25
1.4	97
0.6	96.3
0.425	94.85
0.3	93.6
0.212	91.4
0.15	83.35
0.075	80.35
0.0098	62.7
0.0076	54.5
0.0073	35.9
0.0056	24.56
0.0043	15.27

TABLE A4.4a - Particle size analysis for treated soil at British Standard Light Energy level

BSL 0% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	113.5	86.5	43.25
1.4mm (10)	26.5	60	30
0.6mm (600)	22.8	37.2	18.6
0.425mm (425)	28	9.2	4.6
0.3mm (300)	3.4	5.8	2.9
0.212mm (212)	2.5	3.3	1.65
0.15mm (150)	1.8	1.5	0.75
0.075mm (75)	1.5	0.00	0.00

BSL 1% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	129.5	70.5	35.25
1.4mm (10)	19.4	51.1	25.55
0.6mm (600)	20.1	31	15.5
0.425mm (425)	22.3	8.7	4.35
0.3mm (300)	3.3	5.4	2.7
0.212mm (212)	2.2	3.2	1.6
0.15mm (150)	1.5	1.7	0.85
0.075mm (75)	1.4	0.3	0.15

BSL 0% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	140.1	59.9	29.95
1.4mm (10)	17.5	42.4	21.2
0.6mm (600)	14.7	27.7	13.85
0.425mm (425)	18.7	9	4.5
0.3mm (300)	2.5	6.5	3.25
0.212mm (212)	2.2	4.3	2.15
0.15mm (150)	2.1	2.2	1.1
0.075mm (75)	1.7	0.5	0.25

BSL 1% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	127.8	72.2	36.1
1.4mm (10)	23.6	48.6	24.3
0.6mm (600)	19	29.6	14.8
0.425mm (425)	22.4	7.2	3.6
0.3mm (300)	2.9	4.3	2.15
0.212mm (212)	1.8	2.5	1.25
0.15mm (150)	1.4	1.1	0.55
0.075mm (75)	1.1	2.66E-15	1.3323E-

BSL 0% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	120.8	79.2	39.6
1.4mm (10)	22.9	56.3	28.15
0.6mm (600)	17	39.3	19.65
0.425mm (425)	26.1	13.2	6.6
0.3mm (300)	4.5	8.7	4.35
0.212mm (212)	3.5	5.2	2.6
0.15mm (150)	2.5	2.7	1.35
0.075mm (75)	2.2	0.5	0.25

BSL 1% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	130.2	69.8	34.9
1.4mm (10)	21.2	48.6	24.3
0.6mm (600)	16.4	32.2	16.1
0.425mm (425)	22.2	10	5
0.3mm (300)	3	7	3.5
0.212mm (212)	2.4	4.6	2.3
0.15mm (150)	2.1	2.5	1.25
0.075mm (75)	2	0.5	0.25

SL 0% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	128	72	36
1.4mm (10)	22.2	49.8	24.9
0.6mm (600)	14.7	35.1	17.55

BSL 1% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	124.8	75.2	37.6
1.4mm (10)	20.7	54.5	27.25
0.6mm (600)	18.8	35.7	17.85

0.425mm (425)	20	15.1	7.55
0.3mm (300)	4.2	10.9	5.45
0.212mm (212)	3.9	7	3.5
0.15mm (150)	3.3	3.7	1.85
0.075mm (75)	2.7	1	0.5

0.425mm (425)	22.7	13	6.5
0.3mm (300)	4.6	8.4	4.2
0.212mm (212)	3.2	5.2	2.6
0.15mm (150)	2.4	2.8	1.4
0.075mm (75)	2.2	0.6	0.3

BSL 1% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	114.1	85.9	42.95
1.4mm (10)	21.1	64.8	32.4
0.6mm (600)	20.7	44.1	22.05
0.425mm (425)	22.9	21.2	10.6
0.3mm (300)	7.4	13.8	6.9
0.212mm (212)	5.8	8	4
0.15mm (150)	4.2	3.8	1.9
0.075mm (75)	3.1	0.7	0.35

BSL 2% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	131.2	68.8	34.4
1.4mm (10)	22	46.8	23.4
0.6mm (600)	17.6	29.2	14.6
0.425mm (425)	24	5.2	2.6
0.3mm (300)	2.1	3.1	1.55
0.212mm (212)	1.4	1.7	0.85
0.15mm (150)	1	0.7	0.35
0.075mm (75)	0.7	9.99E-15	4.996E-

