EFFECT OF LOCUST BEAN WASTE ASH ON LIME MODIFIED BLACK COTTON SOIL

BY

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CERTIFICATION

The thesis titled *Effect Of Locust Bean Waste Ash On Lime Modified Black Cotton Soil by* Ovuarume, Ufoma Bernard meets the regulations governing the award of the degree of Master of Science in Civil Engineering of the Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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DECLARATION

I hereby declare that the work in this thesis titled *Effect of Locust Bean Waste Ash on Lime Modified Black Cotton Soil* was performed by me in the Department of Civil Engineering under the supervision of Prof. K. J. Osinubi. The information derived from literature has been duly acknowledged in this text and a list of references provided. No part of this work was previously presented for another degree or diploma at any University.

Ovuarume Ufoma Bernard _____ _____

Signature **Date**

DEDICATION

This research work is dedicated to the Almighty God who made it possible for me to undertake this course, my parents - Mr. Richard Ovuarume and Mrs. Ruth Ovuarume, my wife - Mrs. Gloria O. Ovuarume, my children - Benjamin Onanefe Ovuarume, Benedict Dafinone Ovuarume, Bernardine Oghenetega Ovuarume, and Bennett Oghenerukuwe Ovuarume and all my brothers and sisters.

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ABSTRACT

Black cotton soil classified as an A-7-6(24) soil on the AASHTO classification collected from New Marte area of Borno State was modified with up to 4% lime and locust bean waste ash (LBWA) up to 8% by weight of dry soil. The effect of LBWA on the lime modified soil was studied with respect to particle size distribution, Atterberg limits, compaction characteristics and shear strength parameters using three (3) compactive efforts of British Standard light (BSL), West African Standard (WAS), and British Standard heavy (BSH). Statistical analysis was carried out on results obtained from the tests conducted to determine significant difference (i.e ,$p<0.05$) on the various soil-lime-LBWA mixtures using a two way Analysis of Variance(ANOVA) with the Microsoft Excel Analysis Tool Pak Software Package. Analysis of the results of the soil-lime mixtures considered showed increase in percentage of fine fraction, improvement in the plasticity index, decrease in maximum dry density (MDD), with increase in optimum moisture content (OMC), as well as a decrease in cohesion with increasing angle of internal friction all with higher locust bean waste ash contents. The results also showed that the modified soil met the requirements of the Nigerian General Specifications of not more than 35% passing sieve No.200, maximum plasticity (PI) index of 12%, and liquid limits (LL) of a maximum of 50% when used as a subgrade material in road construction. An optimal blend of 4% lime 8%LBWA is recommended for the modification of black cotton soil

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ABBREVIATIONS

AASHTO	-	American Association of State Highway and Transportation Officials
ANOVA	-	Analysis of Variance
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
BSH	-	British Standard heavy
BSL	-	British Standard light
c	-	Cohesion
CBDA	-	Chad Basin Development Authority
CEC	-	Cation Exchange Capacity
$\mathbf{d_f}$	-	Degree of Freedom
$\mathbf{F_{cal}}$	-	F -calculated
$\mathbf{F_{crit}}$	-	F -critical
HRB	-	Highway Research Board
LBWA	-	Locust Bean Waste Ash
LL	-	Liquid Limit
LSD	-	Least Significance Difference
MDD	-	Maximum Dry Density
NBRRI	-	Nigerian Building and Road Research Institute
OM	-	Organic Matter
OMC	-	Optimum Moisture Content
OPC	-	Ordinary Portland cement
PI	-	Plasticity Index

PL	-	Plastic Limit
TRRL	-	Transport and Road Research Laboratory
USCS	-	Unified Soil Classification System
WAS	-	West African Standard

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Well - built and maintained roads play major role in the development of any nation. Subgrade soil is an integral part of a road pavement structure as it provides the support to the pavement from beneath. The subgrade soil and its properties are important in the design of pavement structure. The main function of the subgrade is to give adequate support to the pavement and for this the subgrade should possess sufficient stability under adverse climatic and loading conditions. Treatment of soils is generally grouped into two major categories namely, soil modification and soil stabilization. The major aim of subgrade modification is to create a working platform for construction equipment, while subgrade stabilization is meant to enhance its strength properties.

1.1.1 Black cotton soil and its origin

Black cotton soil is an expansive soil, which swells or shrinks excessively due to change in moisture content. When an engineering structure is associated with black cotton soil, it experiences either settlement or heave depending on the stress level and the soil swelling pressure. Design and construction of civil engineering structures on and with expansive soils is a challenging task for geotechnical engineers.

Black cotton soils are found mostly in hot environment in the semi – arid regions of the tropical and temperate climate zone with marked alternating wet and dry seasons and where evaporation exceeds precipitation (Chen, 1988). They are generally found on sedimentary plains as a result of thousand years' erosion of the clay content out of the surrounding hills. They can also be found on level areas and depressions. Smaller areas of black cotton soil are found on hills, slopes and piedmont plains.

The soil occupies about 3% of the world land area (i.e., about 340 million hectares). They are found mainly in Africa, in the Gezira cotton fields of the southern black cotton plains of Sudan, South Africa, Ethiopia and Tanzania. In Asia they are found extensively in the Indian Decca Plateau. They could also be found in Australia, West Indies and in vast areas of Russia.

Ola (1983) and NBRRI (1983) reported that the black cotton soil of Nigeria have been laid during the late Tertiary and Quaternary periods as the Chad formations and are composed of a sequence of lacustrine and fluviatile clays and sands of Pleistocene age. According to Ola (1983), black cotton soils with montmorillonite as the predominant clay mineral are the most troublesome soils in Africa. In Nigeria they occupy an estimated area of 104,000 square kilometers (km^2).Usually, there is less or no presence of organic materials in the soil, but the black colour is probably due to iron or titanium (Jha and Sinha, 1993).

1.2 Statement of the Problem

Infrastructural developments in areas where problem soils are identified have been a major concern to the engineer. As such, infrastructure like roads, buildings, bridges to mention but a few within such areas normally undergo foundation problems, that lead to a reduction in the life span of such facilities. Since there is an increasing shortage of good construction materials within localities where problem soils are encountered in addition to the high cost of haulage, what readily comes to mind is making the unsuitable materials fit for use by modification.

It is a common practice today in soil improvement/modification exercise to examine the impact of locally available material often termed waste or residue in the modification of soils for engineering use. The local material considered in this study is the ash obtained from the burning/combustion of the waste (husk) from locust bean.

Locust bean fruit has three major components; the seed commonly used to produce local seasoning for food, and the husk. The waste products are the husks, which when burnt under controlled conditions; result in the locust bean waste ash (LBWA).

1.3 Justification for the Study

The locust bean tree is common in most parts of northern Nigeria and extends north beyond Kano to about latitude 14^0N. It grows up to 15m in height, and has a dark, evergreen pinnate leave. The small red flowers have no petals. The fruit is a brown leathery pod of about between 10 and 30cm long and it contains

gummy pulp of an agreeable sweet taste in which lie a number of seeds. The seeds are edible but the waste product is littered all over our settlements with a corresponding negative environmental impact.

Although a lot of work has been done on the stabilization of the black cotton soil using stabilizers such as lime, Portland cement, bitumen and fly ash (Yoder and Witczak,1975; Osinubi,1995) to improve the strength properties of the soil in the past, modification of the black cotton soil using locust bean waste ash has received little attention. The rising cost of these additives is becoming more challenging and application of locust bean waste ash (LBWA) could result in lower cost. The treatment of the black cotton soil with the locust bean waste ash can be a viable way of handling this problem

1.4 Aim and Objectives

This study was aimed at investigating the effect of locust bean waste ash (LBWA) on lime-modified black cotton soil.

The following specific objectives were considered:

i) To determine the properties of the natural soil.

ii) To modify the black cotton soil with known quantities of lime (i.e, 0, 1, 2, 3, and 4% by dry weight of soil sample) and to determine the effect of locust bean waste ash (i.e., 0, 2, 4, 6, and 8% by dry weight of soil sample) on the soil-lime mixtures.

iii) To compare the changes in properties of the modified black cotton soil with respect to particle size distribution, Atterberg limits, compaction characteristics, and shear strength parameters.

iv) To determine the optimum lime -locust bean waste ash blend that can be used to modify the black cotton soil.

1.5 Scope of the Study

The effect of locust bean waste ash on lime modified black cotton soil was investigated. Preliminary tests were carried out on the black cotton soil sample for the purpose of identification. The tests carried out include particle size distribution, Atterberg limits, specific gravity, compaction characteristics and shear strength parameters (i.e. cohesion(c) and angle of internal friction (ø)).

The black cotton soil sample was modified with up to 4% lime content by weight of the dry soil and each modified specimen was admixed with 0, 2, 4, 6 and 8% locust bean waste ash by weight of dry soil. All the tests were carried out in accordance with the procedures outlined in BS 1377 (1990) and BS1924 (1990).

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil Modification / Stabilization

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

Attom et al. (2000) described soil stabilization as the improvement of soil engineering and physical properties such as increasing its strength and reducing or eliminating its expansion. According to Johnson et al. (1988) stabilization infers improvement in both strength and durability. In soil modification, strength may or may not increase and the procedure is carried out to make the soil in question workable through the modification of the soil properties.

Yoder and Witczak (1975) categorized the various types of stabilizers according to the properties imparted to the soil. The types of additives include cementing agents, modifiers, water proofing and water retaining agents. The behaviour of each of these additives differ vastly from the others, since each has its particular use and its own limitation as well.

Modifiers that are often used in modification processes include cement, lime and bitumen, of which lime is the most commonly used. When lime is used as a modifier, it makes the soil workable for subsequent stabilization with cement or

other agents. Osinubi (1995) stated that cement and lime will change the water film on the soil particles, modify the clay minerals to some extent and reduce soil plasticity. Osula (1991) stated that the purpose of lime in the modification of soils is to modify the soil properties and render it workable for use as modified or for subsequent stabilization with cement or bitumen. Lees et al. (1982) used particle size distribution, plasticity characteristics and shear strength characteristics (c- ø values) as evaluation criteria. Osula (1991) considered the criteria used by Lees et al. (1982) together with the Nigerian General Specifications (1997), the Highway Research Board (1943) as well as the Millard and O'Reilly (1965) free - flow criteria.

Another consideration is the proportion of the modifier to be used. Yoder and Witczak (1975) recommended a proportion of 0.5 - 3% for hydrated lime. Appreciable improvement in soil properties such as decrease in plasticity and increased shear strength using lime as modifier was recorded by Ola (1977) and Osula (1991). Osula (1991) reported 3% lime optimum for the modification of a problem laterite using the particle size and plasticity criteria of the Highway Research Board (1943) limits for soils that can be stabilized with Portland cement. It was also reported that using the plasticity criteria only, the soil could be modified with 2% lime.

2.1.1 **Benefits of soil modification**

The benefits derived from the improved soil properties are reduction in the amount of agent required for stabilization of the improved soil rendering it usable, which could not otherwise be stabilized with agents like cement and

bitumen. Another benefit is the reduction of crack formation, the clay content having been reduced by the addition of lime (Ingles and Metcalf, 1972). On a more practical note, there will also be a reduction in the tendency of picking up under rollers during compaction probably due to the more friable nature of the soil after modification. The direct implication of the second benefit is the increase in the range of usable soils for road construction.

2.1.2 **Mechanism of soil - lime modification reaction**

The addition of lime to soils increases optimum moisture content for a given compactive effort (Osinubi and Katte, 1997). In soil - lime mixes, the general consensus is that when lime is added to a soil, it dissociates in the presence of water into calcium (Ca^{2+}) and hydroxyl (OH^{-}) ions thereby increasing the soil pH. Following this dissociation, one of two things happens, either the excess calcium ions (Ca^{2+}) supplied replace cations of other elements present at the exchange sites in the soil particle, or the calcium ions are absorbed by the soil particle. Both processes are cation exchange reactions. Cation exchange reaction is followed by flocculation and agglomeration of the charge carrying soil particles. Flocculation may be as a result of cation exchange reaction or may more likely be caused by the overcrowding of the excess calcium ions on the absorbed surface of the clay particles, thereby causing the lowering of the zeta potential or the repelling power of like ions in the medium (O'Flaherty, 1988). Agglomeration on the other hand, is caused by the attraction of the remaining soil particles, still carrying negative charges to the positively charged surface of the particles affected by cation exchange or the flocculated particles (Osula, 1991). Likely the implication of this agglomeration with respect to time

is that the resulting changes in the properties of the soil will continue until agglomeration process ceases (Osula, 1996).

Eades and Grim (1960) reported that there exist a chemical reaction between lime and pure clay minerals (kaolinite, illite, and montmorillonite) with accompanying increase in bearing value. The quantity of lime needed to effectively treat a soil to develop increased strength varies with the type of clay mineral present. Akawwi and Al-Kaharabsheh (2002) reported the swelling and shrinkage potential of soils affected by mineralogical constituents and surrounding environment. Ingles and Metcalf (1972) as well as Kedzi (1979) recommended 2-3% of hydrated lime for soil modification whereas Yoder and Witczak (1975) recommend ½ -4% for the same process.

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

According to Chen (1988) and Brown (1996), addition of lime to clay soil provides an abundance of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}). These ions tend to displace other common cations such as Sodium (Na^{+}) or potassium (K^{+}) in a process known as cation exchange. Replacement of sodium

or potassium ions with calcium significantly reduces potential for swelling. The addition of lime increases the soil pH, which also increases the cation exchange capacity. The above reaction is accompanied by pozzolanic reaction, which is a slower or long term reaction. The reactions are little understood, but apparently involve interaction between hydrated lime and siliceous and aluminous minerals in soils. The resulting gel cements the soil and may be similar to certain reaction of products from the hydration of Portland cement. A major difference is that under normal curing conditions considerably more time is required for pozzolanic - cementation reactions to contribute more strength.

2.2 Mechanical Modification/Stabilization

Compaction or mechanical stabilization is one of the oldest means of stabilization. Soil particles are rearranged, that is, by changing the gradation through mixing with other soils and densified, or undercutting the existing soils and replacing them with granular material to improve the soils' engineering properties of strength, permeability and compressibility. An existing soil may have poor strength or stability perhaps because of excess clay, silt or fine sand. If a suitable soil was located within a reasonable haul distance, blending the soils together could effect an improvement in the existing soil (Thompson, 1966).

2.3 Chemical Modification/Stabilization

For close to half a decade, the concern of geotechnical engineers has been to make poor engineering soil much better. This stimulated research for the available chemicals or mechanical means of modifying the soil. These

chemicals most often are organic in nature and are mainly industrial wastes which pose environmental problems. In the absence of organic matter, when a soil contains a certain amount of fines that cause plastic behaviour of the soil, modification is often recommended (Osinubi and Katte, 1997). Modification, a brain child of stabilization, is a process used for improving 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 singly or in combination with one another.

Soil modification or stabilization started since the 1960s in Europe and has spread worldwide, since problematic soils are widespread In most soil modification, stress may or may not increase and the procedure is carried out in other to make the soil in question workable. The main purpose of soil modification is to improve the particle 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. Thorough mixing of the modifier and soil must be done in order to achieve the desired strength and durability. In trying 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 soils, 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 requirements 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. These are to:

a) Improve the strength or increase the soil stability,

b) Waterproof the soil and

c) For dust control.

2.4 Single Agent Modification

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

Most soils improve in strength on the addition of cement. Cement as well as lime has been employed for more than two score years for the stabilization of soil. According to Lorenzo and Bergado (2006), when the pore water of the soil encounters the cement, hydration of the cement occurs rapidly, and the subsequent major products (primary cementations) are hydrated calcium silicates (tricalcium silicate and dicalcium silicate hydrates); hydrated calcium aluminates (tricalcium aluminate and tetracalcium aluminate hydrates) and hydrated lime ($Ca(OH_2)$. They further reported that the hydrated calcium silicates and aluminates are the main cementing products formed, while the

hydrated 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 encloses unaltered soil particles.

Furthermore, the hydration of cement subsequently enhances the increase in pH value of pore water, which is caused by the dissociation of the divalent calcium ion (Ca++) from the hydrated lime during hydrolysis. The dissociation of Ca++ eventually causes flocculation and coagulation of soil particles into large sized aggregates or grains. The soil silica and alumina, which are inherently acidic will then be dissolved by the strong bases of cement compounds from the clay minerals and amorphous materials on the surface of the clay particles in a manner similar to the reaction between a weak acid and a strong base. The hydrous silica and alumina will then gradually react with the calcium ions liberated from the hydrolysis of cement to form a new insoluble compound (secondary cementing product), which hardens when cured thereby stabilizing the soil. Gillot (1987) stated that the presence of organic matter in soils can interfere with these hydration reactions of cement, because of the presence of hydroxyl and carboxyl groups in the organic compound.

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 of cement, lime, bitumen, etc. are being looked at with replacement by the much generated agricultural wastes nationwide. Researches in the Department of Civil Engineering,Ahmadu Bello University, Zaria, of late focused on stabilization of both laterites and black cotton soils using bagasse ash (Osinubi and Mustapha, 2005; Stephen 2006; Osinubi and Eberemu, 2006; Osinubi and Stephen, 2005, 2006a,b, and 2007; Osinubi *et al.*, 2007a,b and 2009). The potential of locust bean waste ash, an agricultural waste, as a stabilizer of black cotton soil was recently studied by Akinmade (2008). The study revealed that the locust bean waste cannot stand alone as a stabilizer but could serve as an admixture.

2.5 Multiple Agents Modification

The ever increasing cost of industrially produced modifiers indicates an increased cost of pavement construction. This is not economically sound for a growing economy like Nigeria because limited resources will have to be unilaterally directed; thus depriving other sectors of the economy of growth. The increase in modifier cost will also be a hindrance to the provision of accessible roads to the rural dwellers that constitute the higher percentage of the population and are agriculturally dependent. Cement, of late, has become so expensive that using it alone for a sub-base or sub-grade construction will be too expensive for the country to cope with economically. The costs of other chemicals are as well becoming high and it is therefore proper to use locally available materials considered as wastes in the society to either substitute these chemicals or complement them in combination with another to improve on the soil as well as the environment. Croft (1968) opined that cement stabilization of

soils with plasticity index greater than 20% or liquid limit in excess of 45-50% is very uneconomical.

Thus, the addition of small amounts of other chemicals to soil-cement, soil-lime mixtures, etc. will reduce the cost of construction and still give more favourable result than with only cement or lime. A pozzolan or pozzolana or pozzolanic material has served in this purpose. A pozzolan is normally defined as a material which on its own has no cementing property, but which in the presence of lime and/or cement and water develops such a property and thus itself acts as cement. Such materials, which are normally grouped into natural and synthetic pozzolanas are therefore normally employed as an admixture with or a partial replacement for ordinary Portland cement in the manufacture of concrete or concrete products; additionally, they find employment in conjunction with lime and/or cement in the stabilization of roads, and the preparation of road base material. The fineness of the pozzolana is an important factor in this respect. Fineness (particle size) represents the specific surface area in square meters per kilogram. Bagasse ash has been found to fall into this category, especially when adequately processed. According to ASTM C618-78 (1978), desirable criteria in respect of the processed ash are that:

i) The combined content of $Si0_2$, $A1_20_3$, and Fe_20_3 should not be less than 70%

ii) The MgO content should not exceed 5%

iii) The loss on ignition should not exceed 10%

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 temperatures. It was also reported that because of the pozzolanic properties of the processed bagasse ash, it is used in the production of pozzolanic road base materials and in the stabilization of roads. Osinubi (1999) reported an appreciable change in both the 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 bottom ash admixed cement stabilization of black cotton soil, Osinubi (2000a) reported that there was a reasonable improvement in the properties of the soil. A combination of other stabilizing agents has also been studied to make use of the abundantly available waste materials 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 in foundation. Their results showed that these engineering properties appreciably increased. The use of bagasse ash and some agents as admixtures in the stabilization of black cotton and lateritic soils has also been studied by Osinubi *et al*. (2007a, 2008, 2009; Osinubi and Mustapha; 2008; 2009); Ochepo (2008).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Black cotton soil

The soil samples used in this study was collected from a borrow pit at the Chad Basin Development Authority (CBDA) reserved site by method of disturbed sampling during the rainy season in New Marte (Latitude $13^0$27'N and Longitude $13^0$50'E) along the Maiduguri - Gamboru Road in Marte Local Government Area of Borno State, North eastern Nigeria. The top soil was removed to a depth of 0.5m in order to avoid the inclusion of organic matter before the soil samples were taken, sealed in plastic bags and put in sack to avoid loss of moisture during transportation. The soil samples were then allowed to dry in the Department of Civil Engineering Soils Research, Laboratory, Ahmadu Bello University (ABU), Zaria before pulverizing to obtain particles passing BS No.40.sieve.

Studies of the geological and soil maps of Nigeria after Akintola (1982) and Areola (1982) and that showing various classes of soil and their locations Figs 3.1 and 3.2, respectively show that the parent material in the study area is basic igneous rock which when weathered formed weakly developed black cotton soils. The study area lies within the North eastern part of Nigeria which is extensively covered by black cotton soils noted for swelling and heaving with changes in seasonal moisture.

