VALORIZATION OF AGRO-WASTE FOR MECHANICAL PROPERTIES' IMPROVEMENT OF LATERITIC SOIL FOR SUSTAINABLE CONSTRUCTION

DISSERTATION

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By:

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VALORIZATION OF AGRO-WASTE FOR MECHANICAL PROPERTIES' IMPROVEMENT OF LATERITIC SOIL FOR SUSTAINABLE CONSTRUCTION

By:

Ifeyinwa Ijeoma Obianyo

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DEDICATION

To my late mother, Mrs Priscilla N. Agina, who is a crusader of quality education for a girl child, I dedicate this thesis. May her gentle soul continue to rest in the Bosom of the Lord, Amen.

ABSTRACT

This study presents the results of a combined theoretical, experimental and statistical study of the mechanical performance of stabilized lateritic soil for sustainable construction applications. The lateritic soil was stabilized with different percentage of bone ash (5%, 10%, 15% and 20%), hydrated lime (3%, 9% and 15%) for the project I whereas four different matrices with bone ash content of 0, 3, 6 and 9% of the weight of lateritic soil were used for the lateritic soil stabilization in project II. The bone ash and palm bunch ash were added to the soil sample in equal proportion at a varying proportion of 0%, 2%, 4% and 6% by weight of the soil in project III. Lateritic brick samples obtained were cured at different temperature and ages. The effects of these stabilizers on the morphology and mechanical properties of the composite were investigated using Scanning Electron Microscopy and Universal Testing Machine respectively. The microstructural analysis gave a morphology with reduced porosity for the stabilized soil samples whereas, the results of the compressive strength tests indicated that the compressive strength of the lateritic soil was improved by the addition of the different stabilizers. The study also presents the prediction of compressive strength of stabilized bricks using Multivariate statistical models. Non-linear and mixed models with higher R^2 performed better than the linear model in predicting the compressive strength of the stabilized bricks. The mixed model with R^2 of 97% was identified as the best-fit model in predicting the compressive strength of the stabilized bricks. The results indicate that agro waste (cow bone and palm bunch) can be valorized through conversion to ash which can be used as an effective stabilizer for lateritic soil. Also, it can be used for making bricks with higher compressive strength compared to conventional stabilizers. The implications of the results for potential applications in the making of lateritic bricks for the construction of sustainable and affordable buildings include lower building costs, bricks with high compressive strength and reduction in the use of cement for building construction.

PREFACE

This dissertation is an original intellectual property of Ifeyinwa Ijeoma Obianyo containing work done from the period of 2018 to November 2020 for the fulfilment of Doctorate of Philosophy degree in the Department of Materials Science and Engineering at the African University of Science and Technology, Abuja-Nigeria.

I was the lead investigator in this work, responsible for all major activities: experiments, data collection and analysis including manuscript composition while Prof. Azikiwe P. Onwualu and Prof Alfred B.O. Soboyejo was the supervisory authors, who were involved in the early stages of the concept formation and manuscript composition.

Valorization of agro-waste for mechanical properties' improvement of lateritic soil for sustainable construction is presented in this work. Lateritic soil, a locally available earth-based material was stabilized with agro-waste ash for affordable and sustainable building. Multivariate regression models for predicting the compressive strength of bone ash stabilized lateritic soil for the sustainable building were also developed.

As at the time this thesis was submitted, two of its chapters (3 and 4) have been published in peer-reviewed journals: Case Studies in Construction Materials Journal; Construction and Building Materials Journal. Chapter 5 is under review in a peer-reviewed journal.

ACKNOWLEDGEMENTS

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I want to extend my sincere appreciation to my PhD Dissertation Committee: Prof. Azikiwe. P. Onwualu, Prof. Alfred .B. Soboyejo, Prof Ruoyu Jin, Dr Kennedy C. Onyelowe and Dr Emeso B. Ojo for their numerous support and technical guidance.