BSL 2% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	120.2	79.8	39.9
1.4mm (10)	24.4	55.4	27.7
0.6mm (600)	17.9	37.5	18.75
0.425mm (425)	29	8.5	4.25
0.3mm (300)	2.7	5.8	2.9
0.212mm (212)	2.3	3.5	1.75
0.15mm (150)	1.7	1.8	0.9
0.075mm (75)	1.4	0.4	0.2

BSL 2% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	131.6	68.4	34.2
1.4mm (10)	21.8	46.6	23.3
0.6mm (600)	17	29.6	14.8
0.425mm (425)	23.1	6.5	3.25
0.3mm (300)	2.6	3.9	1.95
0.212mm (212)	1.5	2.4	1.2
0.15mm (150)	1.4	1	0.5
0.075mm (75)	0.9	0.1	0.05

BSL 2% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	132.1	67.9	33.95
1.4mm (10)	24	43.9	21.95
0.6mm (600)	15.9	28	14
0.425mm (425)	21.4	6.6	3.3
0.3mm (300)	2.5	4.1	2.05
0.212mm (212)	1.7	2.4	1.2
0.15mm (150)	1.2	1.2	0.6
0.075mm (75)	1	0.2	0.1

BSL 3% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	116.8	83.2	41.6
1.4mm (10)	25.1	58.1	29.05
0.6mm (600)	22.3	35.8	17.9
0.425mm (425)	27.3	8.5	4.25
0.3mm (300)	2.9	5.6	2.8
0.212mm (212)	1.8	3.8	1.9
0.15mm (150)	1.8	2	1
0.075mm (75)	1.6	0.4	0.2

BSL 2% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING

BSL 3% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSIN G	% PASSIN

2.4mm (7)	130.4	69.6	34.8
1.4mm (10)	21	48.6	24.3
0.6mm (600)	16.7	31.9	15.95
0.425mm (425)	22.8	9.1	4.55
0.3mm (300)	3.6	5.5	2.75
0.212mm (212)	1.8	3.7	1.85
0.15mm (150)	1.7	2	1
0.075mm (75)	1.4	0.6	0.3

2.4mm (7)	126.9	73.1	36.55
1.4mm (10)	21.8	51.3	25.65
0.6mm (600)	15	36.3	18.15
0.425mm (425)	25.1	11.2	5.6
0.3mm (300)	3.7	7.5	3.75
0.212mm (212)	2.6	4.9	2.45
0.15mm (150)	2.2	2.7	1.35
0.075mm (75)	1.2	1.5	0.75

BSL 3% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	136.4	63.6	31.8
1.4mm (10)	21.3	42.3	21.15
0.6mm (600)	15.2	27.1	13.55
0.425mm (425)	19.7	7.4	3.7
0.3mm (300)	2.2	5.2	2.6
0.212mm (212)	1.7	3.5	1.75
0.15mm (150)	1.5	2	1
0.075mm (75)	1.5	0.5	0.25

BSL 4% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSIN G	% PASSIN
2.4mm (7)	130.6	69.4	34.7
1.4mm (10)	21.1	48.3	24.15
0.6mm (600)	16.7	31.6	15.8
0.425mm (425)	21.6	10	5
0.3mm (300)	3.6	6.4	3.2
0.212mm (212)	2.5	3.9	1.95
0.15mm (150)	2.1	1.8	0.9
0.075mm (75)	1.3	0.5	0.25

BSL 3% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	136	64	32
1.4mm (10)	21.2	42.8	21.4
0.6mm (600)	15.5	27.3	13.65
0.425mm (425)	22.6	4.7	2.35
0.3mm (300)	1.8	2.9	1.45
0.212mm (212)	1.3	1.6	0.8
0.15mm (150)	0.8	0.8	0.4
0.075mm (75)	0.8	-4.219E-15	-2.11E-15

BSL 4% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	128.1	71.9	35.95
1.4mm (10)	21.9	50	25
0.6mm (600)	17.3	32.7	16.35
0.425mm (425)	21.7	11	5.5
0.3mm (300)	3.7	7.3	3.65
0.212mm (212)	2.6	4.7	2.35
0.15mm (150)	2.3	2.4	1.2
0.075mm (75)	1.4	1	0.5