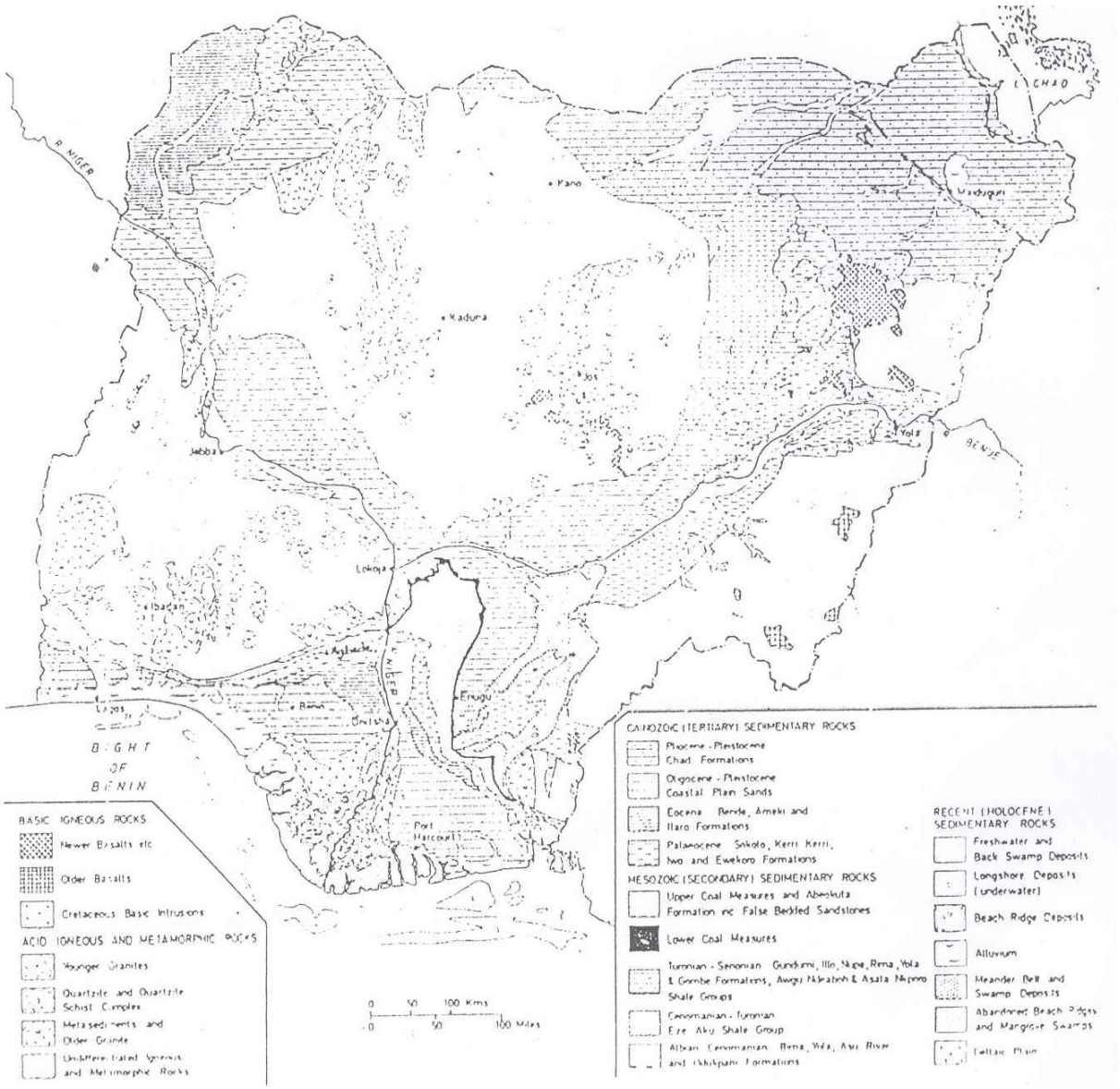

Fig. 3.1 Geological map of Nigeria (After Akintola 1982)

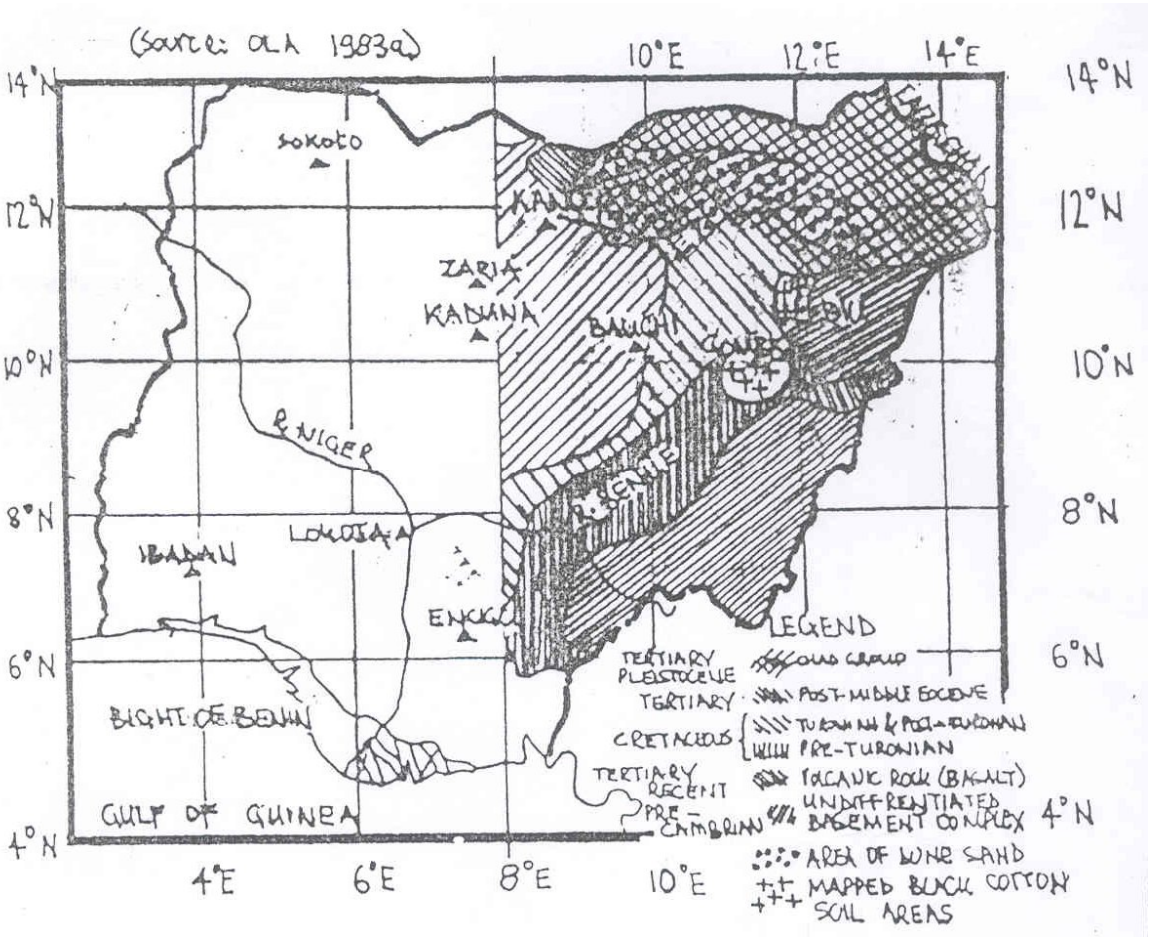

Fig. 3.2 Geological map of Nigeria showing various classes of soil and their locations

3.1.2 **Locust bean waste ash**

The locust bean waste ash (LBWA) used in this study was obtained locally from the burning of locust bean husks sourced from Birnin Yero and Maraban Jos in Kaduna State as well as Doko town in Niger State. The husks were completely burnt under atmospheric condition, sealed up in plastic bags and transported to the Civil Engineering department laboratory. The ash was then passed through BS No.200 sieve and kept to be mixed with the 'soil-lime' in the appropriate percentages.

Typical oxide composition of locust bean waste ash and specifications for pozzolanas are given in Table 3.1and 3.2 respectively.

Table 3.1: Oxide composition of locust bean waste ash

Oxide	**Concentration (%)**
CaO	1.08
SiO_2	55.38
$Al2O_3$	14.93
Fe_2O_3	0.278
MnO	0.09
Na_2O	0.18
K_2O	2.00
SO3	
P_2O_5	0.23
Loss on Ignition	10.63

Source: Akinmade, 2008

Table 3.2: 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, 1978)

3.1.3 Lime

The lime used in this study was purchased from the open market from authorized dealers in Kaduna. The oxide composition of the lime was carried out at the National Geoscience Research Laboratory in Kaduna.

3.2 Methods

3.2.1 Natural moisture content

The natural moisture content of the soil obtained from the site was determined in accordance with BS 1377 (1990) Part 2. Three containers were cleaned and weighed to the nearest 0.01g (M_1). The sample as freshly collected was crumbled and placed loosely in the containers and the containers with the samples were weighed together to the nearest 0.01g as M_2. The containers were then placed in the oven and dried at 105 - 110^{o}C for 24 hours. The containers

and the samples were then removed and weighed dry to the nearest 0.01g as M_3. The natural moisture content (as collected from the site) was calculated as the average value for the three oven dried samples given by eq. (3.1)

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

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 dry soil (g)*

3.2.2 **Specific gravity**

The determination of specific gravity was carried out according to BS 1377 (1990) test (B) for fine–grained soils. The density bottle and the stopper were weighed to the nearest 0.001g (m_1). The air dried soil was transferred into the density bottle, and the bottle, content and the cover were weighed as m_2. Water was then added just enough to cover the soil, the solution was gently stirred to remove any air bubble. The bottle was then completely filled up and covered. The covered bottle was then wiped dry and the whole weighed to the nearest 0.001g (as m_3). The bottle was subsequently emptied and filled completely with water, wiped dry and weighed to the nearest 0.001g (m_4). The specific gravity was calculated using eq. (3.2)

$$G_S = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \tag{3.2}$$

3.2.3 **Cation exchange capacity**

10g of soil passing 2mm sieve was put into a $100m^3$ plastic beaker, about 40ml of Ammonium acetate (1N pH=7.0) were added, stirred with a glass rod and left over night. The soil was filtered with a light suction using a 55mm Bucher funnel, the soil was leached so it could fit in a funnel with Ammonium acetate to a volume of 250 $cm^{3.}$ The leachate was tested from the soil to know if it was calcium free, the presence of calcium is indicated by a white precipitate or turbidity. The electrolyte was washed out with 150-200ml of isopropyl alcohol. Chloride was tested for in the leachate with (0.1N AgNO3) till the leachate became 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 the flask was connected to the steel, 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 distilled was collected .The NH_4 boric was titrated with a standard acid 0.1N HCL. The cation exchange capacity was calculated using the formula

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

where

B = Blank

NA = Normality of acid

The test was repeated for all modified samples.

The cation exchange capacity (CEC) of soils is defined as the capacity of soils to adsorb and exchange cations (Brady and Weil, 2002). Cation exchange capacity is an important parameter of soil because it gives an indication of the

type of clay minerals present in the soil, its capacity to retain nutrients against leaching and assessing their fertility and environmental behaviour.

Generally, the chemical activity of the soil depends on its CEC. The CEC of a soil is strongly affected by the amount and type of clay, and amount of organic matter (OM) present in the soil (Curtis and Courson, 1981). Both clay and colloidal OM are negatively charged and therefore can act as anions (Kimmins, 1997). As a result, these two materials, either individually or combined as a clay-humus complex, have the ability to absorb and hold positively charged ions (cations). Soils with large amounts of clay and OM have higher CEC than sandy soils with low OM. In surface horizons of mineral soils, higher OM and clay contents significantly contribute to the CEC, while in the subsoil particularly where Bt horizon exist, more CEC is contributed by the clay fractions than by OM due to the decline of OM with profile depth (Foth, 1990; Brady and Weil, 2002).

Soil solutions contain dissolved chemicals, and many of these chemicals carry positive charge (cations) or negative charges (anions) (Fisher and Binkley, 2000). Cation exchange is considered to be of greater importance to soil fertility than anion exchange, because the majority of essential minerals are absorbed by plants as cations (Poritchett and Fisher, 1987).

The nutrients required for plant growth are present in the soil in a variety of forms (Kimmins, 1997). They may be dissolved in the soil solution, from where they can be utilized directly.

They may be absorbed onto exchange sites, from where they enter soil solution or be directly exploited by tree roots or microorganisms that come in contact with the exchange site.

Alternatively, they may be firmly fixed in clay lattices, immobilized in decomposition resistant OM, or present in insoluble inorganic compounds. An exchangeable cation is one that is held on a negatively charged surface and displaced by another cation. The exchangeable cation is a desirable form of a nutrient being quickly brought into solution and made accessible to roots by the exchange with proton. Although the cation nutrients held on the exchange sites form a readily available pool, they do not represent the cation supplying ability of the soil (Binkley and Sollins, 1990; Binkley et al., 1992). Cations removed from the exchange sites often are replenished rapidly from other sources, such as OM decomposition, mineral weathering, or release of ions fixed within the layers.

3.2.4 Particle size distribution

The particle size analysis test was carried out in accordance with BS 1377; 1990 Part 2. Wet sieving was conducted by measuring 200g of the soil sample and soaking it for 24hours. The soil sample was then washed through BS sieve No 200 to obtain the total percentage of clay size present for hydrometer analysis. The coarser particles retained were oven dried for 24 hrs and a known weight of solids was passed through a series of standard sieve reducing progressively. The proportion by weight of the solid fraction retained on each sieve was determined for the various treated soil specimens, the respective optimum moisture content

(OMC) for the three energy levels were used for the mixing of the soil before air drying followed by sieving.

3.2.5 **Hydrometer analysis**

A density hydrometer No. 680102 was used to measure the density of the soil pretreated with sodium hexametaphosphate at various intervals of time, according to the procedures given in BS 1377(1990) and Head (1980). The hydrometer was calibrated and the calibration equation obtained as:

$$H_r = 17.67 - 0.176R \quad (3.4)$$

C_m = 0.2; meniscus correction used.

where R = hydrometer reading

The particle diameter, D (mm) for each reading was obtained from the expression:

$$D = k\sqrt{Hr/t} \ (mm) \quad (3.5)$$

where:

H_r = effective depth (mm) corresponding to each value of R

k = constant for a range of working temperatures and particle densities

3.2.6 **Atterberg limits**

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

3.2.6.1 **Liquid limit**

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

This same procedure was then repeated for each of the samples with lime and LBWA admixture for the various percentages considered in this study.

3.2.6.2 **Plastic limit**

A portion of the soil/soil–lime–LBWA mixture used for the liquid limit test was retained for the determination of plastic limit. The ball of the soil/soil admixtures was moulded between the fingers and rolled between the palms of the hand until it dried sufficiently (even though the soil was already relatively

drier than the ones used for liquid limit). The sample was then divided into approximately four equal parts. Each of the parts was rolled into a thread between the first finger and the thumb. The thread was then rolled between the tip of the fingers of one hand and the glass. This continued until the diameter of the thread is reduced to about 3mm in five to ten forward and backward movements of the hand. The movement continued until the thread shears both longitudinally and transversely. The crumbled soil was then put in the moisture container and the moisture content determined.

3.2.6.3 **Plasticity index**

The plasticity index of the soil/soil-lime-LBWA mixture is the difference between the liquid limits of the natural/various mixes of the soil and their corresponding plastic limits. The plasticity index of the samples were calculated as:

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

3.2.7 **Compaction characteristics**

3.2.7.1 **Maximum dry density**

The compaction tests were carried out for the natural soil and the modified soils (in different percentages); all according to BS 1377 (1990) and BS1924 (1990), using the British Standard light (BSL), West African Standard (WAS) and the British Standard heavy (BSH) compactive energies. The WAS energy was applied in accordance with the Nigerian General Specification (1997).

3kg of the soil/soil-admixture sample were mixed thoroughly with 8% of water (and water is added at 8% for each of the compactions). The sample was then

compacted into the 1000 cm^3 (of mass m_1); in three layers of approximately equal mass with each layer receiving 27 blows of 2.5kg rammer falling through a height of 300mm, for the BSL 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 uniformly distributed over the surface of each layer. The collar was then removed and the compacted sample leveled off at the top of the mould with a straight edge. The mould containing the leveled sample was then weighed to the nearest 1g; m_2. Two small samples were then taken from the compacted soil for the determination of moisture content. The sample was then removed from the mould, crushed, additional water added and the same procedure was repeated until minimum of five sets of samples were taken for moisture content determination. The bulk density in Mg/m^3 was later calculated for each compacted specimen using:

$$\rho = \frac{m_2 - m_1}{1000} \tag{3.7}$$

The dry density was also calculated using the equation:

$$\rho_d = 100\rho/(100 + W) \tag{3.8}$$

where w is the moisture content of each compacted specimen.

The values of the dry densities as obtained from eq. (3.8) were plotted against their respective moisture contents and the maximum dry density, MDD was deduced as the maximum point on the resulting curves.

3.2.7.2 **Optimum moisture content**

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

3.2.8 **Shear strength parameters**

The shear strength tests were carried out using the undrained Triaxial test procedure in accordance with BS 1377(1990) at the maximum dry densities and optimum moisture contents of the various soil-lime-LBWA mixtures. The natural soil sample/the treated soil samples were compacted in 1000 cm^3 moulds at their respective OMCs. The samples were extruded from the moulds and trimmed into a cylindrical specimen of 38.1mm diameter and 76.2mm length. The three cylindrical specimens from the mould were then weighed before carrying out the test. Record was taken simultaneously of the axial deformation and the axial force at regular intervals until failure of the sample occurred. The compressive strength was calculated from the following equation (Head, 1992):

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

where E% = v/L_o

E% = Strain percent

v = Amount of compression at any stage

R = Load ring reading at strain E

C_r = Mean calibration of load ring

L_o = Initial length of specimen

A_o = Initial cross sectional area

δ = Compressive stress at strain E

3.3 Methods of analysis

The two methods of analysis used in this research are:

1. Graphical methods using the Microsoft Excel software package.
2. Two way analysis of variance (ANOVA) without replication using the Microsoft Excel software package.

3.3.1 Graphical method using the Microsoft Excel Software Package

In this method Graphs were used to show the relationship between two quantities -- an independent variable usually plotted on the x-axis and a dependent variable usually plotted on the y-axis. The graphs were plotted using the Microsoft Excel software package.

3.3.2 ANOVA - Two way analysis of variance (ANOVA) without replication

In this method the Microsoft Excel software package was used to analyse the results of the tests carried out on the soil-lime mixtures based on the two-way analysis of variance (ANOVA) without replication. The aim of this analysis is to find out if there is any significant difference on the various soil-lime mixtures. The level of significance used in the analysis is 5% level or $p<0.05$.

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CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Preliminary Tests

4.1.1 Identification of Soil

The results of the tests conducted for the identification /determination of the properties of the natural soil before modification are presented in Table 4.1 while the particle size distribution curve for the natural soil is shown in Fig. 4.1. The soil is classified as an A-7-6(24) subgroup soil based on the American Association of State and Highway Transportation Officials Soil Classification System (AASHTO, 1986) or CH based on the Unified Soil Classification System, USCS (ASTM, 1992). The soil is greyish black in colour and has a liquid limit of 66.5%, plastic limit of 30.8% and plasticity index of 35.7%. Based on the Nigerian General Specifications (1997), and the Highway Research Board (1943) suitability limits 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 or sub base material. The percentage passing sieve No.200 was found to be 75.5%. Details of test results are summarized in Table A4.1.

Table 4.1: Properties of the natural black cotton soil

Property	Quantity
Natural moisture content, %	35.0
Percentage passing BS No. 200 sieve	75.5
Liquid Limit, %	66.5
Plastic Limit, %	30.8
Plasticity Index, %	35.7
AASHTO Classification, %	A-7-6(24)
Unified Soil Classification System (USCS)	CH
Specific Gravity	2.30
Maximum Dry Density, Mg/m^3	
British Standard light (BSL)	1.35
West Africa Standard (WAS)	1.36
British Standard heavy (BSH)	1.43
Optimum Moisture Content, %	
British Standard light (BSL)	16.0
West African Standard (WAS)	17.3
British Standard heavy (BSH)	16.2
Cohesion, kN/m^2	
British Standard light (BSL)	165
West African Standard (WAS)	178
British Standard heavy (BSH)	160
Angle of Internal Friction,(^{0})	
British Standard light	13.5
West African Standard	12.0
British Standard heavy	11.0
Colour	Greyish Black

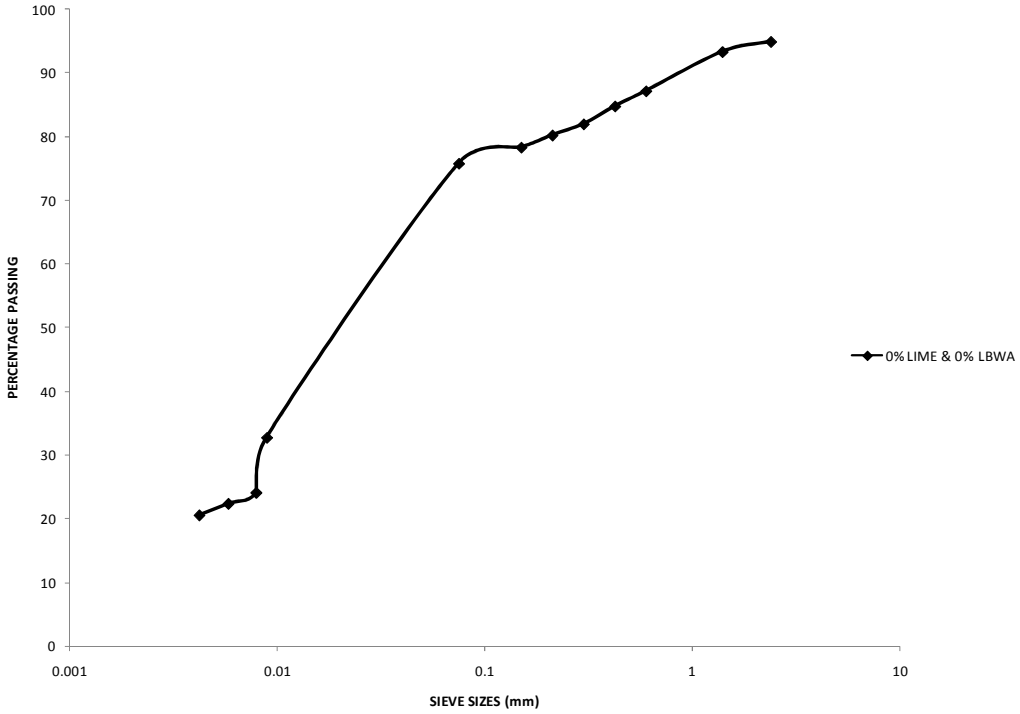

Fig. 4.1: Particle size distribution curve of the natural black cotton soil

4.1.2 **Lime**

The oxide composition of the lime used in this study is shown in Table 4.2

Table 4.2: Oxide composition of lime used

Oxide	Concentration (%)
CaO	54.92
SiO_2	0.35
Al_2O_3	0.60
Fe_2O_3	0.14
MnO	0.09
Na_2O	0.02
K_2O	0.04
SO_3	0.06
V_2O_5	0.05
Loss on Ignition	43.67

A comparison of the calculated compound composition of locust bean waste ash and hydrated lime is shown in Table 4.3.The cementing characteristics of the locust bean waste ash are dependent on its oxide composition. The amount of CaO in LBWA (1.08 %) is very low compared to about 63% in lime. The silicon and aluminium oxides in LBWA on the other hand are higher than that in lime.

4.1.3 Locust bean waste ash

The oxide composition of the locust bean waste ash shown in Table 4.3 indicates that the amount of CaO is low, while other major oxides necessary for the formation of cementitious compounds are high.