This academic pursuit would have been impossible without the continuous prayers and emotional support from my family especially my Sweetheart, Mr Arinze Daniel Obianyo and my wonderful daughter, Deborah. I'm truly grateful to God to be blessed with such a supportive family.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

PEER REVIEW PUBLICATIONS

1. **Obianyo, I. I.**; Anosike-francis, E. N.; Odochi, G.; Geng, Y.; Jin, R.; Peter, A.; Soboyejo, A. B. O. Multivariate Regression Models for Predicting the Compressive Strength of Bone Ash Stabilized Lateritic Soil for Sustainable Building. *Constr. Build. Mater.* **2020**, *263*, 120677. https://doi.org/10.1016/j.conbuildmat.2020.120677. Elsevier Science Publishers, Amsterdam, the Netherlands.

2. **Obianyo, I. I.**; Onwualu, A. P.; Soboyejo, A. B. O. Mechanical Behaviour of Lateritic Soil Stabilized with Bone Ash and Hydrated Lime for Sustainable Building Applications. *Case Stud. Constr. Mater.* **2020**, *12*, e00331. https://doi.org/10.1016/j.cscm.2020.e00331. Elsevier Science Publishers, Amsterdam, the Netherlands.

LIST OF CONFERENCE PRESENTATIONS

1. **Obianyo, I.I.**, Onwualu, A.P. and Soboyejo, A.B. Morphology and Strength of Stabilized Lateritic Soil for Sustainable Building Applications. 74th RILEM Annual Week and 40th Cement and Concrete Science Conference, The University of Sheffield, UK from 31st August – 4th September 2020.

2. **Obianyo, I.I.**, Onwualu, A.P. and Soboyejo, A.B. Strength and Morphology of Stabilized Lateritic Soil for Sustainable Building Applications. 10th International Conference of African Materials Research Society, NM-AIST Arusha, Tanzania from 10-13th December 2019.

3. **Obianyo, I.I.**, Onwualu, A.P., Nwaubani, S. and Soboyejo, A.B. (2018). Optimization of Laterite for Sustainable Building Applications. Proceedings of the 17th Nigerian International Materials Congress (NIMACON 2018).

4. **Obianyo, I.I.**, Onwualu, A.P. and Soboyejo, A.B. Characterization and Stabilization of Laterite for Sustainable Construction Applications. 10th International Conference of African Materials Research Society, Botswana from 10-13th December 2017.

1.0 CHAPTER ONE: INTRODUCTION

1.1 Background

The future of sustainable and affordable housing in Nigeria is seriously dependent on the capacity to harness and utilize our local building materials in an innovative manner. The necessity for sustainable and affordable construction projects in Nigeria and other developing countries is on the increase as a result of the problems of high cost of cement and other conventional building materials [1,2,3]. In Nigeria, neither the government nor the private sector can provide adequate and affordable housing units, particularly to low-income citizens. The housing problem seems to be getting worse as the population of the country continues to increase. According to the 2018 African Housing Finance Yearbook by Centre for Affordable Housing Finance in Africa, formal housing construction is at roughly 100,000 units per annum and this is profoundly deficient on the grounds that the minimum rate of 1000 units is required yearly to achieve the 17 to 20 million housing shortage by government's deadline target of 2033 (if the populace maintains its yearly growth rate of 3.5 per cent). The cost of building a house is high in Nigeria due to the high cost of conventional building materials. National Bureau of Statistics [4] put the estimated cost of building an average house in Nigeria at $50,000. It is estimated that it will cost US$363 billion to check the present housing deficit and the number is predicted to continue increasing with time [5]. According to the U.S Census Bureau, Nigeria's population is projected to increase by 3.2% annually with an estimated population of 402 million people by the year 2050 [6].

The need for the use of eco-friendly materials in construction and building industries arose as a result of the irreversible environmental impacts associated with the production and use of depletable conventional building materials. In addition to the challenge of housing deficit is the global warming caused by the effects of greenhouse gases emission during the production of cement coupled with the high cost of these conventional building materials. These have made it an imperative to seek for alternative, affordable and sustainable building materials. In 2014, CO_2 emissions from cement production for Nigeria was 2,720 thousand metric tons. CO_2 emissions from cement production of Nigeria increased from 134 thousand metric tons in 1965 to 2,720 thousand metric tons in 2014 growing at an average annual rate of 8.29 % [7]. Hence, the housing deficit coupled with ozone layer depletion has prompted researchers to begin to search and identify alternatives to all the processes that involve the emission of greenhouse gases and these efforts have resulted in Green Building Projects.