BSL 3% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	125.3	74.7	37.35
1.4mm (10)	22.1	52.6	26.3
0.6mm (600)	21.8	30.8	15.4
0.425mm (425)	20.5	10.3	5.15
0.3mm (300)	3.3	7	3.5
0.212mm (212)	2.8	4.2	2.1
0.15mm (150)	2	2.2	1.1
0.075mm (75)	1.5	0.7	0.35

BSL 4% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	131.1	68.9	34.45
1.4mm (10)	26	42.9	21.45
0.6mm (600)	16.2	26.7	13.35
0.425mm (425)	21.5	5.2	2.6
0.3mm (300)	1.9	7	3.5
0.212mm (212)	1.4	5.6	2.8
0.15mm (150)	0.9	4.7	2.35
0.075mm (75)	1	3.7	1.85

BSL 4% OPC / 0% LBWA

BSL 4% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	130.2	69.8	34.9
1.4mm (10)	21.7	48.1	24.05
0.6mm (600)	17.1	31	15.5
0.425mm (425)	23.5	7.5	3.75
0.3mm (300)	2.2	5.3	2.65
0.212mm (212)	2.9	2.4	1.2
0.15mm (150)	1.5	0.9	0.45
0.075mm (75)	1.4	-0.5	-0.25

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	129.4	70.6	35.3
1.4mm (10)	24.6	46	23
0.6mm (600)	16.4	29.6	14.8
0.425mm (425)	21.7	7.9	3.95
0.3mm (300)	1.6	6.3	3.15
0.212mm (212)	2.8	3.5	1.75
0.15mm (150)	1.3	2.2	1.1
0.075mm (75)	1.2	1	0.5

TABLE A4.4b - Particle size analysis for treated soil at West Africa Standard Energy level

WAS 0% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	115.3	84.7	42.35
1.4mm (10)	21.4	63.3	31.65
0.6mm (600)	21.8	41.5	20.75
0.425mm (425)	28.1	13.4	6.7
0.3mm (300)	4.3	9.1	4.55
0.212mm (212)	3.5	5.6	2.8
0.15mm (150)	2.7	2.9	1.45
0.075mm (75)	2.3	0.6	0.3

WAS 1% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	89.2	110.8	55.4
1.4mm (10)	28.5	82.3	41.15
0.6mm (600)	29.9	52.4	26.2
0.425mm (425)	36.9	15.5	7.75
0.3mm (300)	6.4	9.1	4.55
0.212mm (212)	3.7	5.4	2.7
0.15mm (150)	2.7	2.7	1.35
0.075mm (75)	2.2	0.5	0.25

WAS 0% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	91.7	108.3	54.15
1.4mm (10)	26.9	81.4	40.7
0.6mm (600)	26.6	54.8	27.4
0.425mm (425)	35.3	19.5	9.75
0.3mm (300)	6.4	13.1	6.55
0.212mm (212)	4.5	8.6	4.3
0.15mm (150)	3.2	5.4	2.7
0.075mm (75)	2.8	2.6	1.3

WAS 1% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	91.2	108.8	54.4
1.4mm (10)	28.6	80.2	40.1
0.6mm (600)	30.3	49.9	24.95
0.425mm (425)	35.6	14.3	7.15
0.3mm (300)	5.5	8.8	4.4
0.212mm (212)	3.9	4.9	2.45
0.15mm (150)	2.4	2.5	1.25
0.075mm (75)	2.2	0.3	0.15

WAS 0% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	85.7	114.3	57.15
1.4mm (10)	26.9	87.4	43.7
0.6mm (600)	26.4	61	30.5
0.425mm (425)	42.1	18.9	9.45
0.3mm (300)	7	11.9	5.95
0.212mm (212)	5.5	6.4	3.2

WAS 1% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	96.8	103.2	51.6
1.4mm (10)	27.3	75.9	37.95
0.6mm (600)	27.8	48.1	24.05
0.425mm (425)	34.3	13.8	6.9
0.3mm (300)	5.6	8.2	4.1
0.212mm (212)	3.5	4.7	2.35

0.15mm (150)	3.4	3	1.5
0.075mm (75)	2.6	0.4	0.2

0.15mm (150)	2.4	2.3	1.15
0.075mm (75)	1.9	0.4	0.2

WAS 0% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	73.5	126.5	63.25
1.4mm (10)	26.8	99.7	49.85
0.6mm (600)	29.4	70.3	35.15
0.425mm (425)	46.4	23.9	11.95
0.3mm (300)	9.2	14.7	7.35
0.212mm (212)	6.8	7.9	3.95
0.15mm (150)	3.9	4	2
0.075mm (75)	3.3	0.7	0.35