Table 4.3: Typical Oxide composition of LBWA and Lime

Oxide	*LBWA (%)	**Lime (%)
CaO	1.08	63.0
SiO_2	55.38	1.59
Al_2O_3	14.93	0.50
Fe_2O_3	0.278	0.61
MnO	0.09	-
Mn_2O_3	-	0.50
Na_2O	0.18	Trace
K_2O	2.00	Trace
SO_3	-	-
TiO_2	-	-
P_2O_5	0.23	-
Loss on Ignition	0.63	26.87

Sources:

***LBWA: Akinmade, 2008**

****Lime: Czernin, 1962**

4.1.4 Cation exchange capacity of the materials

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

When water is added to soil particles, the negative charge on the surface of clay particles 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 the particles (in the case of fine grained soil) which allows the movement of grains over one another. "This property improved the plasticity of the soil", as the soil can deform plastically without cracking when mixed with varying amounts of water.

The cation exchange capacity of the soil increased appreciably with increased locust bean waste ash content while slight increase occurred with increase in lime content. The variation of cation exchange capacity of the lime modified soil with locust bean waste ash is shown in Fig 4.2a. This indicates that the cation exchange capacity of the soil can be improved by mixing it with lime – locust bean waste ash or locust bean waste ash alone because of its high quantity of exchangeable cations. While the variation of cation exchange capacity of the locust bean waste ash modified soil with lime is shown in Fig

4.2b. Results of cation exchange capacity are as summarized in TableA.4.4 in the Appendix.

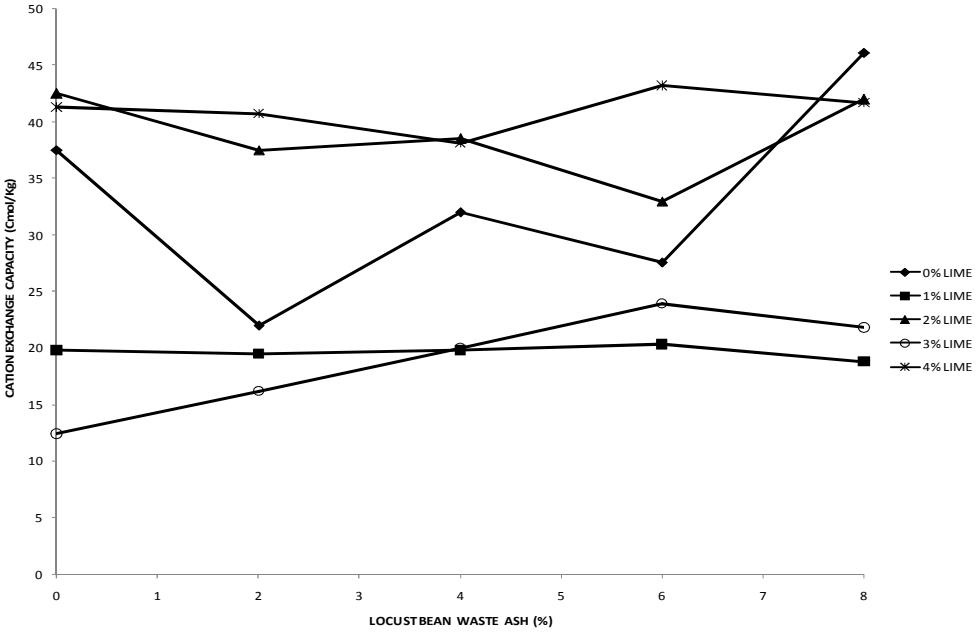

Fig. 4.2a Variation of cation exchange capacity of lime modified soil with locust bean waste ash content

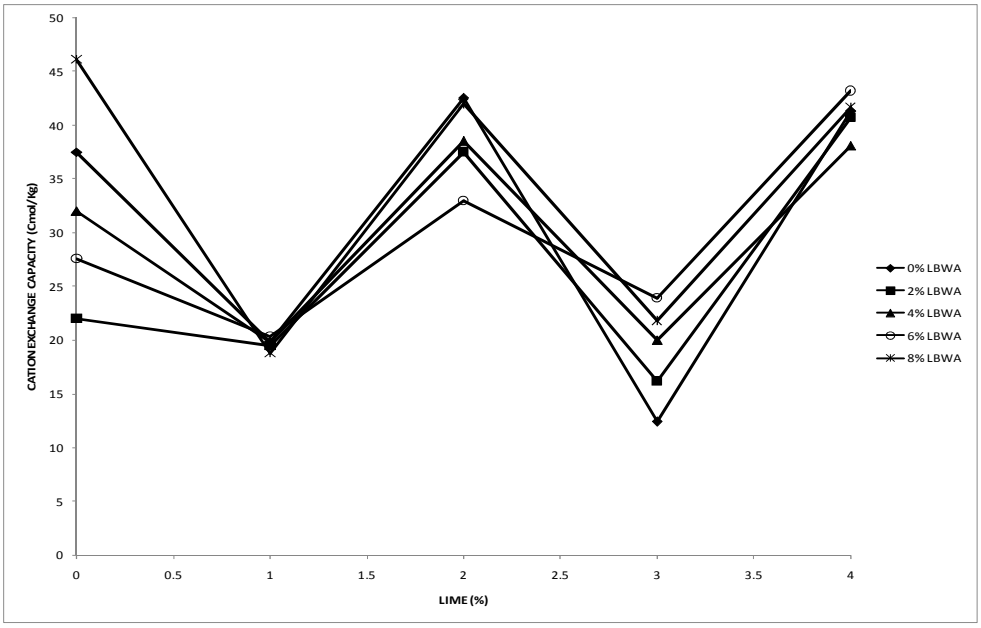

Fig. 4.2b Variation of cation exchange capacity of locust bean waste ash modified soil with lime content

4.2 Modified Soil

4.2.1 Particle size distribution

4.2.1.1 Soil - lime mixtures

The particle size distribution curves for the lime-modified soils (at 0%) locust bean waste ash) are shown in Fig 4.3a. A reduction in the percentage of fines with lime content was observed. There was a marked reduction in the percent of the soil passing BS sieve No.200 from 75.5 % at 0% lime to 6, 3, 2.5, and 0% at 1, 2, 3 and 4 % lime content respectively. The reductions in the proportion of fines were as a result of bonding of clay to silt sizes to form pseudo-sand sizes and of sand sizes to form larger sand sizes.

4.2.1.2 Effect of locust bean waste ash on the particle size distribution of the modified soil

The particles size distribution curves of soil-lime mixtures treated with locust bean waste ash are shown in Figs. 4.3a - 4.3e, Figs 4.4a - 4.4e, Figs 4.5a-4.5e,for the BSL, WAS and BSH compactions, respectively. This showed a decrease in the percentage of fines passing BS sieve No.200. The locust bean waste ash content caused the soil-lime mixture to flocculate and agglomerate more and hence the soil-lime mixture got coarser and thus enabled the clay fraction to form larger soil sizes. This was enhanced by the formation of products of the pozzolanic reaction, taking place between the Ca $(OH)_2$ from lime and silicate from both clay and the locust bean waste ash.

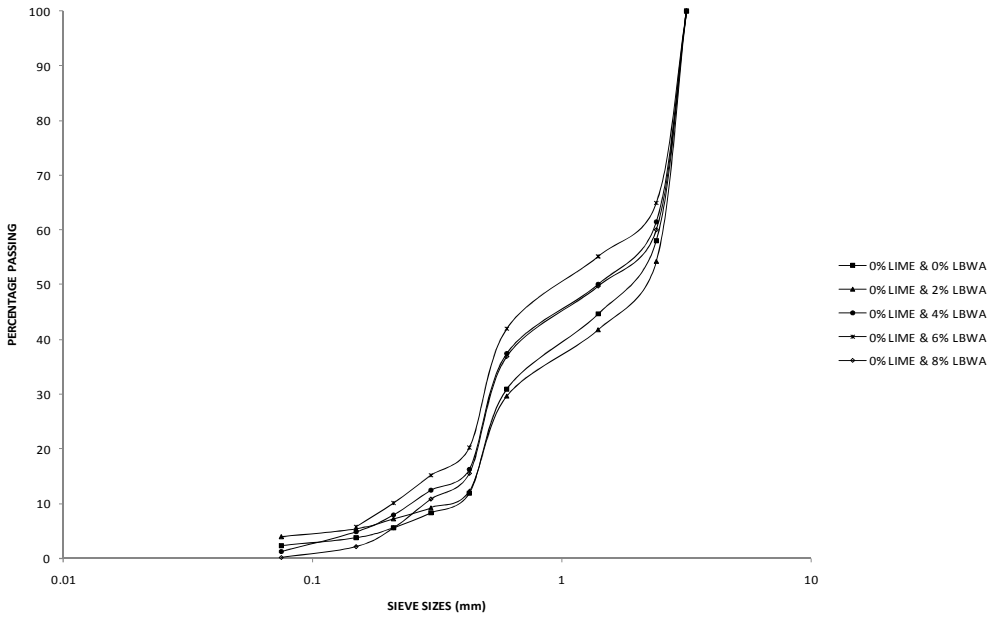

Fig.4.3 (a) Particle size distribution curves for Soil-0% -lime-LBWA mixtures (BSL compaction)

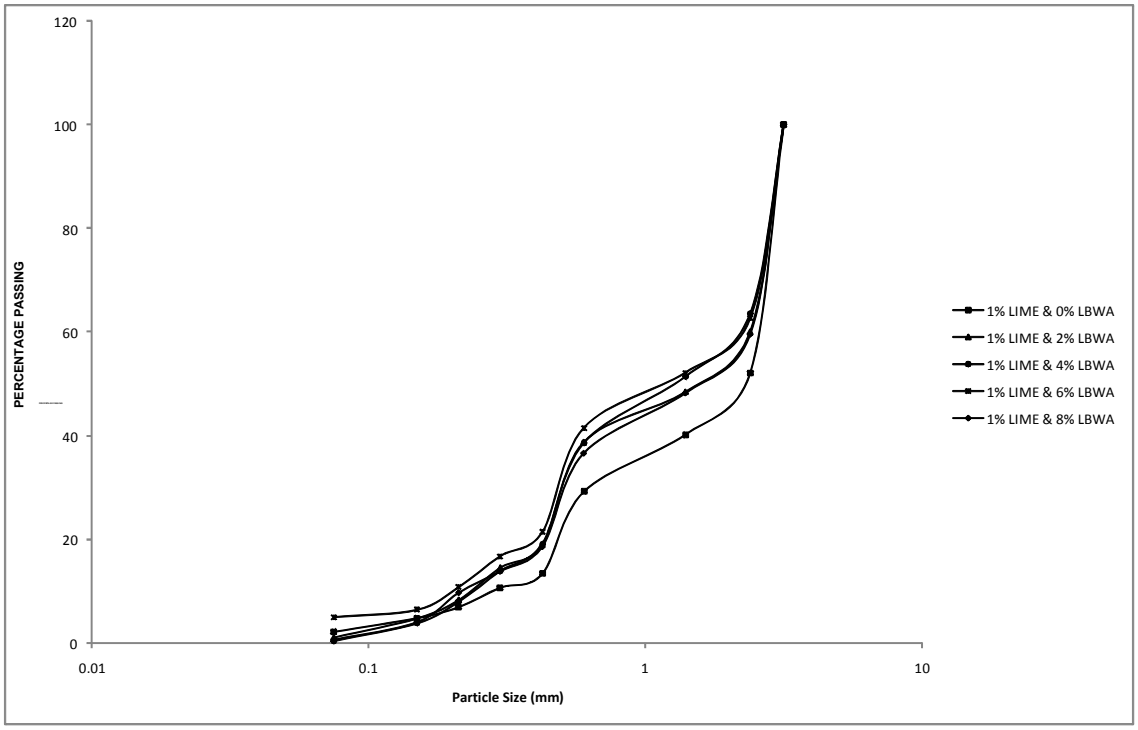

Fig.4.3 (b) Particle size distribution curves for Soil-1% lime -LBWA mixtures (BSL compaction)

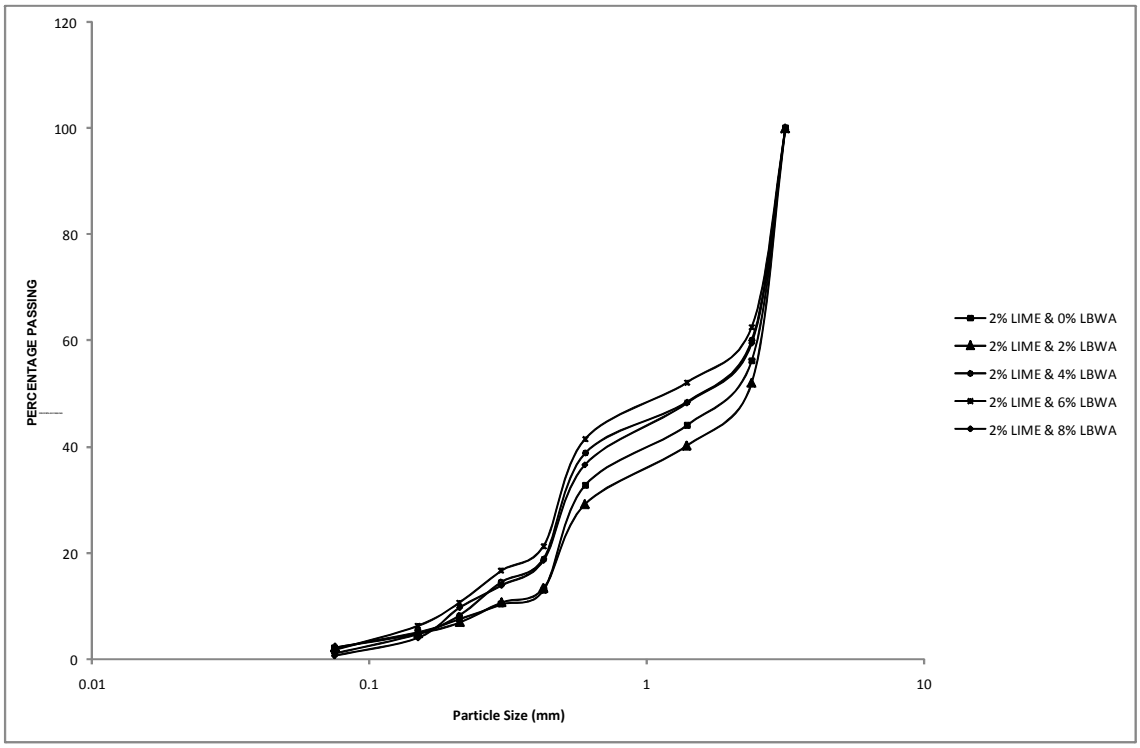

Fig.4.3(c) Particle size distribution curves for Soil-2% lime -LBWA mixtures (BSL compaction)

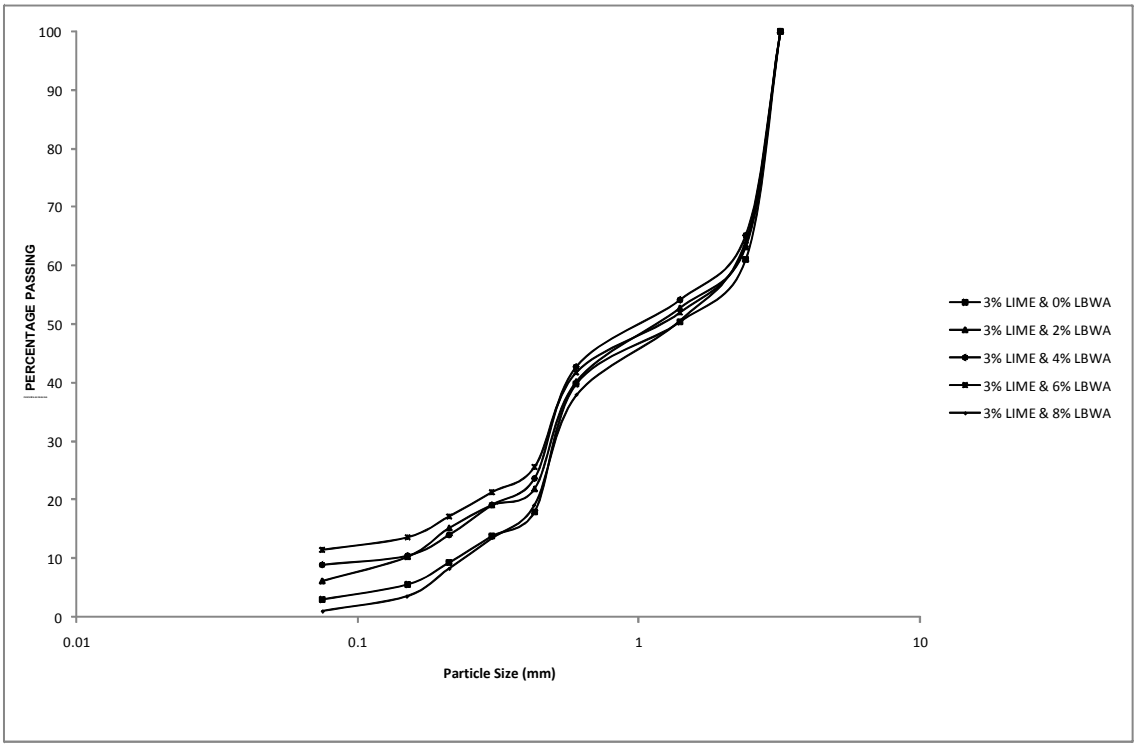

Fig.4.3 (d) Particle size distribution curves for Soil -3% lime – LBWA mixtures (BSL compaction)

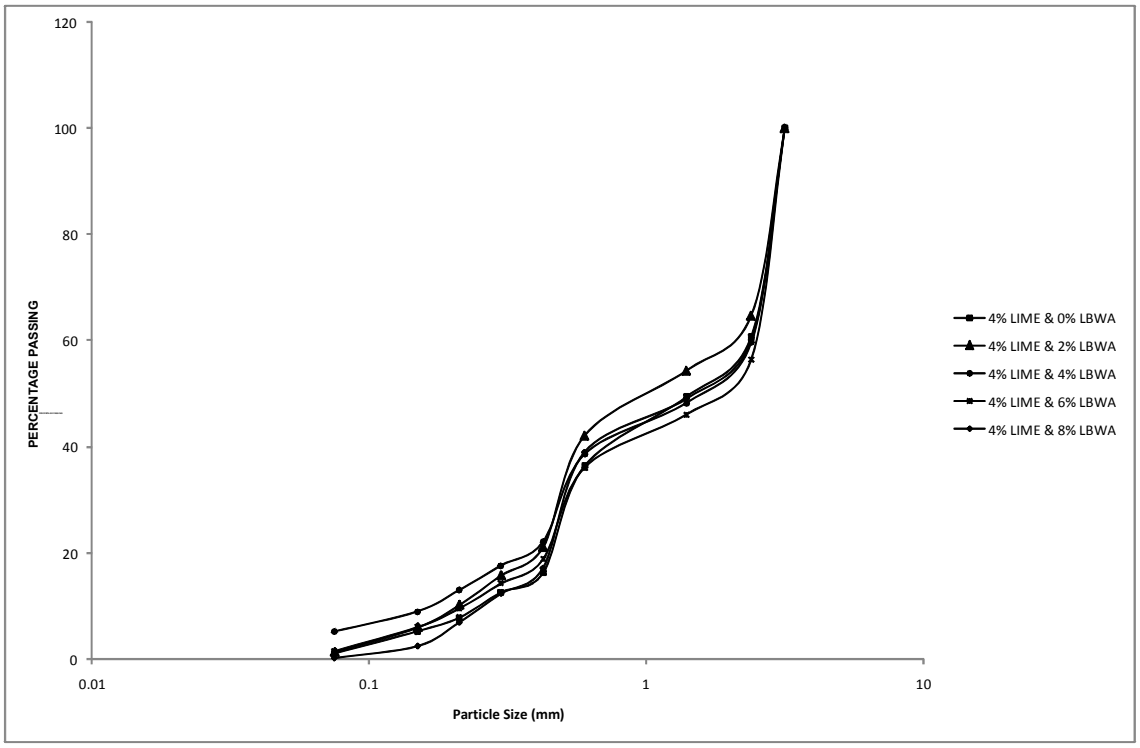

Fig.4.3 (e) Particle size distribution curves for Soil -4% lime -LBWA mixtures (BSL compaction)

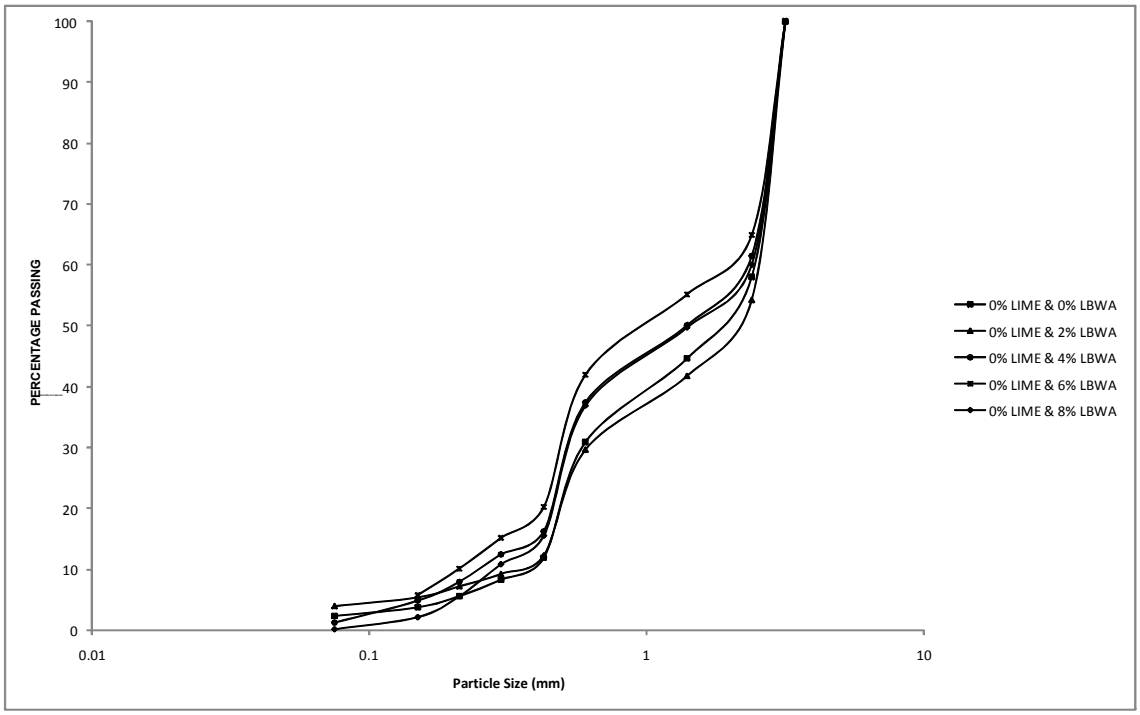

Fig.4.4 (a) Particle size distribution Curves for Soil -0% lime with Locust Bean Waste Ash (WAS compaction)