Lateritic soil is composed mainly of quartz, iron–magnesium–manganese (amphibole group) and kaolinite [8]. Soils having a ratio of silica to sesquioxide [$SiO_2/(Fe_2O_3 + Al_2O_3)$] which are less than 1.33 are classified as laterites whereas the ones between 1.33 and 2.00 are classified as lateritic soil, and those above 2.00 are classified as non-lateritic soils [9]. Lateritic soil deposits exist in abundance in the many States of Nigeria and this can be adequately harnessed for the production of lateritic bricks for affordable construction applications. Lateritic brick is a sustainable alternative to cement block because of the minimal amount of cement required for the stabilization of the lateritic soil which significantly reduces the destructive emission of CO_2 that are common with consumption of cement and concrete. However, the low compressive strength of natural lateritic soil necessitated the search for a sustainable stabilizer other than cement. Research by Nigerian Building and Road Research Institute [10] led to the recommendation of the following specifications: compressive strength of 1.65 N/mm^2, bulk density of 1810kg/m^3, the durability of 6.9%, and water absorption of 12.5% with maximum cement content fixed at 5% as the minimum requirements for laterite bricks.

The effectiveness of using hydrated lime for the stabilization of lateritic soil had been established by various researchers. However, hydrated lime is more expensive than cement in Nigeria, as the cost of 50 Kg of cement can only purchase 12.5kg of hydrated lime [11]. This high cost of hydrated lime has made it a non-viable material for the construction of sustainable buildings. Hence, the need to seek an alternative to lime for stabilization of soil. Agro-waste ash is a promising alternative to lime as agro–wastes are produced in hundreds of metric tonnes yearly in Nigeria [12]. The exploitation of agro-waste for soil stabilization will result in value addition to the agro-wastes as well as clean up the environment from pollution caused by the agro-wastes. The valorization of agro-wastes (corn cobs, cattle bones, rice husk, coconut coir, bagasse, durian peel, oil palm leaves, tobacco residue, sawdust, and cotton waste) in the field of civil engineering is a profitable alternative to cement for sustainable construction applications and have been slightly investigated [13-18,9,19,20]. However, all possible biomass and agro-waste have not been investigated. This study aims at achieving effective stabilization and utilization of lateritic soils using agro-waste ash for sustainable and affordable construction applications. It will lead to a reduction in cement consumption and addition of economic value to agro-waste.

1.2 Problem Statement

The specific problems addressed by this study include;

a. The high cost of conventional building materials;
b. Global warming/ emission of greenhouse gases (CO_2) resulting from a high rate of cement consumption;
c. Environmental pollution from agro-waste;

d. Poor mechanical properties of lateritic soil.

1.3 Unresolved Issues

In a bid to provide affordable building, sustainable infrastructures and clean environment, this study will be addressing the following gaps in knowledge:

- Understanding the behaviour of agro-waste ash – lateritic soil matrix composite when subjected to loading;

- Absence of multivariate stochastic models for predicting the mechanical properties of agro-waste stabilized lateritic soil;

- Although extensive works have been done on the shear strength, settlement potential, swell potential, permeability and other physical properties, little work has been carried out on the compressive strength of agro-wastes stabilized lateritic soil;

- Absence of comparative study on the stabilization potential of the combination of the bone ash and palm bunch ash on lateritic soil.

1.4 Research Objectives

This study aims at achieving effective stabilization and utilization of lateritic soils using agro-wastes for sustainable construction applications.