WAS 1% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	98.8	101.2	50.6
1.4mm (10)	23.7	77.5	38.75
0.6mm (600)	26.4	51.1	25.55
0.425mm (425)	33	18.1	9.05
0.3mm (300)	6.2	11.9	5.95
0.212mm (212)	4.9	7	3.5
0.15mm (150)	3.5	3.5	1.75
0.075mm (75)	3	0.5	0.25

WAS 1% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	78	122	61
1.4mm (10)	28.7	93.3	46.65
0.6mm (600)	31.2	62.1	31.05
0.425mm (425)	36.3	25.8	12.9
0.3mm (300)	9	16.8	8.4
0.212mm (212)	6.7	10.1	5.05
0.15mm (150)	5.6	4.5	2.25
0.075mm (75)	3.7	0.8	0.4

WAS 2% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	103.1	96.9	48.45
1.4mm (10)	25.5	71.4	35.7
0.6mm (600)	27.4	44	22
0.425mm (425)	32	12	6
0.3mm (300)	4.7	7.3	3.65
0.212mm (212)	3.3	4	2
0.15mm (150)	2.7	1.3	0.65
0.075mm (75)	2.2	-0.9	0

WAS 2% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	82.7	117.3	58.65
1.4mm (10)	25.9	91.4	45.7
0.6mm (600)	27.7	63.7	31.85
0.425mm (425)	40	23.7	11.85
0.3mm (300)	7.2	16.5	8.25
0.212mm (212)	6	10.5	5.25
0.15mm (150)	5.4	5.1	2.55
0.075mm (75)	4	1.1	0.55

WAS 2% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	110.5	89.5	44.75
1.4mm (10)	20.3	69.2	34.6
0.6mm (600)	20.7	48.5	24.25
0.425mm (425)	28	20.5	10.25
0.3mm (300)	6.4	14.1	7.05
0.212mm (212)	5.7	8.4	4.2
0.15mm (150)	4.1	4.3	2.15
0.075mm (75)	3.6	0.7	0.35

WAS 2% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	110.3	89.7	44.85
1.4mm (10)	21.2	68.5	34.25
0.6mm (600)	26.3	42.2	21.1
0.425mm (425)	30.9	11.3	5.65

WAS 3% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	129.4	70.6	35.3
1.4mm (10)	27.8	42.8	21.4
0.6mm (600)	18.1	24.7	12.35
0.425mm (425)	19.5	5.2	2.6

0.3mm (300)	4.2	7.1	3.55
0.212mm (212)	3	4.1	2.05
0.15mm (150)	1.9	2.2	1.1
0.075mm (75)	1.9	0.3	0.15

0.3mm (300)	2.3	2.9	1.45
0.212mm (212)	1.6	1.3	0.65
0.15mm (150)	1.2	0.1	0.05
0.075mm (75)	1.1	-1	0

WAS 2% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	109.2	90.8	45.4
1.4mm (10)	23.2	67.6	33.8
0.6mm (600)	23.5	44.1	22.05
0.425mm (425)	29.4	14.7	7.35
0.3mm (300)	5.4	9.3	4.65
0.212mm (212)	4	5.3	2.65
0.15mm (150)	2.7	2.6	1.3
0.075mm (75)	2.2	0.4	0.2

WAS 3% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	105.5	94.5	47.25
1.4mm (10)	27.8	66.7	33.35
0.6mm (600)	25.2	41.5	20.75
0.425mm (425)	29.8	11.7	5.85
0.3mm (300)	4.3	7.4	3.7
0.212mm (212)	3.2	4.2	2.1
0.15mm (150)	2.1	2.1	1.05
0.075mm (75)	1.8	0.3	0.15

WAS 3% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	110.8	89.2	44.6
1.4mm (10)	22.7	66.5	33.25
0.6mm (600)	22.3	44.2	22.1
0.425mm (425)	28.9	15.3	7.65
0.3mm (300)	5.3	10	5
0.212mm (212)	3.9	6.1	3.05
0.15mm (150)	2.9	3.2	1.6
0.075mm (75)	2.7	0.5	0.25

WAS 4% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	107.3	92.7	46.35
1.4mm (10)	25.5	67.2	33.6
0.6mm (600)	27.4	39.8	19.9
0.425mm (425)	29.3	10.5	5.25
0.3mm (300)	4.1	6.4	3.2
0.212mm (212)	2.6	3.8	1.9
0.15mm (150)	1.9	1.9	0.95
0.075mm (75)	1.6	0.3	0.15