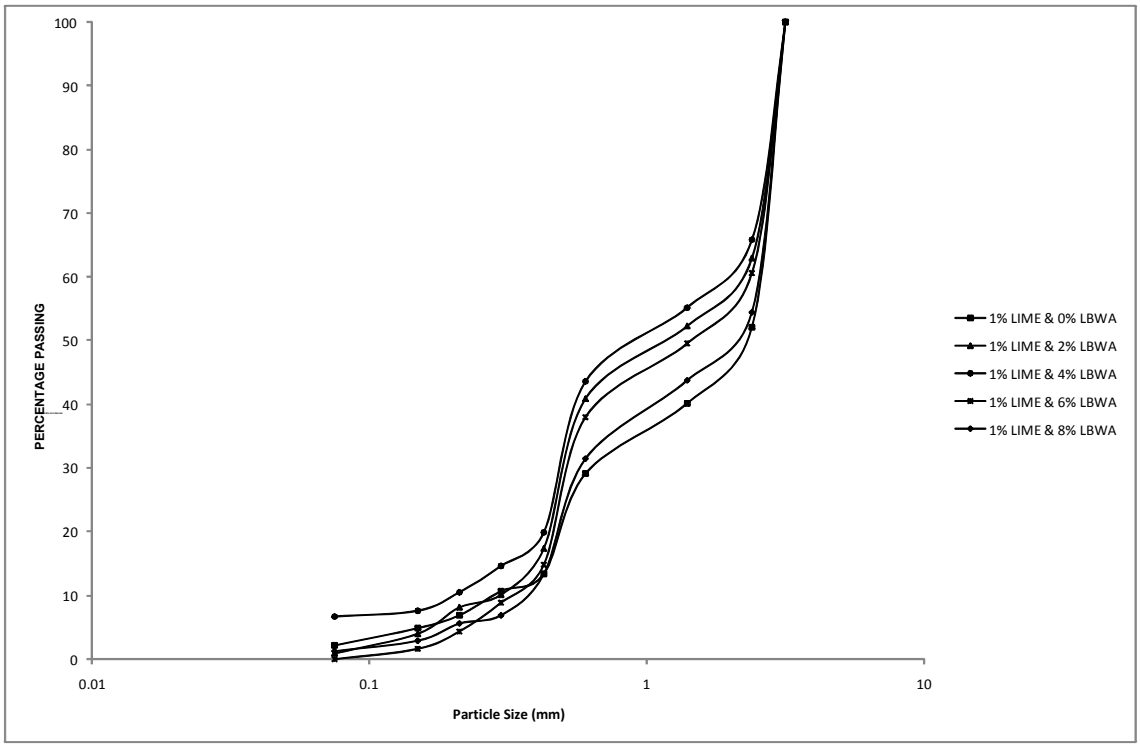

Fig.4.4 (b) Particle size distribution curves for Soil -1% lime -LBWA mixtures (WAS compaction)

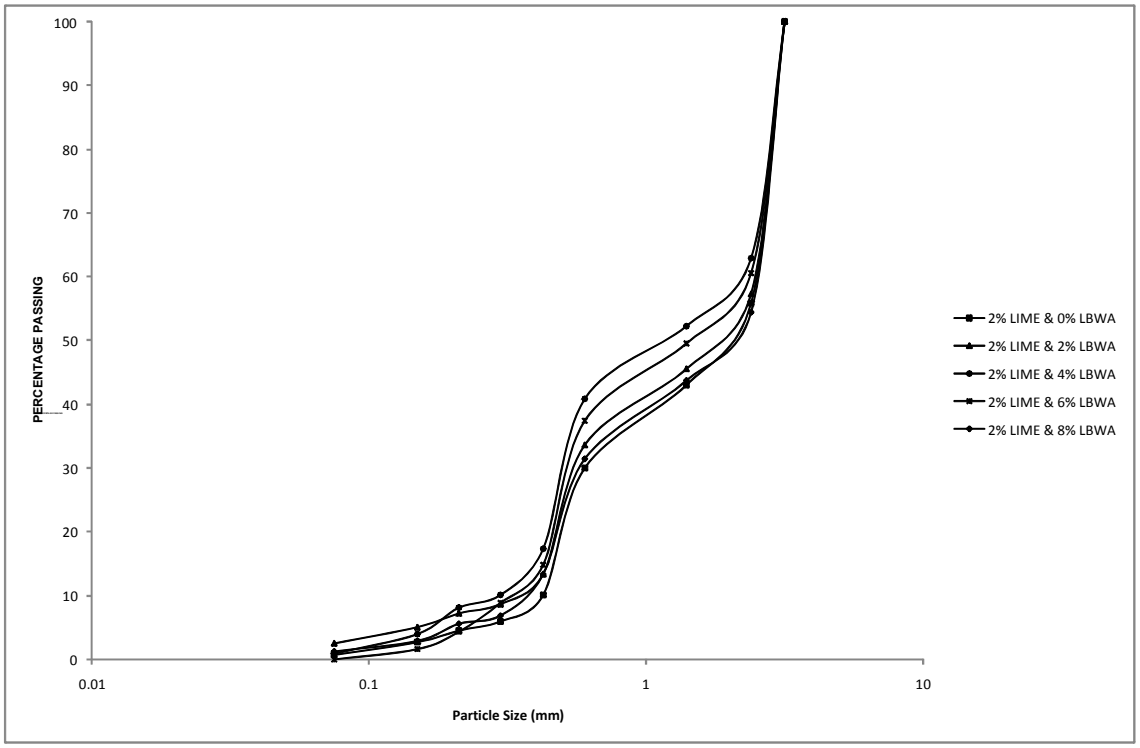

Fig.4.4(c) Particle size distribution curves for Soil -2% lime - LBWA mixtures (WAS compaction)

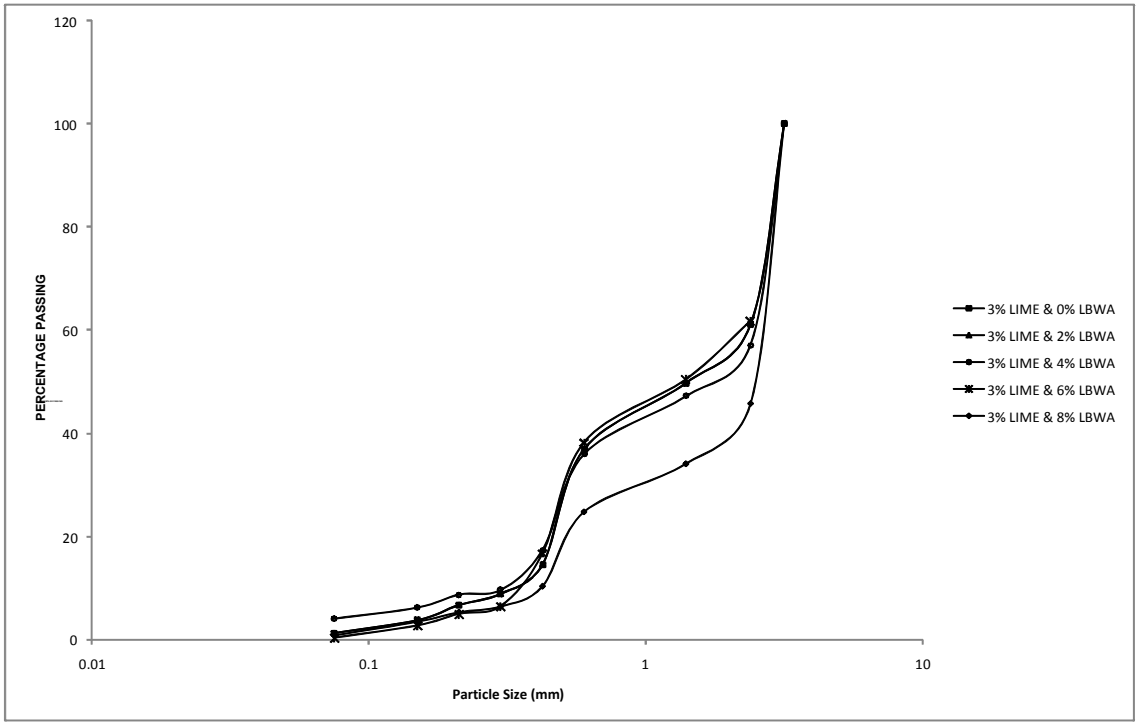

Fig.4.4 (d) Particle size distribution curves for Soil - 3% lime- LBWA mixtures (WAS compaction)

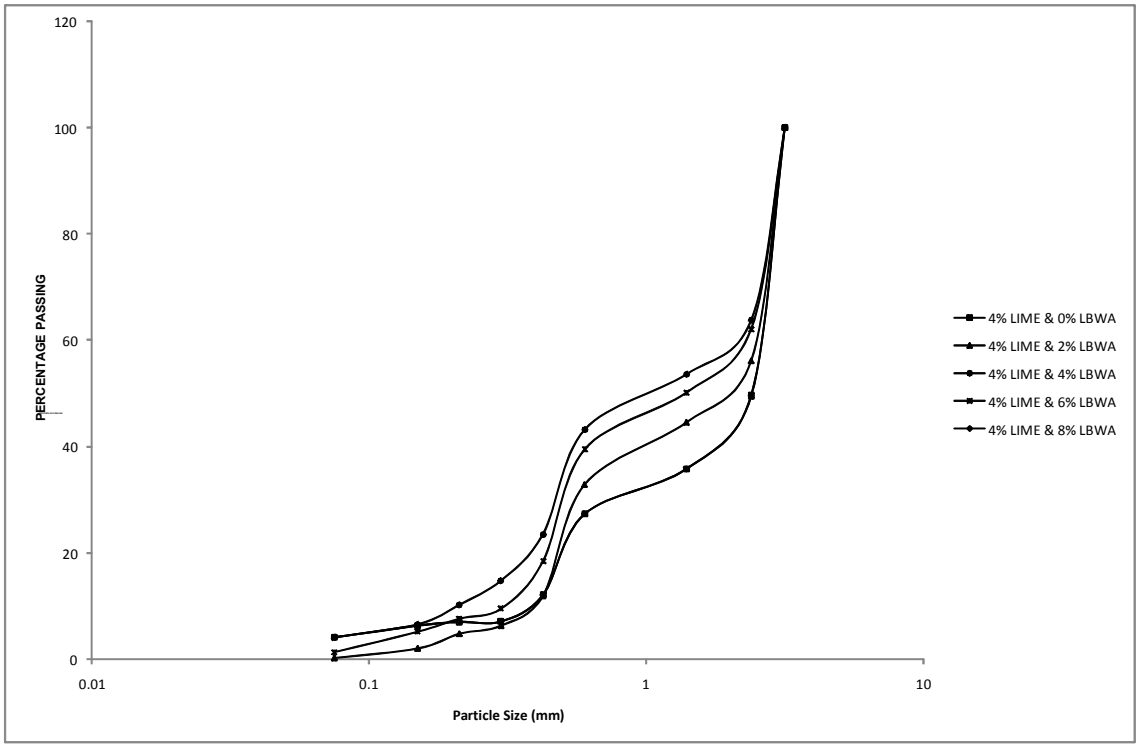

Fig.4.4 (e) Particle size distribution curves for Soil - 4% lime- LBWA mixtures (WAS compaction)

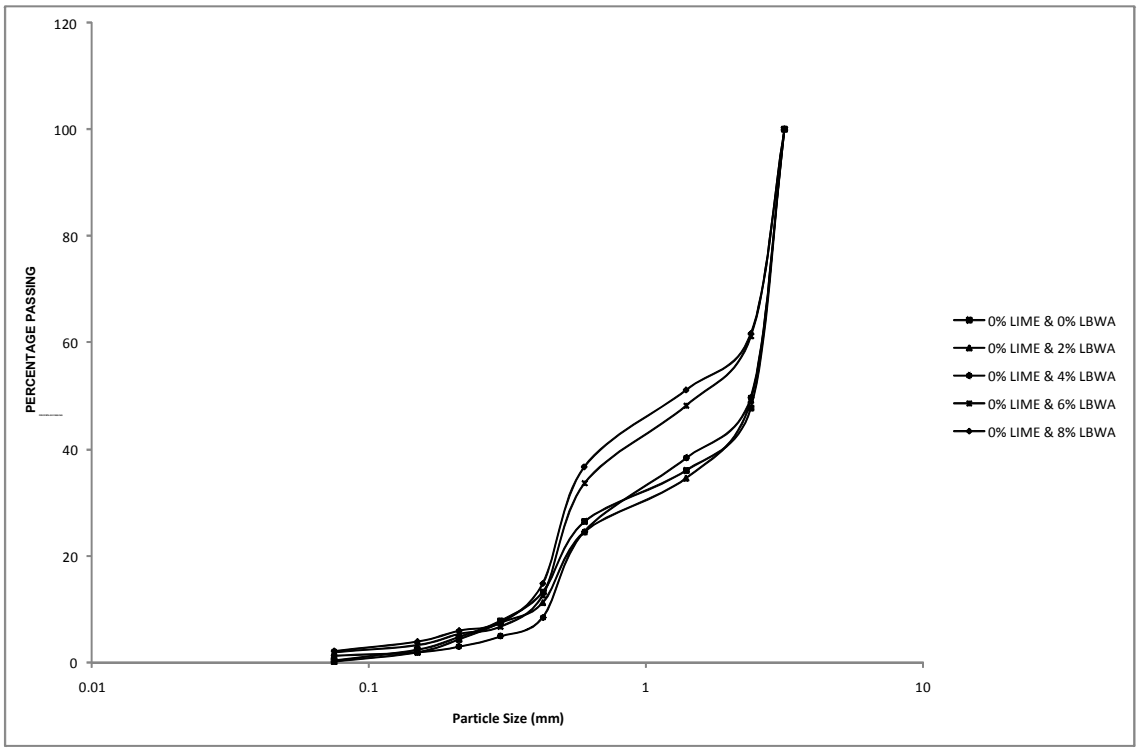

Fig.4.5 (a) Particle size distribution curves for Soil -0% lime -LBWA mixtures (BSH compaction)

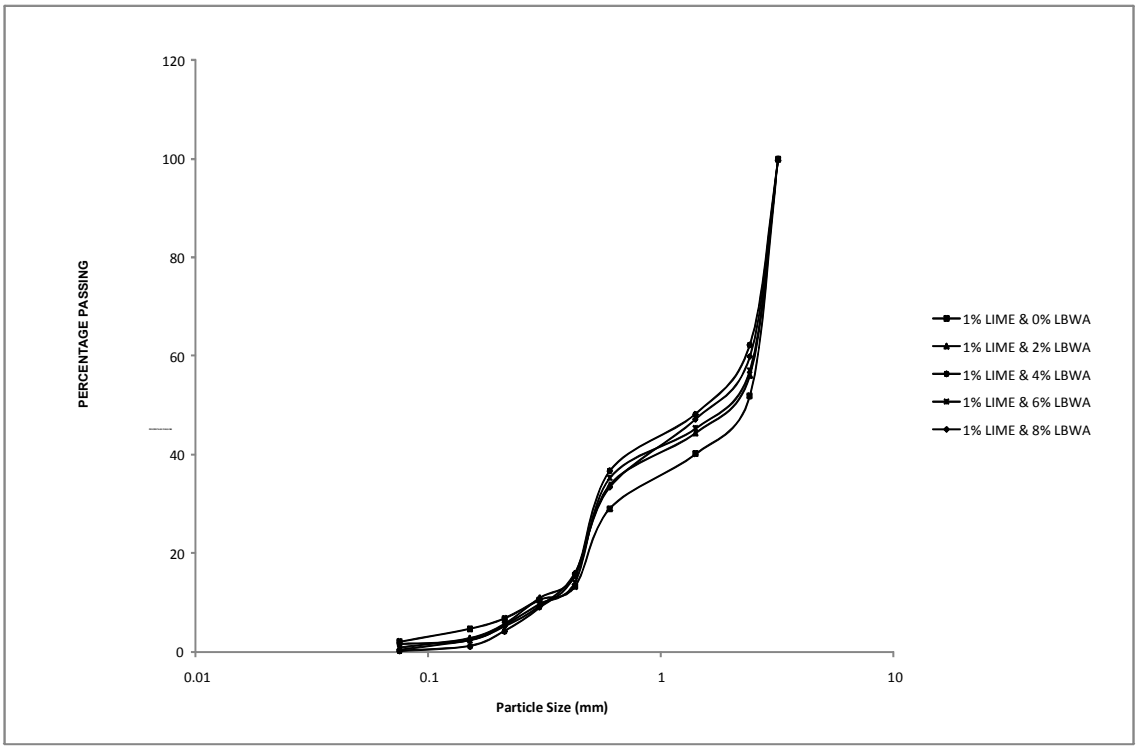

Fig.4.5 (b) Particle size distribution curves for Soil - 1% lime -LBWA mixtures (BSH compaction)

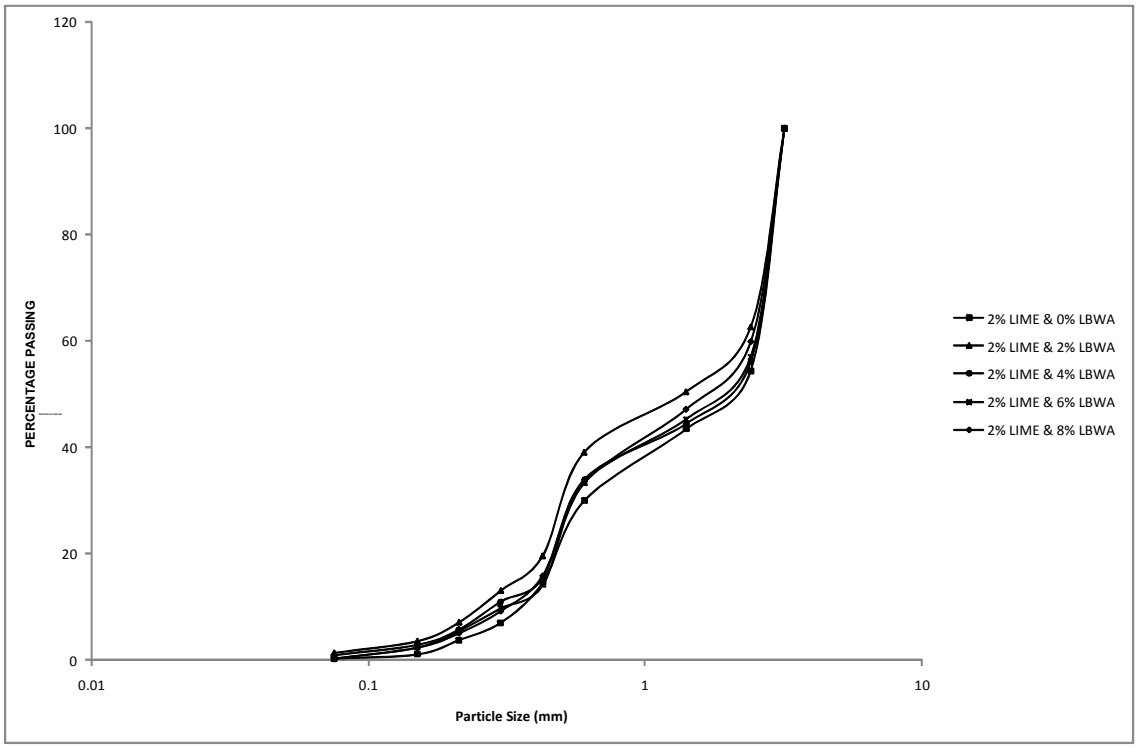

Fig.4.5(c) Particle Size Distribution Curves for Soil -2% lime –LBWA mixtures (BSH compaction)

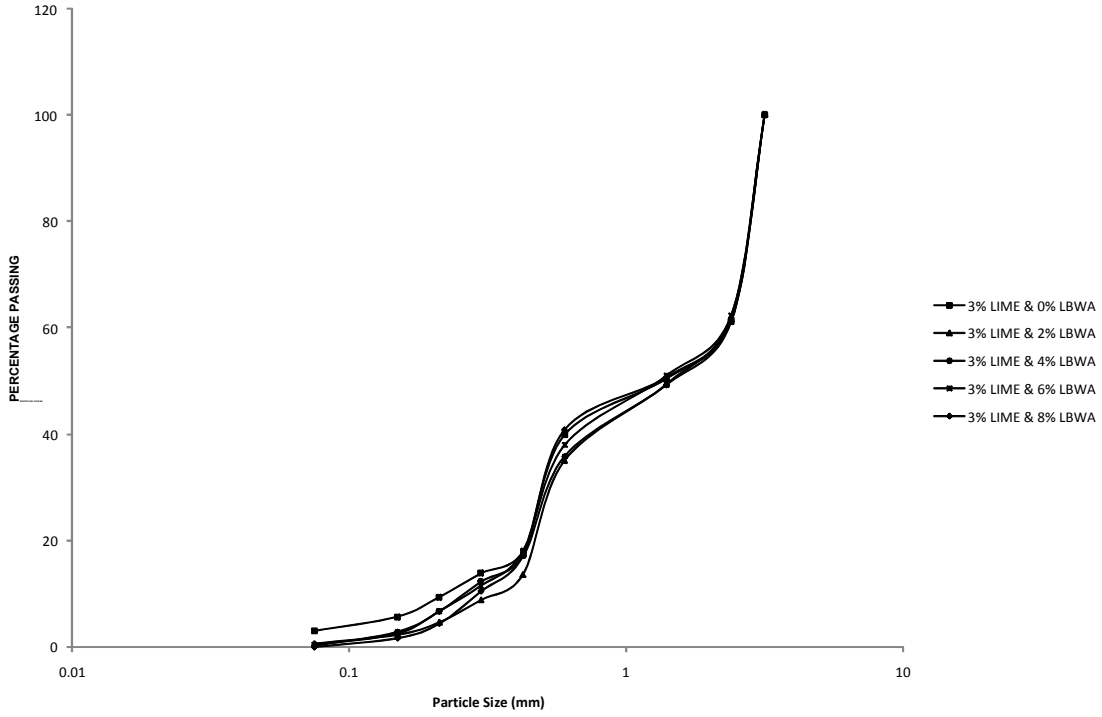

Fig.4.5 (d) Particle Size Distribution Curves for Soil - 3% lime - LBWA mixtures (BSH compaction)