The objectives include:

i. Production and characterization of agro-waste ash for improving the mechanical properties of lateritic soil;

ii. Comparison of the effects of agro-waste ash stabilizers on the mechanical properties of stabilized lateritic bricks;

iii. Determination of the effects of the different compositions of the water content of the mix design on the mechanical properties of stabilized lateritic bricks;

iv. Development and use of multivariate (linear, non-linear and mixed) statistical models to predict the compressive strength of stabilized lateritic bricks as a function of relevant parameters;

1.5 Scope of Work

This research covers the following:

- Production and characterization of agro-waste ashes for lateritic soil stabilization;
- Setting up an experiment to use different levels of agro-waste ashes to develop stabilized lateritic bricks;
- Comparison of the strength of the stabilized lateritic soils to the raw sample collected;
- The use of compressive strength to evaluate the effectiveness of the agro-waste ashes in improving the properties of lateritic soils in the construction industry;
- Evaluation of the effects of the different percentage of water content, curing age, curing temperatures and specimen sample sizes on the strength of compressive strength of both raw and stabilized lateritic soil;
- Development of a statistical relationship relating the identified compressive strength of lateritic soil with respect to the level of agro-waste ashes used;

- Formulation and testing of predictive stochastic models for predicting the compressive strength of stabilized lateritic bricks using the rule of the mixture and regression analysis respectively;

- Comparison of predicted compressive strength of the stabilized bricks with experimental data from the literature.

1.6 Dissertation Layout

This dissertation consists of six chapters whose contents have been published or under review in SCOPUS indexed Journals.

Chapter 1 contains the general introduction of the dissertation which focuses on the background of the study, research problem, gaps in knowledge, scope of the study and dissertation layout.

Chapter 2 covers a detailed literature review which centres on the raw materials used in the study, description of production and characterization techniques used, mechanism of strength improvement of lateritic soil stabilized with agro-waste ash and prediction methods linking lateritic brick mix design to compressive strength.

Chapter 3 exhibits a model study that considers the mechanical behaviour of lateritic soil stabilized with bone ash and hydrated lime for sustainable building applications. The microstructure of the samples and the effects of hydrated lime and bone ash soil stabilizers on lateritic soil was demonstrated.

Chapter 4 explores the use of multivariate regression models for predicting the compressive strength of bone ash stabilized lateritic soil for sustainable building. Comparison of the Different

Models, Regression Analysis using the Best-fit Model, and Individual Factor Analysis were considered. Practical implications of the best-fit model were also presented.

Chapter 5 investigates the performance of lateritic soil stabilized with a combination of bone and palm bunch ash for sustainable building applications**.** The microstructure of the materials and lateritic bricks; the influence of curing temperatures and water content on the compressive strength of lateritic bricks; effect of weight percentage of the soil stabilizers and size effects of the specimens on the compressive strength of lateritic brick; and influence of curing age on the compressive strength of lateritic bricks were evaluated.

Chapter 6 presents the contribution to knowledge, major conclusions arising from this study and areas for future work.

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2.0 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter introduces lateritic soil as a sustainable and affordable building material that is locally available in Nigeria. Sustainable housing in Nigeria was reviewed. The differences between lateritic bricks and sandcrete blocks were explored. The need to improve the compressive strength of lateritic bricks led to the evaluation of the use of agro-waste ash as a stabilizer. Techniques used in the production of bone ash and palm bunch ash were presented in this section. Also, the mechanism of strength improvement of lateritic soil stabilized with agro-waste ash was established. Review of the studies on prediction linking lateritic brick mix design to compressive strength methods was presented.

2.2 Sustainable Housing in Nigeria

Increase in population has led to a rise in demand for housing and urban infrastructure in Nigeria [1]. The projected population of Nigeria in 2030 has huge implications for the wellbeing of society. A major implication is the inability of the government to meet up with the provision of adequate housing and infrastructure for all, leading to homelessness. According to Global Homelessness Statistics [2] by the Homeless World Cup Foundation, the number of homeless people is increasing by the day in Nigeria. United Nations High Commissioner for Refugees (UNHCR) [3] stated that ‘there are an estimated 24.4 million homeless people in Nigeria as a result of many factors, including rapid urbanization, poverty, and terrorism. The use of sustainable local materials is key to ensuring adequate housing and urban development [4] since the cost of building will come down. According to Ibimilua [5], there is a need for a realistic housing policy that must consider slum upgrading, periodic repair and maintenance, as well as urban renewal and encouraging the use of local building materials.