WAS 3% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	114.4	85.6	42.8
1.4mm (10)	21.3	64.3	32.15
0.6mm (600)	21.7	42.6	21.3
0.425mm (425)	27.2	15.4	7.7
0.3mm (300)	5.2	10.2	5.1
0.212mm (212)	3.7	6.5	3.25
0.15mm (150)	3.3	3.2	1.6
0.075mm (75)	2.3	0.9	0.45

WAS 4% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	107	93	46.5
1.4mm (10)	25.8	67.2	33.6
0.6mm (600)	21.1	46.1	23.05
0.425mm (425)	29	17.1	8.55
0.3mm (300)	6.3	10.8	5.4
0.212mm (212)	5.2	5.6	2.8
0.15mm (150)	3.5	2.1	1.05
0.075mm (75)	1.7	0.4	0.2

WAS 3% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	74	126	63

WAS 4% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	101	99	49.5

1.4mm (10)	26.5	99.5	49.75
0.6mm (600)	25.9	73.6	36.8
0.425mm (425)	37.3	36.3	18.15
0.3mm (300)	10.7	25.6	12.8
0.212mm (212)	9.2	16.4	8.2
0.15mm (150)	7.5	8.9	4.45
0.075mm (75)	8.3	0.6	0.3

1.4mm (10)	22.8	76.2	38.1
0.6mm (600)	23.6	52.6	26.3
0.425mm (425)	32.6	20	10
0.3mm (300)	7,8	7	3.5
0.212mm (212)	6.5	0.5	0.25
0.15mm (150)	3.4	-2.9	0
0.075mm (75)	1.8	-4.7	0

WAS 4% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	129.1	70.9	35.45
1.4mm (10)	21.3	49.6	24.8
0.6mm (600)	21.5	28.1	14.05
0.425mm (425)	21	7.1	3.55
0.3mm (300)	3	4.1	2.05
0.212mm (212)	2	2.1	1.05
0.15mm (150)	1.1	1	0.5
0.075mm (75)	1	0.00	0.00

WAS 4% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	89.4	110.6	55.3
1.4mm (10)	25.2	85.4	42.7
0.6mm (600)	29.5	55.9	27.95
0.425mm (425)	30.1	25.8	12.9
0.3mm (300)	8.3	17.5	8.75
0.212mm (212)	7	10.5	5.25
0.15mm (150)	5.2	5.3	2.65
0.075mm (75)	4.5	0.8	0.4

TABLE A4.4c - Particle size analysis for treated soil at British Standard Light Energy level

BSH 0% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	125.1	74.9	37.45
1.4mm (10)	21.8	53.1	26.55
0.6mm (600)	16.1	37	18.5
0.425mm (425)	26.2	10.8	5.4
0.3mm (300)	4.1	6.7	3.35
0.212mm (212)	3.9	2.8	1.4
0.15mm (150)	3	-0.2	0
0.075mm (75)	3	-3.2	0

BSH 1% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	123.6	76.4	38.2
1.4mm (10)	22.6	53.8	26.9
0.6mm (600)	13.9	39.9	19.95
0.425mm (425)	27	12.9	6.45
0.3mm (300)	4.2	8.7	4.35
0.212mm (212)	3.9	4.8	2.4
0.15mm (150)	2.4	2.4	1.2
0.075mm (75)	2.9	-0.5	0

BSH 0% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	114.6	85.4	42.7
1.4mm (10)	19.1	66.3	33.15
0.6mm (600)	17.4	48.9	24.45
0.425mm (425)	32	16.9	8.45
0.3mm (300)	5.6	11.3	5.65
0.212mm (212)	5.3	6	3
0.15mm (150)	4.4	1.6	0.8
0.075mm (75)	4.2	-2.6	0

BSH 1% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	107.1	92.9	46.45
1.4mm (10)	21	71.9	35.95
0.6mm (600)	17.2	54.7	27.35
0.425mm (425)	32.3	22.4	11.2
0.3mm (300)	5.8	16.6	8.3
0.212mm (212)	6.3	10.3	5.15
0.15mm (150)	4.2	6.1	3.05
0.075mm (75)	5.6	0.5	0.25