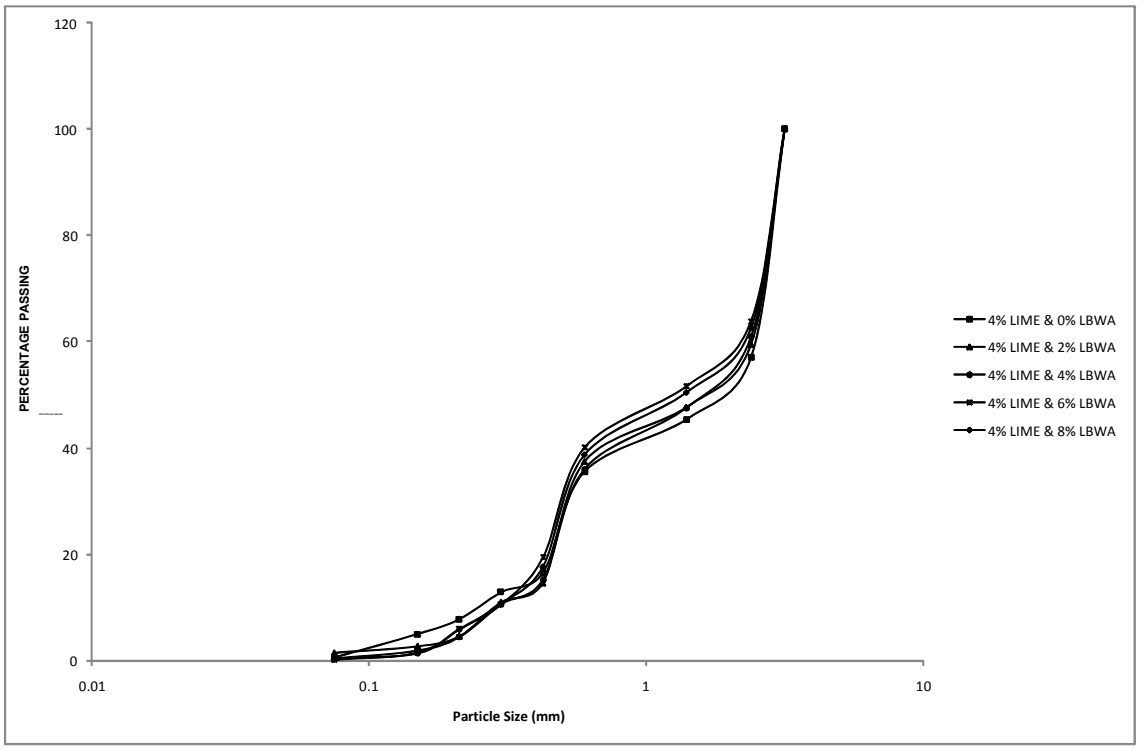

Fig.4.5 (e) Particle size distribution curves for Soil - 4% lime - LBWA mixtures (BSH compaction)

4.2.2 **Atterberg limits**

4.2.2.1 **Soil - lime mixture**

The effect of lime content on the Atterberg limits (i.e, liquid limit, LL, plastic limit, PL and plasticity index, PI, are shown in Figs 4.6, 4.7 and 4.8 for liquid limit, plastic limit, and plasticity index, respectively. The liquid limit and the plasticity index values reduced with increasing lime contents while the plastic limit increased. This trend is in line with earlier findings reported by Ola (1983), Obeahon (1993), as well as Osinubi and Katte (1997) for black cotton soils. The reduction in liquid limit with lime content can be as a result of the exchange reaction which flocculates the soil particles together and reduces the clay size fraction and hence the soil surface area Ola (1983) and Osula (1991).

4.2.2.2 **Effect of locust bean waste ash on the Atterberg limits of the lime modified soil**

The variations of the Atterberg limits with locust bean waste ash content for the soil-lime mixtures are shown in Figs. 4.6 - 4.8.

In Fig 4.6 the value of the liquid limit for the natural soil varied from 66.5% at 0% LBWA to 74.6% at 2% LBWA, and then decreased from 73.5% at 4% LBWA to 67.8% at 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content, LL reduced from 65.4%to 63.7%, 64.1% to 61.0%, 62.0% to 59.5% and 61.0% to 49.0%, respectively. The results of the analysis of variance (ANOVA) of liquid limit showed that the relative effects of lime and LBWA on black cotton soil were statistically significant (F_{Cal} = 5.12 >F_{Crit} = 3.01) for lime (F_{Cal} =26.98 > F_{Crit} = 3.01 for LBWA) .The effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the liquid limit results are shown in Table.A4.6a in the Appendix.

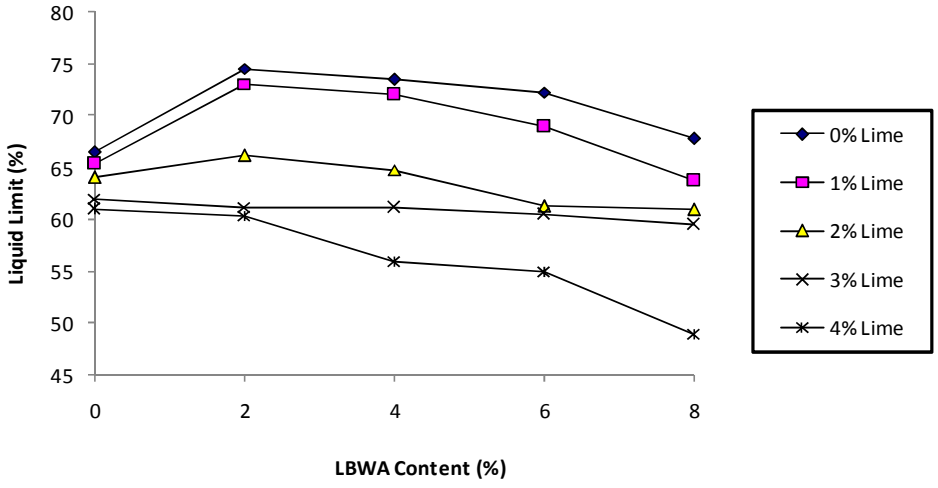

Fig.4.6 Variation of liquid limit of soil-lime mixtures with locust bean waste ash content

The liquid limit (LL) and plasticity index (PI) generally decreased with increasing locust bean waste ash content. The reduction in liquid limit with increase in locust bean waste ash contents lends more credence to the assertion of a reaction of an ion exchange nature between the lime and soil, which is enriched by the locust bean waste ash (Nicholson, 1994).

In Fig 4.7 the value of the plastic limit for the natural soil varied from 30.83% at 0% LBWA to 30.49% at 2% LBWA, and decrease from 32.5% at 4% LBWA to 31.57 % when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime, PL increased from 32.5% at 1% lime/0% LBWA to 39.9% at 1%lime/ 4%LBWA and then decreased from 37.4% at 1%lime/6%LBWA to 36.6% at 1%/lime/8%LBWA, 35% to 37.3%, 38.7 %to 40.2%and 39.1% to 37.5%, respectively. The results of the analysis of variance (ANOVA) of plastic limit showed that the relative effects of lime and LBWA on black cotton soil were statistically significant ($F_{Cal} = 12.8 > F_{Crit} = 3.01$) for lime ($F_{Cal} = 38.87 > F_{Crit} = 3.01$ for LBWA). The effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the plastic limit results are shown in Table.A4.6b in the Appendix.

The increase in plastic limit may be due to the contribution of the highly plastic nature of lime (Osinubi and Katte, 1997), the net result being an immediate increase in the plastic limit (PL) that may be unconnected with any soil-lime reactions (Osula, 1991; Osinubi and Katte, 1997).

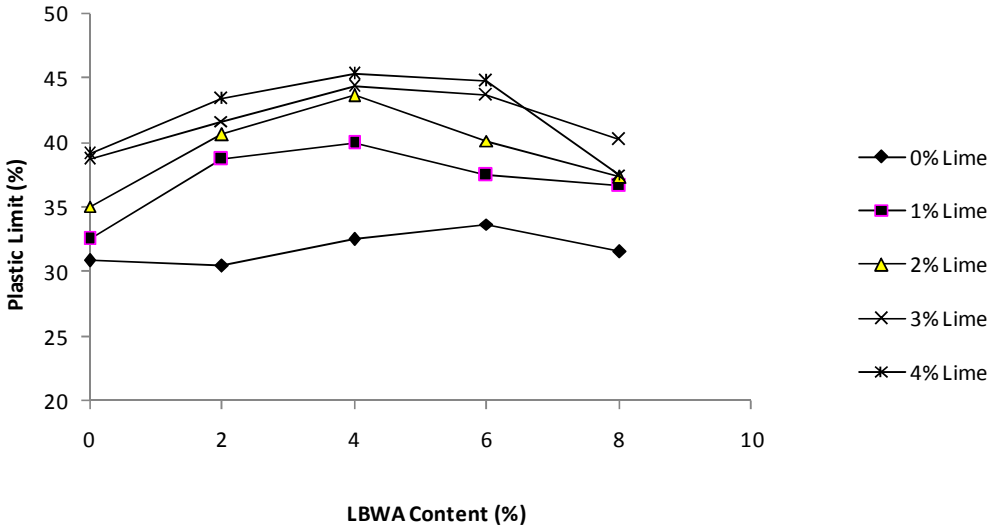

Fig.4.7 Variation of plastic limit of soil-lime mixtures with locust bean waste ash content

In Fig 4.8 the plasticity index value for the natural soil ranged from 35.7 to 36.2% when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content, PI reduced from 32.9 to 27.1%, 29.1 to 23.7%, 23.3 to 19.3% and 21.9 to 11.5%, respectively. The results of the analysis of variance (ANOVA) of plasticity index showed that the relative effects of lime and LBWA on black cotton soil were statistically significant ($F_{Cal} = 3.82 > F_{Crit} = 3.01$ for lime; ($F_{Cal} = 60.67 > F_{Crit} = 3.01$ for LBWA).The effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the plastic limit results are shown in Table A4.6c in the Appendix.

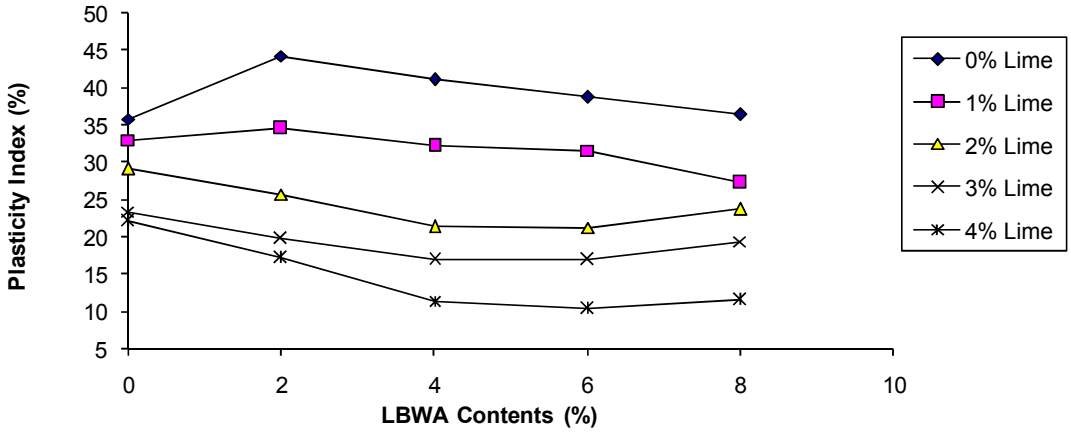

Fig.4.8 Variation of plasticity index of soil-lime mixtures with locust bean waste ash content

The results of the analysis of variance (ANOVA) carried out for the liquid limit, plastic limit and plasticity index is given in Table 4.4.

Table 4.4: Two -way analysis of variance for Atterberg limits of soil-lime - LBWA mixtures

Property	Source of Variation	d_f	F_{cal}	p-Value	F_{crit}	Remarks
Liquid Limit (LL)	Lime	4	5.12	7.50 E-02	3.01	SS
	LBWA	4	26.98	6.15E-07	3.01	SS
Plastic Limit (PL)	Lime	4	12.85	7.17E-05	3.01	SS
	LBWA	4	38.88	4.73E-08	3.01	SS
Plasticity Index (PI)	Lime	4	3.82	0.022908	3.01	SS
	LBWA	4	60.67	1.82E-09	3.01	SS

d_f – degree of freedom

4.2.3 Compaction characteristics

4.2.3.1 Soil - lime mixtures

The variations of maximum dry density (MDD) and optimum moisture content (OMC) for the lime-modified soils are shown in Figs.4.9- 4.11 and Figs.4.12-4.14 respectively. This shows higher OMC and lower MDD values with increasing lime contents for the three compaction energies considered.

4.2.3.2 Effect of locust bean waste ash on the maximum dry density (MDD) of the lime modified soil

The effects of locust bean waste ash on the maximum dry density (MDD) for the soil lime mixtures are shown in Figs.4.9, 4.10 and 4.11 for BSL, WAS and BSH compaction energy levels, respectively. The decrease in MDD with locust bean waste ash content agrees with the findings of Nicholson, (1994) as well as Chu and Kao (1993), which might be attributed to the comparatively low specific gravity of the locust bean waste ash and the enhancement of the flocculation and agglomeration of clay particles.

In Fig. 4.9 for the BSL compactive effort, the value of the MDD of the natural soil varies from 1.3to 1.37 Mg/m^3 when treated with 0 to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values varied from 1.37 to1.34Mg/m^3, 1.43 to 1.36 Mg/m^3, 1.45 to 1.37 Mg/m^3 and 1.48 to 1.39 Mg/m^3, respectively. The results of the analysis of variance (ANOVA) of the MDD of the BSL compaction showed that the relative effects of lime and LBWA on black cotton soil were statistically significant (F_{Cal} =16.04 > F_{Crit} = 3.01) for lime (F_{Cal} = 25.56 > F_{Crit} = 3.0 for LBWA) The

effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the MDD test results for BSL compaction is shown in Table.A4.7a in the Appendix.

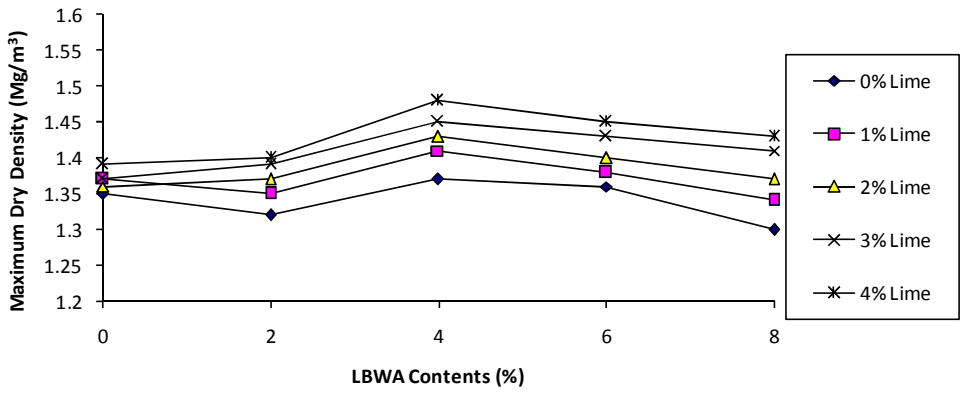

Fig.4.9 Variation of maximum dry densities of soil-lime mixtures with locust bean waste ash content (BSL compaction)

In Fig 4.10 for the WAS compactive effort, the value of the MDD of the natural soil varied from 1.36 to 1.47 Mg/m^3 when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values reduced from 1.5to 1.37 Mg/m^3, 1.53 to 1.37 Mg/m^3, 1.56 to 1.4 Mg/m^3 and 1.59 to 1.43 Mg/m^3, respectively. The results of the analysis of variance (ANOVA) of the MDD of the WAS compaction confirmed a significant effect of hydrated lime ($F_{Cal} = 43.02 > F_{Crit} = 3.01$) and LBWA increments ($F_{Cal} = 30.39 > F_{Crit} = 3.01$) on the black cotton soil, with more significant effects with the addition of LBWA on the modified soil. Details of the MDD test results for WAS are shown in Table.A4.7b.

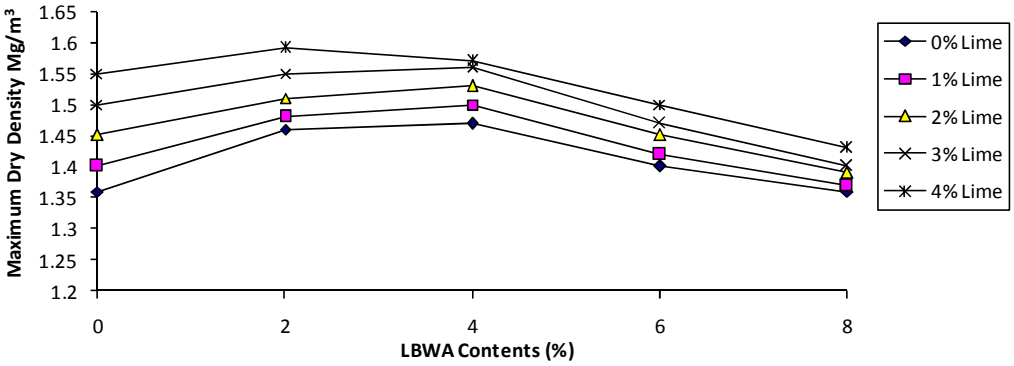

Fig.4.10 Variation of maximum dry densities of soil-lime mixtures with locust bean waste ash content (WAS compaction)

In Fig 4.11 for the BSH compactive effort, the value of the MDD of the natural soil varied from 1.43 to 1.50 Mg/m^3 when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values reduced from 1.55 to 1.45 Mg/m^3, 1.58 to 1. 47 Mg/m^3, 1.6 to 1.51 Mg/m^3 and 1.62 to 1.55 Mg/m^3, respectively. The results of the analysis of variance (ANOVA) of the MDD of BSH compaction showed that the relative effects of lime and LBWA on black cotton soil were statistically significant (F_{Cal} = 18.33 > F_{Crit} = 3.01) for lime (F_{Cal} = 36.36 > F_{Crit} = 3.01 for LBWA). The effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the MDD test results for BSH is shown in Table.A4.7c in Appendix.

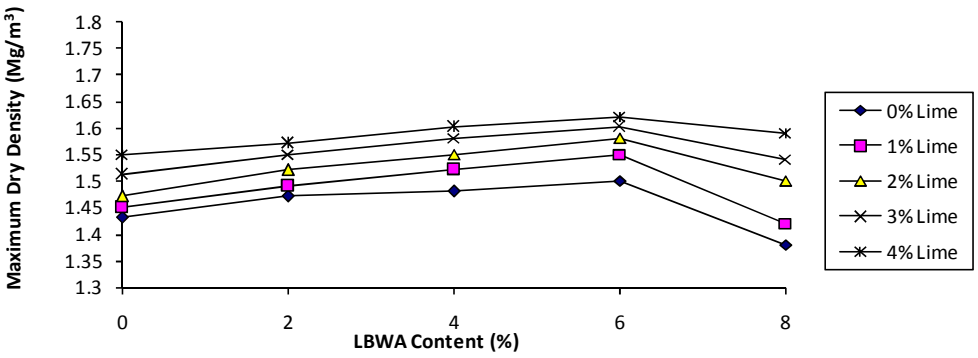

Fig.4.11 Variation of maximum dry densities of soil-lime mixtures with locust bean waste ash content (BSH compaction)

Comparison of the trend of the MDD for the three compaction energy levels considered show that lower MDD were recorded at the BSL energy level. Generally, MDD increased with higher LBWA contents for all the compactive efforts considered.

4.2.3.3 **Effect of locust bean waste ash on Optimum Moisture Content (OMC) of the modified soil**

The variations of the OMC with locust bean waste ash content are shown in Figs.4.12 -4.14 for the three energy levels, respectively, The increasing OMC with increasing lime content is not in line with what is expected with increasing grain size and hence decreasing surface area. The reason is that, the increasing affinity for water is needed for the dissociation of lime into Ca and OH ions to supply more cations for the cation exchange reaction (Ola, 1983 and Osula, 1991).

The variation of optimum moisture content (OMC) of lime modified soil with locust bean waste ash for BSL, WAS and BSH compactions are shown in

Figures 4.12 -4.14 respectively. Generally, OMC increased with higher LBWA contents for all the compactive efforts considered.

In Fig 4.12 for the BSL compactive effort, the OMC of the natural soil varied from 16.0% to 17.4% when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values increased from 16.5 to 19.8%, 17.1 to 20.9%, 17.7 to 20.0% and 19.6 to 23.1%, respectively. The results of the analysis of variance (ANOVA) of the MDD of the BSL showed that the relative effects of lime and LBWA on black cotton soil were statistically significant ($F_{Cal} = 24.04 > F_{Crit} = 3.01$) for lime ($F_{Cal} = 59.14 > F_{Crit} = 3.01$ for LBWA) . The effect of LBWA on black cotton soil was more pronounced than that of lime. Details of the MDD test results for BSL compaction are shown in Table.A4.7d.

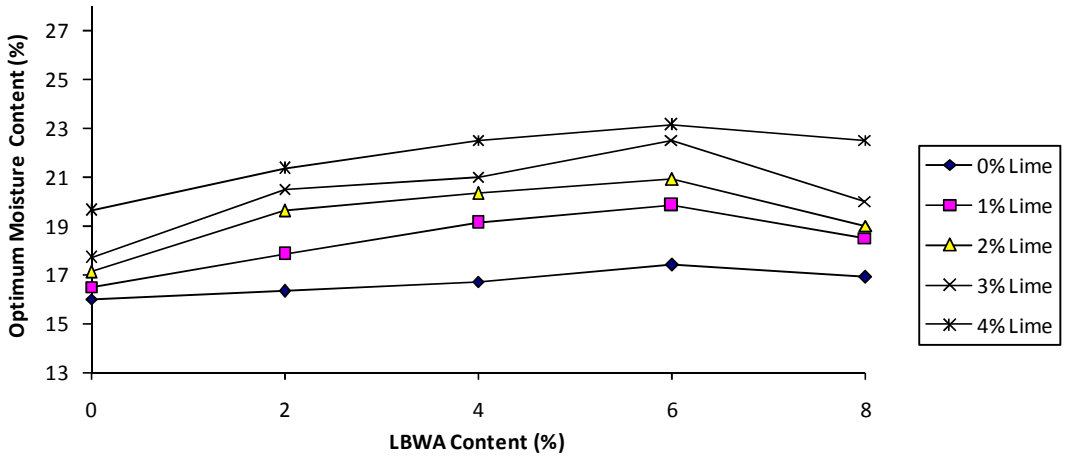

Fig.4.12 Variation of optimum moisture content of soil-lime mixtures with locust bean waste ash content (BSL compaction)

In Fig 4.13 for the WAS compactive effort, the OMC of the natural soil varied from 17.3% to 23.2% when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values increased from 18.3 to 25.8%, 19.0 to 26.0%, 20.5 to 27.8% and 21.3 to 28.7%, respectively. The results of the analysis of variance (ANOVA) of the MDD of WAS compaction confirmed a significant effect of hydrated lime (F_{Cal} = 239.43 >F_{Crit} = 3.01**)** and LBWA increments (F_{Cal} = 88.09 >F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the addition of LBWA on the modified soil. Details of the OMC test results for the WAS compaction are shown in Table.A4.7e.