2.2.1 Obstacles to Sustainable Housing in Nigeria

The challenges of housing and urban development in Nigeria have been discussed by different researchers [6-8]. These include poor maintenance of infrastructure, bribery and corruption, lack of product-driven research, preference of foreign goods and services over local ones, poor policy formulation and implementation, high cost of building materials, poor compliance to regulations and standards, poor budgeting and budget implementation, lack of commercialization of research findings, poor funding mechanism and lack of skilled manpower [5].

i. Poor Maintenance of Infrastructure

Nigeria is ravaged by lack of maintenance culture in public projects and infrastructure [9-11]. This has resulted in the presence of a high number of dilapidated housing and urban infrastructure which increases the housing and urban infrastructure deficit in Nigeria. Poor maintenance of housing and urban infrastructure affects the performance of the infrastructure and can lead to outright damage or failure. Maintenance culture which encompasses provision for adequate care of infrastructure has not been given the desired attention by resource managers in Nigeria over the years [10]. Nigeria has about 195,500 km of road network all over the country. Out of the whole, a proportion of about 32,000 km is federal roads while 31,000 km are state roads. A large proportion of these roads is in poor condition due to lack of maintenance [12]. Tijani et al. [11] opined that most of our public and private facilities are in a total state of a mess because of the non-existence of maintenance policy, or poor implementation of the policy. A good example is the Urban Mass Transit buses introduced in Abuja the administration of President Obasanjo (1999-2007) which are today dilapidated.

ii. Bribery and Corruption

Ogundiya [13] in his work saw corruption as the exploitation of public position, resources and power for private gain. Despite huge allocations of money to the housing sector in the National Development Plans, very little was achieved in terms of meeting specified targets in housing construction. Mismanagement of project funds has led to the presence of many uncompleted projects in Nigeria [14]. According to Crowe [15], political corruption in Nigeria has led to a concentration of wealth among few elite government officials resulting in a poor level of infrastructural development in Nigeria. Report by National Bureau of Statistics [16] pointed out that the fact that almost one-third of Nigerians who had contact with a public official paid one or more bribes over the year shows that bribery is clearly a significant issue in the lives of Nigerians. Despite the concerted efforts by the Economic and Financial Crime Commission (EFCC), Independent Corrupt Practices and Other Related Offenses Commission (ICPC), Nigerian Police, DSS and other government security agencies, the negative narrative about corruption has not changed significantly. The implication of this is that well thought out policies and programmes in the sector are poorly executed.

iii. Land Disputes and Speculation

One of the major causes of conflict in Nigeria is land disputes. The issue of land grabbing has altered the urban cities plans leading to land disputes that have claimed so many lives and properties. Blench [17] pointed out that Fulani pastoralists and farmer crisis represent "the most significant focus of herder/farmer conflict in Nigeria".

iv. Preference of Foreign Goods and Services to Local Ones

There has been neglect of the use of local goods and services by operators in the housing sector. This could be as a result of poor standards, lack of promotion of the use of local goods and services by government and lack of patriotism by citizens. The rate of importation of goods and services in the housing and urban development sector in Nigeria is alarming. According to Abolo [18], imported raw materials are cheaper and considered more appealing despite their poor quality and safety issues sometimes. This is seen in the way the government prefers to engage foreign firms in mega infrastructure probably because of loan-funded arrangements. Hence, the local Engineers and Specialists in housing and urban development sector are left with minor projects. This unfair competition with foreign goods and services results in poor patronage of local goods and services in the housing and urban development sector in Nigeria [19]. In most building materials markets in Nigeria, over 80% of goods (plumbing, wiring, tools, equipment, steel, etc.) are imported. It is only in cement and granite that significant progress has been achieved in local content.

v. Poor Policy Formulation and Implementation

In 1991, the National Housing Policy was enacted in order to propose possible solutions to housing problems in Nigeria [20]. At inception, the basic goal of the policy was to provide affordable housing to accommodate Nigerian households in a livable environment. However, twenty-seven years after the promulgation of the policy and eighteen years after the target year 2000, many Nigerians are still unable to own a house while several others are living in indecent houses.