BSH 0% OPC / 6% LBWA

BSH 1% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	95.5	104.5	52.25
1.4mm (10)	23.4	81.1	40.55
0.6mm (600)	19.4	61.7	30.85
0.425mm (425)	37.5	24.2	12.1
0.3mm (300)	7.8	16.4	8.2
0.212mm (212)	8.9	7.5	3.75
0.15mm (150)	5.2	2.3	1.15
0.075mm (75)	5.5	-3.2	0

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	112.9	87.1	43.55
1.4mm (10)	20.7	66.4	33.2
0.6mm (600)	16.4	50	25
0.425mm (425)	23.5	26.5	13.25
0.3mm (300)	5.7	20.8	10.4
0.212mm (212)	6.2	14.6	7.3
0.15mm (150)	4.8	9.8	4.9
0.075mm (75)	5.4	4.4	2.2

BSH 0% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	78.7	121.3	60.65
1.4mm (10)	21.6	99.7	49.85
0.6mm (600)	7.2	92.5	46.25
0.425mm (425)	56.3	36.2	18.1
0.3mm (300)	15.1	21.1	10.55
0.212mm (212)	10.7	10.4	5.2
0.15mm (150)	7.5	2.9	1.45
0.075mm (75)	7.1	-4.2	0

BSH 1% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	112.2	87.8	43.9
1.4mm (10)	14.8	73	36.5
0.6mm (600)	14.6	58.4	29.2
0.425mm (425)	36.7	21.7	10.85
0.3mm (300)	9	12.7	6.35
0.212mm (212)	8.3	4.4	2.2
0.15mm (150)	5.8	-1.4	0
0.075mm (75)	5.8	-7.2	0

BSH 1% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	96.8	103.2	51.6
1.4mm (10)	17.9	85.3	42.65
0.6mm (600)	14.4	70.9	35.45
0.425mm (425)	40.2	30.7	15.35
0.3mm (300)	9.5	21.2	10.6
0.212mm (212)	10.1	11.1	5.55
0.15mm (150)	7.9	3.2	1.6
0.075mm (75)	8.7	-5.5	0

BSH 2% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	110.6	89.4	44.7
1.4mm (10)	19	70.4	35.2
0.6mm (600)	13.7	56.7	28.35
0.425mm (425)	32.6	24.1	12.05
0.3mm (300)	8.5	15.6	7.8
0.212mm (212)	8.3	7.3	3.65
0.15mm (150)	6.2	1.1	0.55
0.075mm (75)	6.5	-5.4	0

BSH 2% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	123	77	38.5
1.4mm (10)	18.3	58.7	29.35
0.6mm (600)	15.6	43.1	21.55
0.425mm (425)	30.7	12.4	6.2
0.3mm (300)	5.3	7.1	3.55
0.212mm (212)	3.8	3.3	1.65
0.15mm (150)	3.4	-0.1	0

BSH 2% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	116.2	83.8	41.9
1.4mm (10)	16.7	67.1	33.55
0.6mm (600)	14.9	52.2	26.1
0.425mm (425)	33.3	18.9	9.45
0.3mm (300)	8.3	10.6	5.3
0.212mm (212)	8	2.6	1.3
0.15mm (150)	5.4	-2.8	0

0.075mm (75)	3.3	-3.4	0

0.075mm (75)	6.4	-9.2	0

BSH 2% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	118.6	81.4	40.7
1.4mm (10)	20.2	61.2	30.6
0.6mm (600)	14.2	47	23.5
0.425mm (425)	29.4	17.6	8.8
0.3mm (300)	5.8	11.8	5.9
0.212mm (212)	5.1	6.7	3.35
0.15mm (150)	4.1	2.6	1.3
0.075mm (75)	4.4	-1.8	0

BSH 3% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	120.3	79.7	39.85
1.4mm (10)	20.1	59.6	29.8
0.6mm (600)	17.4	42.2	21.1
0.425mm (425)	32.1	10.1	5.05
0.3mm (300)	4.6	5.5	2.75
0.212mm (212)	4.3	1.2	0.6
0.15mm (150)	3.6	-2.4	0
0.075mm (75)	4.1	-6.5	0

BSH 2% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	129.8	70.2	35.1
1.4mm (10)	14.2	56	28
0.6mm (600)	15.6	40.4	20.2
0.425mm (425)	25.8	14.6	7.3
0.3mm (300)	4.8	9.8	4.9
0.212mm (212)	6.4	3.4	1.7
0.15mm (150)	5.2	-1.8	0
0.075mm (75)	5.2	-7	0