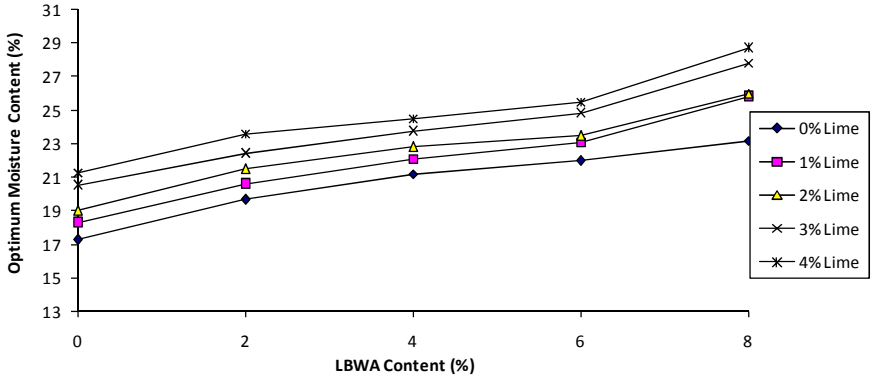

Fig.4.13 Variation of optimum moisture content of soil-lime mixtures with locust bean waste ash content (WAS compaction)

In Fig 4.14 for the BSH compactive effort, the OMC of the natural soil varied from 16.2% to 18.0% when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content the values increased from 16.5 to 19.0%, 16.7 to 19.9%, 17.0 to 21.3% and 17.2 to 24%, respectively. The results of the analysis of variance (ANOVA) of the OMC of the BSH compaction confirmed a significant effect of hydrated lime (F_{Cal}

=15.40 > F_{Crit} = 3.01) and LBWA increments (F_{Cal} = 21.32 > F_{Crit} = 3.01) on the black cotton soil, with more significant effects with the addition of LBWA on the modified soil. Details of the OMC test results for BSH is shown in Table.A4.7f.

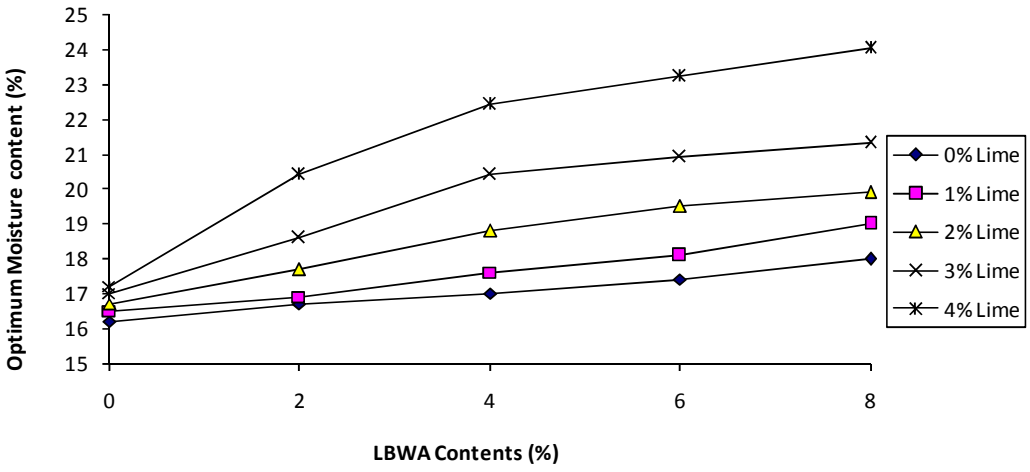

Fig.4.14 Variation of optimum moisture content of soil-lime mixtures with locust bean waste ash content (BSH compaction)

The results of the analysis of variance (ANOVA) of the MDD and OMC for the three energy levels is given in Table 4.5

Table 4.5: Two-way analysis of variance for compaction characteristics of soil-lime - LBWA mixtures

Property		Source of Variation	df	F_{cal}	p-Value	F_{crit}	Remarks
BSL	MDD	Lime	4	16.04	1.80E-05	3.01	SS
		LBWA	4	25.56	8.90E-07	3.01	SS
	OMC	Lime	4	24.04	1.35E-06	3.01	SS
		LBWA	4	59.14	2.2E-09	3.01	SS
WAS	MDD	Lime	4	43.02	2.28E-08	3.01	SS
		LBWA	4	30.39	2.70E-07	3.01	SS
	OMC	Lime	4	230.43	4.71E-14	3.01	SS
		LBWA	4	88.09	1.10E-10	3.01	SS
BSH	MDD	Lime	4	18.34	8E-06	3.01	SS
		LBWA	4	36.36	7.65E-08	3.01	SS
	OMC	Lime	4	15.40	2.40E-05	3.01	SS
		LBWA	4	21.33	3.0E-06	3.01	SS

d_f – degree of freedom

4.2.4 Shear strength parameters

4.2.4.1 Soil-lime mixtures

The effects of lime content on the cohesion and angles of internal friction, for the compaction energy levels used in this study are shown in Figs.4.15-4.17. This indicated cohesion reducing, while the angle of internal friction increased

with increasing lime content. This was as a result of the reduction in clay size fraction, a consequence of ion exchange reaction (Osula, 1991).

The trend of the increased angle of internal friction with increase lime content is in agreement with Fossberg (1965), Lees et at (1982), Osula (1991) and Osinubi (1995), while the reducing trend of cohesion with increasing lime content agrees with Osula (1991), The reduction in cohesion could be associated with the breakdown of the weak forces holding the clay particles together to form stronger bonds thereby reducing the cohesive nature of the natural soil.

4.2.4.2 **Effect of locust bean waste ash on the cohesion (c) of the lime modified black cotton soil**

The variation of cohesion with LBWA content for the three compaction energies are shown in Figs.4.15-4.17 for BSL, WAS and BSH compactive efforts respectively, while the variation of angle of internal friction with LBWA are shown in Figs. 4.18- 4.20 for BSL, WAS and BSH compaction energy levels, respectively.

In Fig 4.15 for the BSL compaction, values of cohesion of the natural soil varied from 165 to 80 kN/m^2 when treated with 0 to 8% LBWA content. The values reduced from 140 to 100kN/m^2, 139 to 70kN/m^2, 150 to 97kN/m^2 and 125 to 79kN/m^2, respectively when treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content. Analysis of variance (ANOVA) of the cohesion test results for BSL is given in Table 4.6.The results also confirmed a significant effect of hydrated lime (F_{Cal} = 29.47 >F_{Crit} = 3.01**)** and LBWA increments (F_{Cal} = 7.08 >F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the

addition of LBWA on the modified soil. Details of the cohesion test results are shown in Table.A4.8a in the Appendix.The cohesion was reduced by addition of the locust bean waste ash. This was as a result of the enhancement of the ion exchange reaction between the lime and soil, which was further enriched with silica from the locust bean waste ash.

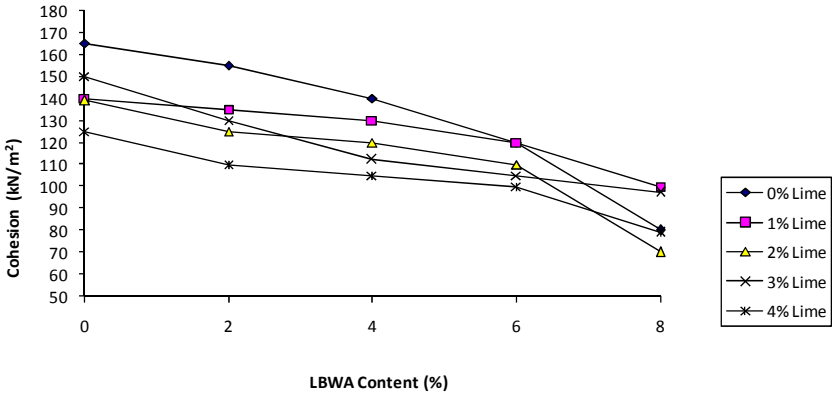

Fig.4.15 Variation of cohesion of soil-lime mixtures with locust bean waste ash content (BSL compaction).

In Fig 4.16 for the WAS compaction, values of cohesion of the natural soil varied from 178 to 80kN/m^2 when treated with 0 to 8% LBWA content. The values reduced from 145 to 110kN/m^2, 150 to 105kN/m^2, 150 to 95kN/m^2 and 140 to 100 kN/m^2 respectively, when treated with 1, 2, 3 and 4% lime and with 0 to 8% LBWA content. Analysis of variance (ANOVA) of the cohesion results for WAS is given in Table 4.6. The results confirmed a significant effect of hydrated lime (F_{Cal} = 41.16 >F_{Crit} = 3.01) and LBWA increments (F_{Cal} = 14.82 >F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the addition of LBWA on the modified soil. Details of the cohesion results is shown in Table.A4.8b in the Appendix.

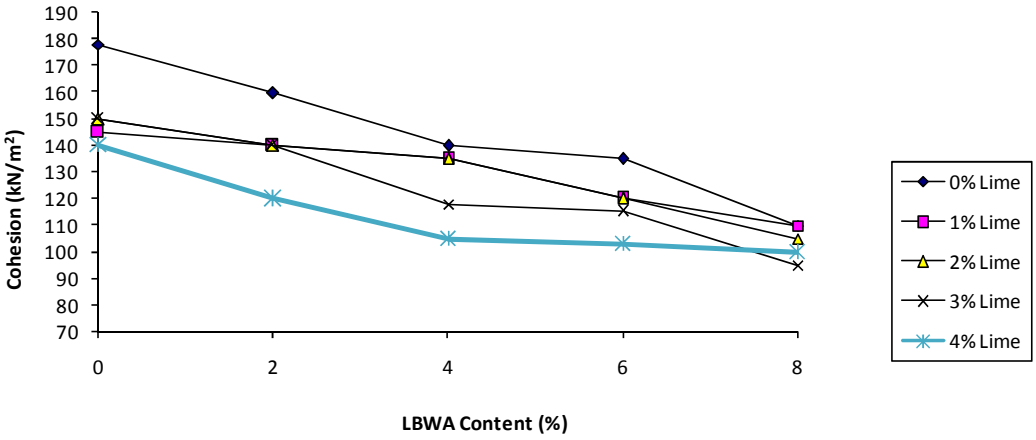

Fig.4.16 Variation of cohesion of soil-lime mixtures with locust bean waste ash content (WAS compaction).

In Fig 4.17 for the BSH compaction, values of cohesion of the natural soil varied from 160 to 120kN/m^2 when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values reduced from 145 to 110kN/m^2, 160 to 90kN/m^2, 155 to 78kN/m^2 and 160 to 80kN/m^2, respectively. The cohesion was observed to reduce with increase in locust bean waste ash and lime contents..The results of the analysis of variance (ANOVA) of the cohesion of the BSH compaction also confirmed a significant effect of hydrated lime (F_{Cal} = 21.13> F_{Crit} = 3.01**)** and LBWA increments (F_{Cal} = 8.77>F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the addition of LBWA on the modified soil. Details of the cohesion results are shown in Table.A4.8c in the Appendix.

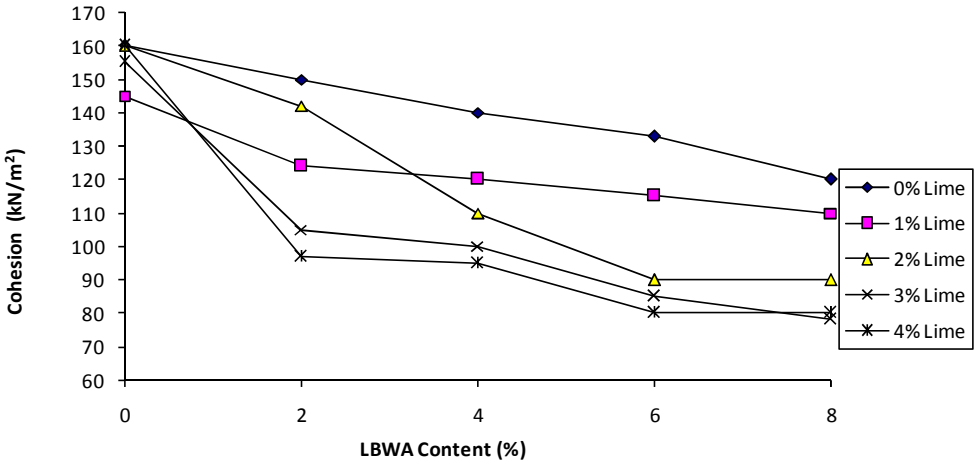

Fig.4.17 Variation of cohesion of soil- lime mixtures with locust bean waste ash content (BSH compaction).

4.2.4.3 **Effect of locust bean waste ash on the Angle of internal friction of the lime modified black cotton soil**

The effect of locust bean waste ash content on the angle of internal friction of the lime modified soil are shown in Figure 4 .18 - 4.20 for BSL, WAS and BSH compactive effort respectively. Generally, angle of internal friction increased with higher LBWA contents for all the compactive efforts considered

The angle of internal friction also increased with increase in the locust bean waste ash content, the increase being the result of the increase in the particle sizes (as can be seen with particle size distribution curves) and reduction in the clay content of the soil. This increase in strength is in agreement with Nixon and Skipp, (1957), Little (1967) and Osinubi (2001a).

The trend of variations in the cohesion and angle of internal friction with locust bean waste ash contents are similar for the three compaction energy levels considered. The higher values of cohesion and angle of internal friction recorded at the WAS and BSH compaction levels were due to the relatively

higher compactive efforts applied. Generally, cohesion reduced with higher LBWA contents for all the compactive efforts considered.

In Fig 4.18 for the BSL compaction, values of angle of internal friction of the natural soil varied from 13.5 to 19^{O} when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values increased from 14.5 to 20^{O}, 15 to 20.5^{O}, 16 to 22^{O} and 16.5 to 23.5^{O}, respectively. The results of the analysis of variance (ANOVA) of the angle of internal friction of the BSL compaction also confirmed a significant effect of hydrated lime (F_{Cal} = 152.14 >F_{Crit} = 3.01) and LBWA increments (F_{Cal} = 39.03 >F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the addition of LBWA on the modified soil. Details of the angle of internal friction for BSL compaction results is shown in Table A4.8a.

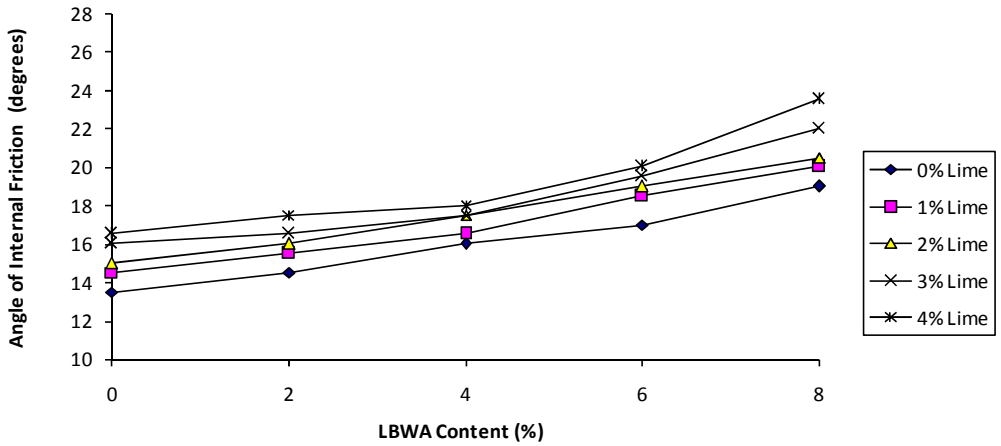

Fig.4.18 Variation of angle of internal friction of soil-lime mixtures with locust bean waste ash content (BSL compaction).

In Fig 4.19 for the WAS compaction, values of angle of internal friction of the natural soil varied from 12 to 19.5^{O} when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values increased from 14 to 21^{O}, 15 to 22^{O}, 15 to 22.5^{O} and16 to 23.5^{O}, respectively.

in Table 4.6.The results of the analysis of variance (ANOVA) of the angle of internal friction of the WAS compaction confirmed a significant effect of hydrated lime (F_{Cal} = 111.08 >F_{Crit} = 3.01) and LBWA increments (F_{Cal} = 41.53 >F_{Crit} = 3.01) on the black cotton soil, with less significant effects with the addition of LBWA on the modified soil. Details of the angle of internal friction for the WAS compaction results is shown in Table A4.8b in the Appendix.

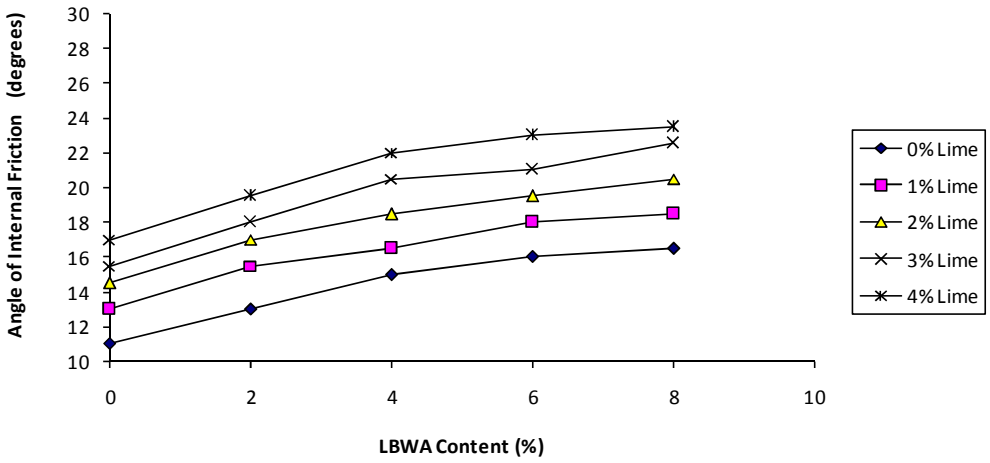

Fig.4.19 Variation of angle of internal friction of soil-lime mixtures with locust bean waste ash content WAS compaction).

In Fig 4.20 for the BSH compaction, values of angle of internal friction of the natural soil varied from 11 to 16.5^{O} when treated with 0 to 8% LBWA content. When treated with 1, 2, 3 and 4% lime and 0 to 8% LBWA content the values

increased from 13 to 18.5^{O}, 14.5 to 20.5^{O}, 15.5 to 22.5^{O} and 17 to 23.5^{O}, respectively. The results of the analysis of variance (ANOVA) of the angle of internal friction of the BSH compaction showed that the effect of LBWA on black cotton soil was more pronounced than that of lime. (F_{Cal} = 245.18 >F_{Crit} = 3.01) for lime (F_{Cal} = 282.33 >F_{Crit} = 3.01 for LBWA). Details of the angle of internal friction for the BSH compaction results are shown in Table A4.8c in the Appendix.

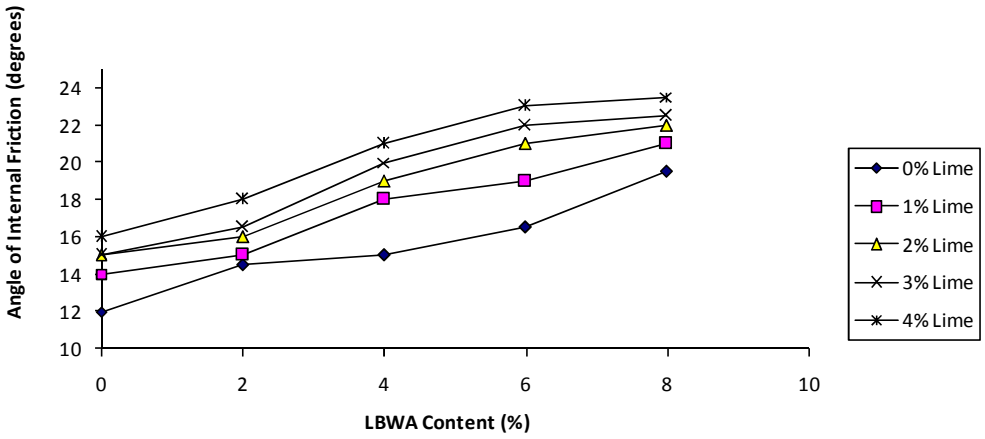

Fig.4.20 Variation of angle of internal friction of soil-lime mixtures with locust bean waste ash content (BSH compaction).

The decrease in cohesion could be attributed to reduction in the clay fraction which resulted from the cation exchange reaction. Cohesion is proportional to the quantity of fines i.e. the lower the quantity of fines the lower the cohesion of the lateritic soil sample, as the lime and LBWA increased, the quantity of fines decreased thereby decreasing the cohesion of the soil (Bello, 2006)

The locust bean waste ash reduced the cohesion while increasing the angle of internal friction. The increases are due to weak bonds formed between the clay mineral surface and the water molecules. The formation of these bonds resulted in an increase in strength with the passage of time (Akinmade, 2008). However, the increase in strength could also be attributed to the presence of iron oxide (goethite) which dehydrates with time to yield higher strength in agreement with Nixon and Skipp, (1957), Little (1967) and Osinubi (2001a). In general, the values of cohesion decreased while the angles of internal friction increased. These observations give indication of improved shear strength of the modified soil.

The results of the analysis of variance (ANOVA) of the Cohesion and the angle of internal friction is given in Table 4.6.