The Nigerian housing policy was well conceived with the fundamental elements of feasibility, affordability and limited time frame required for the completion of the programs. To some extent, the various policies and programs of housing in Nigeria have been able to make significant improvements in housing production and delivery. The guidelines for housing construction, maintenance and delivery are stipulated by the housing policies. Nevertheless, the policies and programs are besieged by shortcomings such as poverty, ever-increasing costs of construction and building materials, homelessness, weak institutional frameworks for housing delivery, administrative bottlenecks in plan approval and collection of certificates of occupancy, program monitoring as well as review. The gap between policy formulation and policy implementation must be bridged to achieve the desired development in the sector. This can be achieved through more effective implementation, monitoring and evaluation strategy. Government agencies such as Federal Housing Authority (FHA), State Housing Development Authority, National Office for Technology Acquisition and Promotion (NOTAP), Federal Ministry of Works and Housing (FMWH), State Ministry of Works and Housing (SMWH), National Assembly Committee on Housing (NACH) and State Assembly Committee on Housing (SACH) will be instrumental in achieving policy formulation and implementation.

vi. High Cost of Building Materials

It is becoming increasingly difficult for an individual to own a house as a result of the high cost of building materials in Nigeria. This is because building material is a major component of construction cost and a reduction in the cost of material will result in the reduction in the overall construction cost. According to Babatunde [21], the average earning the power of a middle-class Nigerian is in the range of 75,000-100,000 Naira per month whereas the cost of owning a house in Nigeria runs into several millions of Naira. Reliance on expensive conventional building materials has escalated the cost of housing and other infrastructure. A shift towards the use of alternative and local building materials will definitely bring down the cost of materials and affordable housing will be possible. Alternative and local building materials are cheaper but seldom used because of poor efficiency in terms of strength and durability. The inability of improving the strength and durability of the alternative building materials to make them more appealing to Nigerians has kept the price of the conventional building materials very high.

vii. Poor Compliance to Regulations and Standards

Professional bodies such as Nigerian Institution of Civil Engineers (NICE), Nigerian Institute of Architects and Nigerian Institute of Building (NIOB) are entrusted with the task of developing standards for the regulation of building and urban infrastructures whereas Council of Registered Builders of Nigeria (CORBON) and Council for the Regulation of Engineering in Nigeria (COREN) and Federal/State Ministry of Works and Housing are mandated to enforce the codes and standard of building and urban infrastructure. The Standard Organization of Nigeria (SON) and the Nigerian Society of Engineers (NSE) are also empowered to enforce engineering codes and standards among practitioners across the country [22]. The ineffectiveness of the regulatory bodies to ensure strict adherence to regulation and standards in housing and urban development sector has affected the sector adversely. The rate of building collapse in Nigeria is alarming (Table 2.1). Averagely, more than 100 buildings collapse annually in Nigeria. However, most of the building collapse in Nigeria are not documented.

Table 2.1

Building Collapse in Nigeria [23-28]

S/No.	Description	Date of Collapse
1	Ita Faji, Lagos Island	March 2019
2	Sogoye area, Ibadan	March 2019