BSH 3% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	139.8	60.2	30.1
1.4mm (10)	15.5	44.7	22.35
0.6mm (600)	12.5	32.2	16.1
0.425mm (425)	25.9	6.3	3.15
0.3mm (300)	3.2	3.1	1.55
0.212mm (212)	3.9	-0.8	0
0.15mm (150)	3	-3.8	0
0.075mm (75)	3.4	-7.2	0

BSH 3% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	140.5	59.5	29.75
1.4mm (10)	17.4	42.1	21.05
0.6mm (600)	11.6	30.5	15.25
0.425mm (425)	23.3	7.2	3.6
0.3mm (300)	4.4	2.8	1.4
0.212mm (212)	4.4	-1.6	0
0.15mm (150)	3	-4.6	0
0.075mm (75)	3.6	-8.2	0

BSH 4% OPC / 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	145.1	54.9	27.45
1.4mm (10)	15.7	39.2	19.6
0.6mm (600)	12.4	26.8	13.4
0.425mm (425)	25.9	0.9	0.45
0.3mm (300)	3.4	-2.5	0
0.212mm (212)	3.2	-5.7	0
0.15mm (150)	2.7	-8.4	0
0.075mm (75)	3	-11.4	0

BSH 3% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	73.7	126.3	63.15
1.4mm (10)	16.8	109.5	54.75
0.6mm (600)	18	91.5	45.75
0.425mm (425)	40.4	51.1	25.55

BSH 4% OPC / 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSI
2.4mm (7)	104.1	95.9	47.95
1.4mm (10)	16	79.9	39.95
0.6mm (600)	16.9	63	31.5
0.425mm (425)	36.7	26.3	13.15

0.3mm (300)	12.2	38.9	19.45
0.212mm (212)	11.4	27.5	13.75
0.15mm (150)	12.2	15.3	7.65
0.075mm (75)	14.4	0.9	0.45

0.3mm (300)	8.5	17.8	8.9
0.212mm (212)	11.1	6.7	3.35
0.15mm (150)	6.8	-0.1	0
0.075mm (75)	9.8	-9.9	0

BSH 3% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	78.2	121.8	60.9
1.4mm (10)	22	99.8	49.9
0.6mm (600)	19.5	80.3	40.15
0.425mm (425)	42.1	38.2	19.1
0.3mm (300)	10.4	27.8	13.9
0.212mm (212)	4.6	23.2	11.6
0.15mm (150)	9.4	13.8	6.9
0.075mm (75)	10.7	3.1	1.55

BSH 4% OPC / 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	113	87	43.5
1.4mm (10)	20.2	66.8	33.4
0.6mm (600)	16.2	50.6	25.3
0.425mm (425)	31.2	19.4	9.7
0.3mm (300)	7.8	7	3.5
0.212mm (212)	7.5	-0.5	0
0.15mm (150)	5.9	-6.4	0
0.075mm (75)	7.4	-13.8	0

BSH 4% OPC / 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	149	51	25.5
1.4mm (10)	15.7	35.3	17.65
0.6mm (600)	11.1	24.2	12.1
0.425mm (425)	23.6	0.6	0.3
0.3mm (300)	3.5	-2.9	0
0.212mm (212)	2.4	-5.3	0
0.15mm (150)	1.8	-7.1	0
0.075mm (75)	2.4	-9.5	0

BSH 4% OPC / 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSIN
2.4mm (7)	108.9	91.1	45.55
1.4mm (10)	22	69.1	34.55
0.6mm (600)	15.9	53.2	26.6
0.425mm (425)	31.8	21.4	10.7
0.3mm (300)	7.6	13.8	6.9
0.212mm (212)	8.2	5.6	2.8
0.15mm (150)	6	-0.4	0
0.075mm (75)	8.7	-9.1	0

Table A4.4: Specific Gravity values for Soil-Cement–LBWA mixtures

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	2.01	1.93	1.95	1.92	1.93
2	1.93	1.91	1.90	1.90	1.91
4	1.94	1.93	1.92	1.91	1.89
6	1.91	1.92	1.90	1.93	1.89
8	1.92	1.94	1.93	1.92	1.94

Table A4.5: Liquid Limit Test Results for Soil–Cement–LBWA mixtures

LBWA	CEMENT CONTENT, %

CONTENT, %	0	1	2	3	4
0	63	64	70	74	78
2	63.5	64.5	70	75	78.2
4	65	67.5	72.5	76	78.5
6	66	67,4	75	78	79
8	65	65	71	77	78

Table A4.6: Plastic Limits Test Results for Soil-Cement-LBWA mixtures

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	26.6	28	28.9	31.3	31.6
2	26.2	27.3	28	29	31
4	25.4	27	27.4	27.6	28.3
6	25	25.6	26	27	24.6
8	26	26.6	27.3	27.4	26