Table 4.6: Two way analysis of variance for shear strength parameters of soil-Lime-LBWA mixtures

Property		Source of Variation	df	F_{cal}	p-value	F_{crit}	Remarks
BSL	Cohesion (C)	Lime	4	29.47	3.35E-07	3.01	SS
		LBWA	4	7.08	1.77E-03	3.01	SS
	Friction angle Ɵ	Lime	4	152.14	1.63E-12	3.01	SS
		LBWA	4	39.03	4.60E-08	3.01	SS
WAS	Cohesion (C)	Lime	4	41.16	3.14E-08	3.01	SS
		LBWA	4	14.83	3.03E-05	3.01	SS
	Friction angle Ɵ	Lime	4	111.08	1.86E-11	3.01	SS
		LBWA	4	41.54	2.94E-08	3.01	SS
BSH	Cohesion (C)	Lime	4	21.14	3.18E-06	3.01	SS
		LBWA	4	8.77	6.01E-04	3.01	SS
	Friction angle Ɵ	Lime	4	245.18	3.91E-14	3.01	SS
		LBWA	4	382.33	1.29E-14	3.01	SS

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The following conclusions can be drawn from the results of the study/investigation carried out on the effect of locust bean waste ash on lime-modified black cotton soil within the scope of the study.

i) The black cotton soil used in the study was classified as an A-7-6(24) soil based on the AASHTO soil classification system or CH in the Unified Soil Classification System. It is highly clayey with 75.5% of the natural soil passing the BS No. 200 sieve. The natural soil has moisture content of 35%, liquid limit of 66.5%, plastic limit of 30.8%, and plasticity index of 35.7%.

ii) The particle sizes of the fines fraction increased and the gradation of the lime-modified soil improved with higher LBWA content for all the energy levels (BSL,WAS,BSH) considered. The decrease in percentage passing 0.075mm (sieve No 200) aperture sieve met the limits set by the Nigerian General Specifications (1997), which specifies a percentage of fines passing through sieve with aperture size 0.075mm (sieve No 200) not exceeding 35% for subbase and base courses.

The liquid limit (LL) and plasticity index (PI) decreased while plastic limit value increased with increase in lime content. The liquid limit value for the natural soil ranged from 66.5% to 74.6% when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content, LL reduced from 65.4%to 63.7%, 64.1% to 61.0%, 62.0% to 59.5% and 61.0% to 49.0%, respectively. The effect of LBWA on black cotton soil was more pronounced than that of lime.

The plastic limit value for the natural soil ranged from 30.8% to 31.6% treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content, PL increased from 32.5 to 36.6%, 35% to 37.3%, 38.7% to 40.2%and 39.1% to 37.5%, respectively. The results of the two –way analysis of variance carried out showed that the effect of LBWA on black cotton soil was more pronounced than that of lime.

The plasticity index value for the natural soil ranged from 35.7 to 36.2% when treated with up to 8% LBWA content. On treatment with 1, 2, 3 and 4% lime and up to 8% LBWA content, PI reduced from 32.9 to 27.1%, 29.1 to 23.7%,23.3 to19.3% and 21.9 to 11.5%, respectively. The results obtained from the two –way analysis of variance carried out showed that the effect of LBWA on black cotton soil was more pronounced than that of lime

iii) The optimum moisture content (OMC) increased with increasing locust bean ash content while the maximum dry density (MDD) values

decreased with increased locust bean ash content. The trend of the MDD was similar with findings of Osinubi (1997).

iv) The shear strength characteristics, the cohesion of the modified soils decreased while the angle of internal friction increased for the various energy levels considered with increase in LBWA.

v) Based on the Nigerian General Specifications (1997) requirements, the modified soil with 4%lime/8% LBWA met the value of not more than 35% passing sieve No.200(0.075mm aperture) and 12% maximum plasticity index value for use as subgrade material.

5.2 **Recommendation**

The results of this study conducted showed that the optimal mix ratio of 4 % lime and 8%Locust bean waste ash can be used effectively to modify the black cotton soil for use in road construction works.

REFERENCES

AASHTO (1986). *Standard Specification for Transportation, Material and Methods of Sampling and Testing. 14th Edition.* Amsterdam Association of State Highway and transportation official Washington D.C.

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

Akinmade O. B. (2008). *Stabilization of Black Cotton Soil with Locust Bean Waste Ash*. Unpublished M.Sc. thesis, Civil Engineering Department Ahmadu Bello University Zaria, Nigeria.

Akintola F.A (1982). "*Geology and Geomorphology* In *Nigeria in Map*." Edited by K.M. Barhous, Hodder and Stoughton London".

Areola O. (1982). *Soils`* In *Nigeria in Maps*. Edited by K.M. Barhous Hodder and Stoughton London.

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

ASTM C618 - 78 (1978). *Specification for Fly Ash and Raws or Calcined Ntaural Pozzolanas for Use as a Mineral Admixure in Portland Cement Concrete*. American Society for Testing and Materials, Philadelphia.

Attom, F.M., Taqieddin, S. A., and Mubeideen, T. (2000) "Shear strength and swelling stabilization of unsaturated clayey soil using pozzolanic material". *Proceeding of Sessions of Geo-Denver*, Geo. Spec. Pub. No. 909 ASCE. pp275-281.

Binkley, D and Sollins. P (1990).Factors determining differences in Soil pH in adjacent conifer and alder conifer stands. *Soil Science Society of America Journal.No.54, pp1427-1433.*

Bello A.O. (2006). *"Effect of Fines Content on the Compressive Strength and Undrained Shear Strength parameters of Reconstituted Lateritic Soils*". Unpublished B.Eng Project submitted to the Dept. of Civil Engineering, Ahmadu Bello University Zaria. pp72.

Binkley,D.,Dunkin,K.A,Debell,D, and Ryan,M.G (1992). Production and Nutrient cycling in mixed plantation of Eucalyptus and Albizia in Hawaii. Forest Science.No.38, pp393-408

Brady,N.C. and Weil,R. (2002). *The Nature and Properties of Soils,* 13th Ed. Prentice Hall Inc New Jersey, USA 960p

Brown, R.W. (1996). "*Practical Foundation Engineering Handbook* Mc - Graw Hill, New York

BS 1377(1990). *Method of Testing Soil for Civil Engineering Proposes*, British Standard Institute, BS I, London.

BS 1924(1990). *Method of Test for Stabilized Soils*, British Standard Institute, BSI, London.

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

Chu. Shi-Chi and Kao, Hsiang (1993). " A study of engineering properties of a clay modified by fly ash slag*."* In*: Fly Ash for Soil Improvement.* K. D Sharp (ed), Geotechnical Engrg. Division of the ASCE. Geotechnical Special Publications No. 36, pp 88-99.

Croft, H. F (1968). 'The problems of predicting the suitability of soils for cementitious stabilization' Engineering. Geology, Vol. 2, pp397-424.

Curtis,P.E. and Courson, S (1981) *Outline of Soil Fertility and Fertilizers,* 2nd Ed Stips Publishing Company, Champaign 250 pp.

Czernin, W. (1962). *Cement Chemistry and Physics for Civil Engineers*. Crosby Lockwood, London.

Eades, J. L. and Grim, R. E. (1960). "A quick test to determine lime requirements for lime stabilization" *Highway Res. Bull; Washington, D.C. 139: 61 - 72.*

Fisher,R.F and D. Binkley (2000): *Ecology and Management of Forest Soil,* 3rd Ed. John Wiley & Sons Inc., New York. pp. 489

Foth, H.D. (1990). *Fundamentals of Soil Science* 8th Ed John Wiley & Sons Inc., New York.USA 360 pp.

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

Hausman, M.R (1990). *Engineering Principles of Ground Modification*. McGraw-Hill. New York.

Head, K.H (1980**).** *Manual of Soil Laboratory Testing Vol. 1:* Pentech Press, London, Plymouth.

Head, K.H (1992**).** *Manual of Soil Laboratory Testing Vol. 2* Pentech Press, London, Plymouth

Highway Research Board (1943). "Use of Soil-cement mixture for base course", *Wartime Road Problems,* No. 7 *Nat. Council Div. Engg. Indust. Res. Washington.*

Ingles, O.G and Metcalf, J.B. (1972). *Soil stabilization - Principles and Practice.* Buther Worths, Sydney, pp 374.

Jha, J. and Sinha, S.K. (1993). *Construction and Foundation Engineering*. 5th Edition Khanna Publishers,Delhi.

Johnson, W. A., Herrin, M., Davidson, T. D. and Handy, L.R. (1988) Soil stabilization In: *Highway Design Reference Guide*, edited by Woods, K. B and Ross, S. S. Mc Graw Hill Book Company. New York.

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

Keogh, B.T (2006) *Pozzolanic Product Produced from Bagasse* United States Patent 4249954www.

Kimmins, J. P (1997). *Forest Ecology: A Foundation for Sustainable Management.* 2nd Ed. New Jersey, 596pp

Lees, G., Abdelkader, M.P. and Hamdani, S.K. (1982) "Effect of the clay fraction on some mechanical properties of lime - soil mixtures" *Journal First. Highway Eng*; Vol. 29, No .11 pp 2-9.

Little A.L (1967) "The use of tropically weathered soil in the construction of earthdams." *Proc. of 3rd Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Haifa, Israel, Vol.1, pp 35-41.

Lorenzo, G. A. and Bergado, D. T. (2006). "Fundamental characteristics of cement-admixed clay in deep mixing". *Journal of Materials in Civil Engineering, ASCE* Vol.18, No.2, pp.161-174.

Millard R.S. and O' Relly M.P. (1965). "Standards for road building practice in the Tropics: *Proc. of the 2nd Conf. Road Res.Ed. Australia Road Research Board Melbourne, Vol.2, pp. 830-854.*

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

Nicholson. P. G, Kashyap .V and Fuji. C. F. (1994). 'Lime and fly ash admixture improvement of tropical Hawaiian soil'. *Transportation Research Record* No.1440, National Academy Press, Washington D.C, pp71-78.

Nixon.I.K and Skipp. H.O. (1957)."Airfield construction on overseas soils and laterite." *Proc. of British Inst. Civil Engineering*, London, United Kingdom. Vol.8, pp.253-292.

Nigerian General Specifications (1997). *Road and Bridges*. Federal Government of Nigeria, Abuja, Nigeria.

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

Ochepo, J. (2008). *The Effect of Elapsed Time on the Geotechnical Properties of Black Cotton Soils Stabilized with Lime-Bagasse Ash Admixture*. Unpublished M.Sc. Thesis, Department of Civil Engineering, Ahmadu Bello University, Zaria.

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

Ola, S.A. (1977) “Geotechnical Properties and behaviour of some stabilized Nigerian lateritic soil.” *Quarterly Journal of Engineering Geology*, London, Vol. 11, *pp.* 148-160.

Ola. S.A. (1978). Geotechnical properties and behaviour of some stabilized Nigerian Laterite Soil, *Quarterly Journal of Engineering Geology,* London Vol.III pp.145-160.

Ola, S.A. (1983). "The geotechnical properties of black cotton soils of North Eastern Nigeria" In: S.A. Ola (Editor). *Tropical Soils of Nigeria in Engineering Practice*, A.A. Balkema, the Netherlands, Rotterdam, pp 155-171.

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

Osinubi K. J and Katte V. Y. (1997) “Effect of elapsed time after mixing on grain size, plasticity characteristic:-Soil - lime mixes” *Nigerian Society of Engineers Technical Publication,* Vol. 34, No 3,pp.38-46.

Osinubi, K. J. and Medubi. A. M. (1997).“Evaluation of cement and phosphoric waste admixture on tropical black clay road foundation.” *Proceeding. of the 4th International Conference on Structural Engineering Analysis & Modeling,* SEAM 4, Kumasi, Ghana, 9-11 July, Vol. 2.pp.297-307.

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

Osinubi, K. J. (1998a). "Laboratory investigation of engineering use of phosphatic waste." *Journal of Engineering Research,* University of Lagos, Vol. JER-6, No 2, pp 47-60.

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

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

Osinubi, K. J. (2000b). "Laboratory trial of soil stabilization of Nigerian black cotton soil" *Nigerian Society of Engineers Technical Transactions,* Vol. 35, No 4 pp 13 – 21.

Osinubi, K. J. (2000c) "Treatment of laterite with anionic bitumen emulsion and cement: A Comparative Study." *Ife Journal of Technology,* Obafemi Awolowo University, Ile-Ife, Vol. 9, No 1, pp. 139 - 145.

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

Osinubi, K.J and Stephen, T.A (2005). "Economic utilization of an agro-industrial waste-bagasse ash." *Proceedings of the 4th Nigerian Materials Congress "*NIMACON 2005", Zaria, Nigeria, 17-19 November, pp.36-40.

Osinubi, K. J. and Mustapha, A. M. (2008). 'Effect of compactive efforts on cement sugarcane bagasse ash - laterite mixture.'*Nigerian Society of Engineers Technical Transactions*, Vol. , No , pp. -

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

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

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

Osinubi, K. J. and Stephen, T.A. (2007). 'Influence of compactive efforts on bagasse ash treated black cotton soil.' *Nigerian Journal of Soil and Environmental Research*, Vol. 7, pp. 92 – 101.

Osinubi,K.J,Eberemu.A.O. and Aliu,O.S (2007a).'Stabilization of laterite with cement and bagasse ash admixture.' Proceedings. of the *First Inter. Conf. on Environ. Res., Techn. and Policy "ERTEP 2007"*under the auspices of International Society of Environmental Geotechnology, Accra, Ghana, 16 - 19 July, Category B: Mining and Environment, pp. 1 - 14.

Osinubi,K.J, Bafyau,V and Eberemu.A.O.(2007b). 'Bagasse ash stabilization of lateritic soil.' Proc. of the *First Inter. Conf. on Environ. Res., Techn. and Policy "ERTEP 2007"* under the auspices of International Society of Environmental Geotechnology, Accra, Ghana, 16 -19 July, Category E: State-of-the-Art Technologies for Environmental Performance and Protection, pp.1 - 17.

Osinubi K.J, Bafyau,V and Eberemu.A.O.(2008). 'Bagasse ash stabilization of Lateritic soil.' In: Appropriate Technologies for Environmental Protection in the Developing World. Edited by E. K. Yanful Springer, Netherlands.

Osinubi,K.J,Ijimdiya,T.S. and Nmadu,I. (2008a). 'Effect of compactive effort on lime treated black cotton soil using bagasse ash as admixture.' Book of Abstracts of the 2nd International Conference on Engineering Research & Development:

Innovations (ICER&D 2008), Benin City, Nigeria, 15-17 April. *Technical Session 9B - Construction and Structures, Paper ICERD08056, p. 216 - 217.*

Osinubi Ijimdiya,T.S. and Nmadu,I (2009). 'Lime stabilization of black cotton soil using bagasse ash as admixture.' *Advanced Materials Research*, Vols. 62 - 64, pp.3-10.In: *Advances in Materials Systems Technologies II* Online http://www.scientific.net Trans Tech Publications, Switzerland.

Osinubi, K.J and Eberemu, A.O. (2009). "Compatibility and attenuative properties of laterite-blast furnace slag mixture." *Journal of Solid Waste Technology and fManagement,* Vol. 35, No. 1, pp.7-16.

Osinubi et al. (2009). "Stabilization potential of locust bean waste ash on black cotton soil" *Journal of Engineering Research*, University of Lagos, Nigeria, Vol. 14, No. 2, pp. 1-13.

Osula D. O. A. (1984). "*Cement stabilization using hydrated lime as an admixture*." An Unpublished M.Sc. Thesis Civil Engineering Department Ahmadu Bello University Zaria.

Osula D.O.A (1991). "Lime modification of problem laterite." *Engineering Geology.* 30, pp 141-149.

Osula D.O.A (1996). "A comparative evaluation of cement and lime modification of laterite." *Engineering Geology.Vol* 42, pp 71-81.

Poritchett, W.L and R.F.Fisher (1987). *Properties and Management of Forest Soils,* 2nd Edition, John Wiley & Sons, Inc., New York 494 pp

Thompson (1966*). Lime Reactivity of Illinous Soils J.Soil Mechanics and Foundation Engineering Division ASCE, SM5Vol.96; Pp120-123.*

Yoder E.J.and Witczak M. W (1975). P*rinciples of Pavement Design*, 2nd Ed., John Wiley and Sons. Inc. pp. 200 - 321.

APPENDIX A: TEST RESULTS

Table A4.1: Natural moisture content test results

Container No.	*Container + Wet (g)*	*Container + Dry (g)*	*Empty Container (g)*	*Dry Weight (g)*	*Loss of moisture (g)*	*Moisture Content (%)*
3J	33.00	31.50	13.80	17.70	1.50	8.50
X5	33.60	32.20	14.40	17.80	1.40	7.90
37	26.40	25.30	11.60	13.70	1.10	8.00
Average moisture content (%)						**10.3**

Table A4.2 Test Results of Specific Gravity of the Soil Particles

Bottle No.	*1*	*2*	*3*
Wt. of bottle + water W4 (g)	98.60	94.40	89.20
Wt. of bottle + soil water W3(g)	103.30	97.80	93.40
Wt. of bottle + soil W2(g)	50.90	50.40	46.50
Wt. of bottle W1(g)	43.20	45.10	39.70
Wt. of Additional water (W4 - W1) (g)	55.40	49.30	49.50
Wt. of water added to soil (W3 - W2)(g)	52.40	47.40	46.90
Wt. of soil (W2 - W1) (g)	7.70	5.30	6.80
Wt of water displaced by soil (W4 - W1) - (W3 - W2) = W(g)	3.00	1.90	2.60
Specific gravity of the soil particles (W2 - W1)/ W	2.57	2.79	2.62
Average Specific gravity			**2.30**

Table A4.3: Test Results of hydrometer test

0% LIME & 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	10.2	189.8	94.9
1.4mm (10)	3.2	186.6	93.3
0.6mm (600)	12.3	174.3	87.15
0.425mm (425)	4.8	169.5	84.75
0.3mm (300)	5.6	163.9	81.95
0.212mm (212)	3.5	160.4	80.2
0.15mm (150)	3.8	156.6	78.3
0.075mm (75)	5.1	151.5	75.75

0% LIME & 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	6.3	193.7	96.85
1.4mm (10)	3.3	190.4	95.2
0.6mm (600)	4.7	185.7	92.85
0.425mm (425)	13.5	172.2	86.1
0.3mm (300)	4.8	167.4	83.7
0.212mm (212)	3.7	163.7	81.85
0.15mm (150)	6.5	157.2	78.6
0.075mm (75)	10.2	147	73.5

0% LIME & 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	7.8	192.2	96.1
1.4mm (10)	5.3	186.9	93.45
0.6mm (600)	4.3	182.6	91.3
0.425mm (425)	11.8	170.8	85.4
0.3mm (300)	4.9	165.9	82.95
0.212mm (212)	4	161.9	80.95
0.15mm (150)	8.1	153.8	76.9
0.075mm (75)	11.5	142.3	71.15

0% LIME & 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	6.4	193.6	96.8
1.4mm (10)	3.6	190	95
0.6mm (600)	5.9	184.1	92.05
0.425mm (425)	14.3	169.8	84.9
0.3mm (300)	5.3	164.5	82.25
0.212mm (212)	4.5	160	80
0.15mm (150)	7.9	152.1	76.05
0.075mm (75)	12.2	139.9	69.95

1% LIME & 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	0.9	199.1	99.55
1.4mm (10)	0.4	198.7	99.35
0.6mm (600)	0.4	198.3	99.15
0.425mm (425)	1.5	196.8	98.4
0.3mm (300)	2.1	194.7	97.35
0.212mm (212)	4.5	190.2	95.1
0.15mm (150)	5	185.2	92.6
0.075mm (75)	6.4	178.8	89.4

1% LIME & 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	4.3	195.7	97.85
1.4mm (10)	0.4	195.3	97.65
0.6mm (600)	0.3	195	97.5
0.425mm (425)	1.3	193.7	96.85
0.3mm (300)	0.7	193	96.5
0.212mm (212)	4	189	94.5
0.15mm (150)	5.8	183.2	91.6
0.075mm (75)	6.2	177	88.5

0% LIME & 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	6.2	193.8	96.9
1.4mm (10)	3.9	189.9	94.95
0.6mm (600)	4.5	185.4	92.7
0.425mm (425)	12.6	172.8	86.4
0.3mm (300)	4.9	167.9	83.95
0.212mm (212)	3.9	164	82
0.15mm (150)	7.3	156.7	78.4
0.075mm (75)	11.8	144.9	72.5

1% LIME & 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	3.1	196.9	98.45
1.4mm (10)	0.8	196.1	98.05
0.6mm (600)	0.5	195.6	97.8
0.425mm (425)	1.8	193.8	96.9
0.3mm (300)	1	192.8	96.4
0.212mm (212)	3.5	189.3	94.65
0.15mm (150)	5	184.3	92.15
0.075mm (75)	4.6	179.7	89.85

1% LIME & 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.4	197.6	98.8
1.4mm (10)	0	197.6	98.8
0.6mm (600)	0	197.6	98.8
0.425mm (425)	4	193.6	96.8
0.3mm (300)	1.8	191.8	95.9
0.212mm (212)	5	186.8	93.4
0.15mm (150)	8.2	178.6	89.3
0.075mm (75)	8.4	170.2	85.1

1% LIME & 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.6	197.4	98.7
1.4mm (10)	0.3	197.1	98.55
0.6mm (600)	0.3	196.8	98.4
0.425mm (425)	1.2	195.6	97.8
0.3mm (300)	1.3	194.3	97.15
0.212mm (212)	3.3	191	95.5
0.15mm (150)	9.6	181.4	90.7
0.075mm (75)	12.5	168.9	84.45

2% LIME & 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	1.4	198.6	99.3
1.4mm (10)	0.3	198.3	99.15
0.6mm (600)	0	198.3	99.15
0.425mm (425)	1.5	196.8	98.4
0.3mm (300)	1.4	195.4	97.7
0.212mm (212)	7.2	188.2	94.1
0.15mm (150)	8.8	179.4	89.7
0.075mm (75)	10.8	168.6	84.3

2% LIME & 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	1.6	198.4	99.2
1.4mm (10)	0.4	198	99
0.6mm (600)	0	198	99
0.425mm (425)	1.2	196.8	98.4
0.3mm (300)	1.2	195.6	97.8
0.212mm (212)	7	188.6	94.3
0.15mm (150)	9.7	178.9	89.5
0.075mm (75)	10.9	168	84

2% LIME & 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	3.1	196.9	98.45
1.4mm (10)	0.4	196.5	98.25
0.6mm (600)	0.6	195.9	97.95
0.425mm (425)	2.6	193.3	96.65
0.3mm (300)	1.2	192.1	96.05
0.212mm (212)	6.9	185.2	92.6
0.15mm (150)	10.9	174.3	87.15
0.075mm (75)	11.3	163	81.5