3	Apo Mechanic Village, Abuja	December 2018
4	Port Harcourt, Rivers State	November 2018
5	Benue State University Makurdi, Benue State	November 2018
6	Otolo Nnewi, Anambra State	October 2018
7	Zaria, Kaduna State	September 2018
8	Jabi, Abuja	August 2018
9	Opi, Enugu State	June 2018
10	Agege, Lagos State	March 2018
11	Ibadan, Oyo State	March 2017
12	Ogidi, Anambra State	March 2017
13	Unguwar Tambai, Maigatari, Jigawa State	April 2017
14	Ilasa area, Lagos State	May 2017
15	Obi/Akpor, River State	May 2017
16	Massey Street, Lagos Island, Lagos State	July 2017
17	Umuguma, Owerri, Imo State	July 2017
18	Ojo area, Lagos State	August 2017
19	OniFufu Compound, Ogun State	March 2016
20	Lekki District, Lagos State	March 2016
21	Itokun Market, Ogun State	May 2016
22	Ndiagu-Ogidi, Anambra State	July 2016
23	Obosi and Oko, Anambra State	July 2016
24	Asaba, Delta State	July 2016
25	Uratta village, Imo State	August 2016
26	Kano State University, Kano State	August 2016
27	Gwarimpa, Abuja	August 2016
28	Kado Village, Abuja	October 2016
29	Uyo, Akwa-Ibom State	December 2016
30	Yaba area, Lagos State	July 2015
31	Bukuru, Jos, Plateau State	September 2015
32	Swamp Street, Odunfa, Lagos Island, Lagos State	October 2015
33	Ibadan, Oyo State	May 2014
34	Ikotun Egbe, Lagos State	September 2014

35	Bukuru, Jos, Plateau State	September 2014
36	Umuahia, Abia State	May 2013
37	Ibadan, Oyo State	July 2013
38	Ebute Meta, Lagos State	July 2013
39	Hadeja Road, Kaduna State	July 2013
40	Lagos Island, Lagos State	September 2013
41	Muri Okunola Street, Lagos State	November 2013
42	Angwan Dosa, Kaduna State	December 2013
43	Gwarimpa, Abuja	January 2012
44	Freeman Street, Oyingbo, Lagos State	July 2012
45	Apo Mechanic Village, Abuja	August 2012
46	Anikantamo Street, Adeniji-Adele, Lagos State	August 2012
47	Dutse-Alhaji, Abuja	August 2012
48	Jakande Estate, Isolo, Lagos State	November 2012
49	Idumota/Ebute Ero, Lagos State	July 2011
50	Mararaba, Abuja	July 2011
51	Mpape, Abuja	August 2011
52	Maryland, Lagos State	October 2011
53	Cairo Market, Oshodi, Lagos State	May 2010
54	Ikole Street, Abuja	August 2010
55	Gimbiya Street, Garki, Abuja	August 2010
56	Victoria Island, Lagos State	September 2010
57	Ogbomosho, Oyo State	February 2009
58	GRA, Enugu	August 2009
59	Ibadan, Oyo State	March 2008
60	Ojota, Lagos State	April 2008
61	Wuse, Abuja	August 2008
62	Farm Center Layout, Kano State	August 2008
63	Egerton Street, Oke-Arin, Lagos State	June 2007
64	Ebute-Metta, Lagos State	June 2007
65	Ajeromi Ifelodun, Lagos State	January 2006
66	Broad Street, Lagos Island, Lagos State	March 2006
67	Ikpoba-Okha, Edo State	April 2006

68	FCT, Abuja	June 2006
69	Ebute Metta, Lagos State	July 2006
70	GRA, Port Harcourt, Rivers State	July 2005
71	Mushin, Lagos State	April 2001
72	Iju-Ijesa, Lagos State	August 1999
73	Ifo, Ogun State	October 1999
74	Akure, Ondo State	October 1998
75	Abeokuta, Ogun State	November 1998
76	Mushin, Lagos State	June 1997
77	Oshodi, Lagos State	May 1996
78	Ogba, Lagos State	October 1995
79	Port Harcourt, Rivers State	June 1990
80	Barnawa Housing Estate, Kaduna	August. 1977
81	Mokola, Ibadan, Oyo State	October 1974

viii. Poor Funding Mechanism

Access to finance is a serious challenge for Nigeria economic sector. Lack of access to finance affects the supply of housing and urban infrastructures in Nigeria. Although there is a reasonable supply of housing credit by financial institutions, there is limited access to finance by low-income households. Okonkwo [29] advocated that the Federal Mortgage Bank of Nigeria should be given adequate resources by the government to strengthen its financial and operational capabilities. Housing and urban infrastructure funding mechanism in Nigeria includes Federal Mortgage Bank of Nigeria (FMBN), Commercial Mortgage Banks, Micro Finance Banks (MFB), National Housing Fund (NHF), Infrastructure Banks Plc (IB Plc), Lapo Micro Finance Bank (Lapo MFB), Central Bank of Nigeria (CBN), Nigeria Mortgage Refinance Company (NMRC) and Private Developers. Despite the available funding mechanism in Nigerian housing and urban infrastructural sector, the desired result of housing for all has not been achieved because of the high-interest rate of housing loans and administrative bottlenecks in getting a housing loan.