Table A4.7: Plasticity Index Tests Result for Soil-Cement-LBWA mixtures

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	36.4	33	41.1	42.9	46.4
2	37.3	37.2	42	46	47.2
4	39.6	40.5	45.1	48.6	50.2
6	41	41.8	49,4	52	54.4
8	39	38.4	43.7	49.7	52

Table A4.8 (a): Maximum Dry Density Test Results for Soil–Cement–LBWA mixes (BSL Compaction)

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	1.30	1.32	1.34	1.39	1.41
2	1.32	1.34	1.35	1.40	1.42
4	1.35	1.36	1.37	1.42	1.44
6	1.36	1.37	1.38	1.44	1.48
8	1.35	1.37	1.37	1.44	1.47

Table A4.8 (b): Maximum Dry Density Test Results for Soil-Cement–LBWA mixes (WAS Compaction).

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	1.42	1.43	1.44	1.46	1.47
2	1.43	1.44	1.45	1.47	1.48
4	1.45	1.46	1.47	1.48	1.49
6	1.47	1.47	1.52	1.53	1.55
8	1.47	1.48	1.50	1.53	1.54

Table A4.8 (c): Maximum Dry Density Test Results for Soil-Cement–LBWA mixes (BSH compaction)

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	1.50	1.51	1.52	1.57	1.59
2	1.51	1.53	1.54	1.57	1.60
4	1.52	1.53	1.55	1.58	1.61
6	1.54	1.56	1.54	1.61	1.62
8	1.55	1.57	1.58	1.6	1.61

Table A4.9 (a): Optimum Moisture Content Tests Results for Soil–Cement–LBWA mixtures (BSL Compaction)

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	24	25	26	29	30
2	25	27	28	30	32
4	31	32	34	35	36
6	33	34	38	37	39
8	26	30	32	38	37

Table A4.9 (b): Optimum Moisture content Tests Results for Soil–Cement–LBWA mixes (WAS Compaction)

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	20	21	23	25	27
2	22	24	26	28	29
4	23	25	27	29	32
6	24	26	28	30	33
8	25	27	30	32	32

Table A4.9 (c): Optimum Moisture Content Test Result for Soil-Cement-LBWA mixes (BSH Compaction)

LBWA CONTENT, %	CEMENT CONTENT, %				
	0	1	2	3	4
0	19	20	22	24	25
2	20	21	23	25	27
4	22	23	25	27	29
6	23	24	26	29	30
8	24	26	28	29	30

TABLE A4.10a - Values of cohesion (kN/m^2) for various OPC / LBWA blend for BSL Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	75	70	61	53	47
2	70	64	55	48	40
4	65	60	53	42	38
6	58	56	40	36	22
8	50	48	30	28	23

TABLE A4.10b - Values of cohesion (kN/m^2) for various OPC / LBWA blend for WAS Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	70	60	55	50	38
2	65	52	46	40	35
4	60	40	38	35	20
6	55	39	34	30	15
8	50	35	32	29	20

TABLE A4.10c - Values of cohesion (kN/m^2) for various OPC / LBWA blend for BSH Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	60	56	52	50	42
2	55	50	47	44	35
4	50	48	43	41	24
6	48	44	40	36	20
8	42	38	35	30	21

TABLE A3.11a - Values of Internal friction (degree) for various OPC / LBWA blend for BSL Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	18	20	23	27	29
2	19.5	23	24	30	33
4	25	28	30	32	33
6	25.5	30	31	34	34
8	30	30.5	33	35.5	35

TABLE A3.11b - Values of internal friction (degree) for various OPC / LBWA blend for WAS Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	16	20	25	28	30
2	33	34	35	32.5	33
4	36	37	36	38	40
6	37	38	42	43.5	44
8	42	42.5	43	45	44.5

TABLE A3.11c - Values of internal friction (degrees) for various OPC / LBWA blend for BSH Compaction

LBWA Content %	Cement Content %				
	0	1	2	3	4
0	14	16	22	22	28
2	21	28	29	30	29.5
4	33	32	36	33	32
6	35	37	36.5	38	37
8	38	39	39.5	40	40