2% LIME & 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	3.5	196.5	98.25
1.4mm (10)	0.6	195.9	97.95
0.6mm (600)	0.2	195.7	97.85
0.425mm (425)	1.8	193.9	96.95
0.3mm (300)	1.6	192.3	96.15
0.212mm (212)	7.6	184.7	92.35
0.15mm (150)	11.2	173.5	86.75
0.075mm (75)	12.1	161.4	80.7

2% LIME & 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	4.8	195.2	97.6
1.4mm (10)	0.4	194.8	97.4
0.6mm (600)	0.3	194.5	97.25
0.425mm (425)	2.8	191.7	95.85
0.3mm (300)	2	189.7	94.85
0.212mm (212)	8.1	181.6	90.8
0.15mm (150)	9.5	172.1	86.05
0.075mm (75)	13	159.1	79.55

3% LIME & 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	3.8	196.2	98.1
1.4mm (10)	0	196.2	98.1
0.6mm (600)	0.3	195.9	97.95
0.425mm (425)	1.1	194.8	97.4
0.3mm (300)	1.1	193.7	96.85
0.212mm (212)	4.5	189.2	94.6
0.15mm (150)	8.1	181.1	90.55
0.075mm (75)	10.3	170.8	85.4

3% LIME & 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	1.9	198.1	99.05
1.4mm (10)	0	198.1	99.05
0.6mm (600)	0	198.1	99.05
0.425mm (425)	1	197.1	98.55
0.3mm (300)	1.9	195.2	97.6
0.212mm (212)	5.5	189.7	94.85
0.15mm (150)	9.3	180.4	90.2
0.075mm (75)	11	169.4	84.7

3% LIME & 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.5	197.5	98.75
1.4mm (10)	0.3	197.2	98.6
0.6mm (600)	0.4	196.8	98.4
0.425mm (425)	1.3	195.5	97.75
0.3mm (300)	1.6	193.9	96.95
0.212mm (212)	4.1	189.8	94.9
0.15mm (150)	9.6	180.2	90.1
0.075mm (75)	10.3	169.9	84.9

3% LIME & 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.2	197.8	98.9
1.4mm (10)	0.3	197.5	98.75
0.6mm (600)	0.3	197.2	98.6
0.425mm (425)	1.6	195.6	97.8
0.3mm (300)	1.3	194.3	97.15
0.212mm (212)	4.6	189.7	94.85
0.15mm (150)	11.5	178.2	89.1
0.075mm (75)	8.1	170.1	85.05

3% LIME & 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	1.9	198.1	99.05
1.4mm (10)	0.4	197.7	98.85
0.6mm (600)	0.5	197.2	98.6
0.425mm (425)	1.5	195.7	97.85
0.3mm (300)	2	193.7	96.85
0.212mm (212)	4.3	189.4	94.7
0.15mm (150)	10.8	178.6	89.3
0.075mm (75)	12.4	166.2	83.1

4% LIME & 0% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	4.1	195.9	97.95
1.4mm (10)	0.5	195.4	97.7
0.6mm (600)	0.2	195.2	97.6
0.425mm (425)	1.9	193.3	96.65
0.3mm (300)	1.7	191.6	95.8
0.212mm (212)	7.9	183.7	91.85
0.15mm (150)	11.8	171.9	85.95
0.075mm (75)	13.3	158.6	79.3

4% LIME & 2% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	3.2	196.8	98.4
1.4mm (10)	0.3	196.5	98.25
0.6mm (600)	0.3	196.2	98.1
0.425mm (425)	4	192.2	96.1
0.3mm (300)	2.3	189.9	94.95
0.212mm (212)	12.4	177.5	88.75
0.15mm (150)	10.2	167.3	83.65
0.075mm (75)	16.1	151.2	75.6

4% LIME & 4% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.7	197.3	98.65
1.4mm (10)	0.6	196.7	98.35
0.6mm (600)	0.8	195.9	97.95
0.425mm (425)	5.2	190.7	95.35
0.3mm (300)	3.4	187.3	93.65
0.212mm (212)	10.5	176.8	88.4
0.15mm (150)	12.6	164.2	82.1
0.075mm (75)	14.8	149.4	74.7

4% LIME & 6% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	2.1	197.9	98.95
1.4mm (10)	0.5	197.4	98.7
0.6mm (600)	0.7	196.7	98.35
0.425mm (425)	7.2	189.5	94.75
0.3mm (300)	4.6	184.9	92.45
0.212mm (212)	18.3	166.6	83.3
0.15mm (150)	13.2	153.4	76.7
0.075mm (75)	15.9	137.5	68.8

4% LIME & 8% LBWA

B.S SIEVE SIZE	WEIGHT RETAINED	WEIGHT PASSING	% PASSING
2.4mm (7)	1.1	198.9	99.45
1.4mm (10)	0.4	198.5	99.25
0.6mm (600)	0.5	198	99
0.425mm (425)	3.6	194.4	97.2
0.3mm (300)	2.7	191.7	95.85
0.212mm (212)	11.9	179.8	89.9
0.15mm (150)	18.3	161.5	80.75
0.075mm (75)	15.6	145.9	72.95

Table A4.4 **cation exchange capacity(cec)**

LBWA Content %	**LIME %**				
	0	**1**	**2**	**3**	**4**
0	37.5	19.8	42.5	12.4	41.3
2	22	19.5	37.5	16.2	40.7
4	32	19.8	38.5	20	38.1
6	27.6	20.3	33	23.9	43.2
8	46.1	18.8	42	21.8	41.7

Table A4.5: Sieve Analysis Results for the Natural soil

BS Sieve Size (mm)	Percent Passing %
3.175	100
2.4	98.2
1.18	96.5
600µm	92.9
425µm	86.1
300µm	83.7
212µm	81.9
150µm	78.6
75µm	75.5

Table A4.6a: Values of Liquid Limits (%) for Soil-Lime-LBWA mixtures

LBWA CONTENT, %	LIME CONTENT, %				
	0	1	2	3	4
0	66.5	65.4	64.1	62	61
2	74.6	73.1	66.2	61.2	60.4
4	73.5	72	64.8	61.1	56
6	72.3	68.9	61.3	60.5	55
8	67.8	63.7	61	59.5	49

Table A4.6b: Values of Plastic Limits (%) for Soil-Lime-LBWA mixtures

LBWA CONTENT, %	LIME CONTENT, %				
	0	1	2	3	4
0	30.83	32.5	35.04	38.7	39.08
2	30.49	38.64	40.56	41.6	43.29
4	32.5	39.9	43.54	44.28	45.29
6	33.67	37.4	40.11	43.6	44.68
8	31.57	36.6	37.31	40.2	37.5

Table A4.6c: Values of Plastic Index (%) for Soil-Lime-LBWA mixtures

LBWA CONTENT, %	LIME CONTENT, %				
	0	1	2	3	4
0	35.67	32.86	29.06	23.3	21.92
2	44.11	34.46	25.64	19.6	17.11
4	40.96	32.1	21.23	16.82	11.32
6	38.63	31.5	21.19	16.9	10.3
8	36.23	27.1	23.69	19.3	11.5

*Table A4.7 (a): Values of Maximum Dry Density (**Mg/m^3**) for Soil-Lime-LBWA mixtures (BSL Compaction)*

LBWA CONTENT, %	**LIME CONTENT, %**				
	0	**1**	**2**	**3**	**4**
0	1.35	1.37	1.36	1.37	1.39
2	1.32	1.35	1.37	1.39	1.4
4	1.37	1.41	1.43	1.45	1.48
6	1.36	1.38	1.4	1.43	1.45
8	1.3	1.34	1.37	1.41	1.43

*Table A4.7 (b): Values of Maximum Dry Density (**Mg/m^3**) for Soil-Lime-LBWA mixtures (WAS Compaction).*

LBWA CONTENT, %	**LIME CONTENT, %**				
	0	**1**	**2**	**3**	**4**
0	1.36	1.4	1.45	1.5	1.55
2	1.46	1.48	1.51	1.55	1.59
4	1.47	1.5	1.53	1.56	1.57
6	1.4	1.42	1.45	1.47	1.5
8	1.36	1.37	1.37	1.4	1.43

*Table A4.7 (c): Values of Maximum Dry Density (**Mg/m^3**) for Soil-Lime-LBWA mixtures (BSH compaction)*

LBWA CONTENT, %	**LIME CONTENT, %**				
	0	**1**	**2**	**3**	**4**
0	1.43	1.45	1.47	1.51	1.55
2	1.47	1.49	1.52	1.55	1.57
4	1.48	1.52	1.55	1.58	1.6
6	1.50	1.55	1.58	1.6	1.62

Table A4.7 (d): Values of Optimum Moisture Content (%) for Soil-Lime-LBWA mixtures (BSL Compaction)

LBWA CONTENT, %	**LIME CONTENT, %**				
	0	**1**	**2**	**3**	**4**
0	16	16.5	17.1	17.7	19.6
2	16.3	17.8	19.6	20.5	21.3
4	16.7	19.1	20.3	21	22.5
6	17.4	19.8	20.9	22.5	23.1
8	16.9	18.5	19.0	20.0	22.5

Table A4.7 (e): Optimum Moisture content (%) for Soil-Lime-LBWA mixtures (WAS Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	1	2	3	4
0	17.3	18.3	19.0	20.5	21.3
2	19.7	20.6	21.5	22.4	23.6
4	21.2	22.1	22.8	23.7	24.5
6	22.0	23.1	23.5	24.8	25.5
8	23.2	25.8	26.0	27.8	28.7

Table A4.7 (f): Optimum Moisture Content (%) for Soil-Lime-LBWA mixtures (BSH Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	1	2	3	4
0	16.2	16.5	16.7	17	17.2
2	16.7	16.9	17.7	18.6	20.4
4	17.0	17.6	18.8	20.4	22.4
6	17.4	18.1	19.5	20.9	23.2
8	18.0	19	19.9	21.3	24

Table A4.8 (a): Values of Cohesion (kN/m^2) for various Soil-Lime-LBWA mixtures (BSL Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	165	140	139	150	125
2	155	135	125	130	110
4	140	130	120	112	105
6	120	120	110	105	100
8	80	100	70	97	79

Table A4.8 (b): Values of Cohesion (kN/m^2) for various for Soil-Lime-LBWA mixtures (WAS Compaction).

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	178	145	150	150	140
2	160	140	140	140	120
4	140	135	135	118	105
6	135	120	120	115	103
8	80	110	105	95	100

Table A4.8 (c): Values of Cohesion (kN/m^2) for various Soil-Lime-LBWA mixtures (BSH Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	160	145	160	155	160
2	150	124	142	105	97
4	140	120	110	100	95
6	133	115	90	85	80
8	120	110	90	78	80

TableA4.8 (d): Values of Angle of internal friction (^{0}) for various Soil-Lime-LBWA mixtures (BSL Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	13.5	14.5	15	16	16.5
2	14.5	15.5	16	16.5	17.5
4	16	16.5	17.5	17.5	18.0
6	17	18.5	19	19.5	20.0
8	19	20	20.5	22.0	23.5

TableA.8 (e): Values of Angle of internal friction (^{0}) for various Soil-Lime-LBWA mixtures (WAS Compaction)

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	12.0	14.0	15	15	16
2	14.5	15.0	16	16.5	18
4	15.0	18.0	19	20	21
6	16.5	19.0	21	22.0	23.0
8	19.5	21.0	22	22.5	23.5

TableA4.8 (f): Values of Angle of internal friction (^{0}) for various for Soil-Lime-LBWA mixtures (BSH Compaction).

LBWA CONTENT, %	LIME CONTENT, %				
	0	**1**	**2**	**3**	**4**
0	11.0	13.0	14.5	15.5	17
2	13.0	15.5	17.0	18.0	19.5
4	15.0	16.5	18.5	20.5	22.0
6	16.0	18.0	19.5	21.0	23.0
8	16.5	18.5	20.5	22.5	23.5

Results of two-way ANOVA for Atterberg limit test of various Soil-Lime-LBWA mixtures

Liquid Limit

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	319	63.8	5.255
Row 2	5	335.5	67.1	43.19
Row 3	5	327.4	65.48	54.087
Row 4	5	318	63.6	48.16
Row 5	5	301	60.2	49.145
Column 1	5	354.7	70.94	12.843
Column 2	5	343.1	68.62	16.537
Column 3	5	317.4	63.48	5.107
Column 4	5	304.3	60.86	0.863
Column 5	5	281.4	56.28	23.492

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	132.1696	4	33.0424	5.122932	7.50E-03	3.006917
LBWA	696.1496	4	174.0374	26.98296	6.15E-07	3.006917
Error	103.1984	16	6.4499			
Total	931.5176	24				

Plastic Limit

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	176.19	35.238	13.37382
Row 2	5	194.58	38.916	25.02803
Row 3	5	205.58	41.116	27.12043
Row 4	5	199.46	39.892	20.41127
Row 5	5	183.18	36.636	9.89213
Column 1	5	159.1	31.82	1.6881
Column 2	5	185.08	37.016	7.82748
Column 3	5	196.59	39.318	10.64567
Column 4	5	208.38	41.676	5.38088
Column 5	5	209.84	41.968	12.11047

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	114.8538	4	28.71344	12.84839	7.17E-05	3.006917
LBWA	347.5461	4	86.88652	38.87907	4.73E-08	3.006917
Error	35.75662	16	2.234789			
Total	498.1565	24				

Plasticity Index

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	142.81	28.562	35.26232
Row 2	5	140.92	28.184	123.954
Row 3	5	122.43	24.486	143.0196
Row 4	5	118.52	23.704	128.9612
Row 5	5	117.82	23.564	84.16713
Column 1	5	195.6	39.12	12.1951
Column 2	5	158.02	31.604	7.56928
Column 3	5	120.81	24.162	10.95677
Column 4	5	95.92	19.184	6.98328
Column 5	5	72.15	14.43	24.6491

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	121.908	4	30.47701	3.824384	2.29 E-02	3.006917
LBWA	1933.951	4	483.4878	60.67008	1.82E-09	3.006917
Error	127.5061	16	7.96913			
Total	2183.365	24				

Results of two-way ANOVA for Compaction characteristics of various Soil-Lime-LBWA mixtures (BSL, WAS and BSH Compaction).

Maximum Dry Density for BSL Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	6.84	1.368	0.00022
Row 2	5	6.83	1.366	0.00103
Row 3	5	7.14	1.428	0.00172
Row 4	5	7.02	1.404	0.00133
Row 5	5	6.85	1.37	0.00275
Column 1	5	6.7	1.34	0.00085
Column 2	5	6.85	1.37	0.00075
Column 3	5	6.93	1.386	0.00083
Column 4	5	7.05	1.41	0.001
Column 5	5	7.15	1.43	0.00135

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	0.015304	4	0.003826	16.04193	1.86E-05	3.006917
LBWA	0.024384	4	0.006096	25.55975	8.9E-07	3.006917
Error	0.003816	16	0.000239			
Total	0.043504	24				

Maximum Dry Density for WAS Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	7.26	1.452	0.00577
Row 2	5	7.59	1.518	0.00277
Row 3	5	7.63	1.526	0.00173
Row 4	5	7.24	1.448	0.00157
Row 5	5	6.95	1.39	0.00075
Column 1	5	7.05	1.41	0.0028
Column 2	5	7.17	1.434	0.00298
Column 3	5	7.33	1.466	0.00308
Column 4	5	7.48	1.496	0.00423
Column 5	5	7.64	1.528	0.00412

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	0.062984	4	0.015746	43.02186	2.28E-08	3.006917
LBWA	0.044504	4	0.011126	30.39891	2.7E-07	3.006917
Error	0.005856	16	0.000366			
Total	0.113344	24				

Maximum Dry Density for BSH Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	7.41	1.482	0.00232
Row 2	5	7.6	1.52	0.0017
Row 3	5	7.73	1.546	0.00228
Row 4	5	7.85	1.57	0.0022
Row 5	5	7.43	1.486	0.00738
Column 1	5	7.26	1.452	0.00227
Column 2	5	7.43	1.486	0.00273
Column 3	5	7.62	1.524	0.00183
Column 4	5	7.78	1.556	0.00123
Column 5	5	7.93	1.586	0.00073

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	0.028864	4	0.007216	18.33799	8E-06	3.006917
LBWA	0.057224	4	0.014306	36.35578	7.65E-08	3.006917
Error	0.006296	16	0.000394			
Total	0.092384	24				

Optimum Moisture Content for BSL Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	86.9	17.38	1.947
Row 2	5	95.5	19.1	4.145
Row 3	5	99.6	19.92	4.752
Row 4	5	103.7	20.74	5.183
Row 5	5	96.9	19.38	4.297
Column 1	5	83.3	16.66	0.293
Column 2	5	91.7	18.34	1.603
Column 3	5	96.9	19.38	2.137
Column 4	5	101.7	20.34	3.053
Column 5	5	109	21.8	1.94

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	30.9536	4	7.7384	24.03976	1.35E-06	3.006917
LBWA	76.1456	4	19.0364	59.13762	2.2E-09	3.006917
Error	5.1504	16	0.3219			
Total	112.2496	24				

Optimum Moisture Content for WAS Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	96.4	19.28	2.632
Row 2	5	107.8	21.56	2.313
Row 3	5	114.3	22.86	1.683
Row 4	5	118.9	23.78	1.927
Row 5	5	131.5	26.3	4.49
Column 1	5	103.4	20.68	5.187
Column 2	5	109.9	21.98	7.827
Column 3	5	112.8	22.56	6.643
Column 4	5	119.2	23.84	7.463
Column 5	5	123.6	24.72	7.362

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	135.6616	4	33.9154	239.431	4.71E-14	3.006917
LBWA	49.9136	4	12.4784	88.09319	1.1E-10	3.006917
Error	2.2664	16	0.14165			
Total	187.8416	24				

Optimum Moisture Content for BSH Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	83.6	16.72	0.157
Row 2	5	90.3	18.06	2.273
Row 3	5	96.2	19.24	4.808
Row 4	5	99.1	19.82	5.377
Row 5	5	102.2	20.44	5.433
Column 1	5	85.3	17.06	0.468
Column 2	5	88.1	17.62	0.977
Column 3	5	92.6	18.52	1.732
Column 4	5	98.2	19.64	3.243
Column 5	5	107.2	21.44	7.408

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	43.9096	4	10.9774	15.40363	2.4E-05	3.006917
LBWA	60.7896	4	15.1974	21.32519	3E-06	3.006917
Error	11.4024	16	0.71265			
Total	116.1016	24				

Results of two-way ANOVA for Shear Strength parameter of various Soil-Lime-LBWA mixtures (BSL, WAS and BSH Compaction).

Cohesion for BSL Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	719	143.8	219.7
Row 2	5	655	131	267.5
Row 3	5	607	121.4	194.8
Row 4	5	555	111	80
Row 5	5	426	85.2	163.7
Column 1	5	660	132	1132.5
Column 2	5	625	125	250
Column 3	5	564	112.8	681.7
Column 4	5	594	118.8	452.7
Column 5	5	519	103.8	279.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	9849.44	4	2462.36	29.46817	3.35E-07	3.006917
LBWA	2365.84	4	591.46	7.078267	1.77E-03	3.006917
Error	1336.96	16	83.56			
Total	13552.24	24				

Cohesion for WAS Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	763	152.6	218.8
Row 2	5	700	140	200
Row 3	5	633	126.6	215.3
Row 4	5	593	118.6	132.3
Row 5	5	520	104	42.5
Column 1	5	723	144.6	665.8
Column 2	5	650	130	212.5
Column 3	5	650	130	312.5
Column 4	5	618	123.6	472.3
Column 5	5	568	113.6	277.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	7074.16	4	1768.54	41.16234	3.14E-08	3.006917
LBWA	2548.16	4	637.04	14.82695	3.03E-05	3.006917
Error	687.44	16	42.965			
Total	10309.76	24				

Cohesion for BSH Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	780	156	42.5
Row 2	5	618	123.6	522.3
Row 3	5	565	113	320
Row 4	5	503	100.6	509.3
Row 5	5	478	95.6	346.8
Column 1	5	703	140.6	236.8
Column 2	5	614	122.8	181.7
Column 3	5	592	118.4	992.8
Column 4	5	523	104.6	913.3
Column 5	5	512	102.4	1101.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	11522.96	4	2880.74	21.13684	3.18E-06	3.006917
LBWA	4782.96	4	1195.74	8.773498	6.01E-04	3.006917
Error	2180.64	16	136.29			
Total	18486.56	24				

Angle of internal friction for BSL Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	75.5	15.1	1.425
Row 2	5	80	16	1.25
Row 3	5	85.5	17.1	0.675
Row 4	5	94	18.8	1.325
Row 5	5	105	21	3.125
Column 1	5	80	16	4.625
Column 2	5	85	17	5
Column 3	5	88	17.6	4.925
Column 4	5	91.5	18.3	6.075
Column 5	5	95.5	19.1	7.675

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	110.3	4	27.575	152.1379	1.63E-12	3.006917
LBWA	28.3	4	7.075	39.03448	4.6E-08	3.006917
Error	2.9	16	0.18125			
Total	141.5	24				

Angle of internal friction for WAS Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	72	14.4	2.3
Row 2	5	80	16	1.875
Row 3	5	93	18.6	5.3
Row 4	5	101.5	20.3	6.7
Row 5	5	108.5	21.7	2.325
Column 1	5	77.5	15.5	7.625
Column 2	5	87	17.4	8.3
Column 3	5	93	18.6	9.3
Column 4	5	96	19.2	11.075
Column 5	5	101.5	20.3	10.45

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	180.5	4	45.125	111.0769	1.86E-11	3.006917
LBWA	67.5	4	16.875	41.53846	2.94E-08	3.006917
Error	6.5	16	0.40625			
Total	254.5	24				

Angle of internal friction for BSH Compaction

Anova: Two-Factor Without Replication

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	5	71	14.2	5.325
Row 2	5	83	16.6	6.175
Row 3	5	92.5	18.5	8.125
Row 4	5	97.5	19.5	7.25
Row 5	5	101.5	20.3	8.2
Column 1	5	71.5	14.3	5.2
Column 2	5	81.5	16.3	4.825
Column 3	5	90	18	5.5
Column 4	5	97.5	19.5	7.625
Column 5	5	105	21	7.375

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Lime	120.14	4	30.035	245.1837	3.91E-14	3.006917
LBWA	138.34	4	34.585	282.3265	1.29E-14	3.006917
Error	1.96	16	0.1225			
Total	260.44	24				