ix. Lack of Skilled Manpower

The skilled manpower required in the building and infrastructure industry include artisans, electricians, tilers, carpenters, plumbers, welders, painters, etc. Inadequate availability of skilled manpower has affected the provision of adequate housing and urban infrastructure in Nigeria [30]. The managing director of Bank of Industry, Mr Olukayode Pitan, bemoaned that the stock of competent skilled construction workers is rapidly decreasing, with a 15 per cent annual decline of artisans in the construction sector [31]. Poor quality work leading to high maintenance cost and project failures has besieged the nation as a result of a deficit in skilled manpower. Establishment of functional training Institutions by the government and private sector for artisans and other skilled personnel in the field of housing and urban development will go a long way in providing adequate skilled manpower. Certification, retraining and continuous personal development courses are important in having competent skilled construction worker. Closely related to skills is a lack of tools and machines for the construction industry.

x. Poor Budgeting and Budget Implementation

In Nigeria, research and innovation are mainly funded by the government with a meagre budget of 0.1% of GDP (Gross Domestic Product) instead of at least 1% of GDP as stipulated by *United Nations Educational, Scientific and Cultural Organization* (UNESCO). The infrastructural need of the Nigerian society keeps increasing as the population of the nation keeps increasing. There is a huge gap between the infrastructural need an annual budget allocation in Nigeria. Late passage of the annual budget in Nigeria has led to poor implementation of the budget and sometimes the budget release is about 50% or less. Ojoye [8] recommended that the government must ensure adequate funds are not only allocated to capital expenditure but also disbursed timely and utilized as budgeted. Hence, there is a need for the Nigerian government to increase its budgetary allocation to infrastructural development in order to bridge the gap in infrastructure. The idea of government estates was discontinued in 1999. This needs to be revisited as private estates are expensive.

xi. Lack of Product-driven Research

Research on building and infrastructure development is currently going on in Universities, Polytechnics, Nigerian Building and Road Research Institute (NBRRI) and Federal Ministry of Works and Housing. The Obasanjo Housing Estate, Ado-Ekiti, Nigeria was constructed with local building materials (red bricks) using NBRRI fabricated interlocking block-making machine. The use of earth materials for building in Nigeria has arisen out of extensive applied research and development notably by the NBRRI [10]. The problem with the research institutions is that there are no adequate linkages with industry [32]. Lack of linkages between research institutions and industries is as a result of lack of product-driven research. National Board for Technology Incubation (NBTI) provides institutional infrastructure and mechanism for the development and commercialization of research and development (R&D) outputs and inventions. Research ventures are expected to end in products that could be commercialized to add value to society. This is not the case of most research works in Nigeria. Most of the research findings in Africa end up on the shelves in the library [33]. The lack of interaction among elements of the innovation system, weakness in R&D activities and marketing plan, poor or no incentives from the government to drive the industry to utilize local technology or research results have led to poor commercialization of research findings [34, 35]. There is a lack of product-driven research that will drive the development of housing and urban infrastructure in Nigeria. These researches are required in the areas of building materials, methods of construction, housing delivery systems, financial products, maintenance, etc.

xii. Lack of Commercialization of Research Findings

In Nigeria, the issue of research commercialization is not receiving the desired attention [35, 36]. Ogunwusi and Ibrahim [37] noted that ‘effective commercialization of research results in any nation will depend on rapid technological innovation, effective strategic management of knowledge and a clear focus on value-added goods, services and industries’. This is not yet happening in Nigeria as a result of inadequate supports and poor funding of research by institutions, government and private sector. The Nigerian government is yet to fully support research works like its counterpart in developed countries. National Board for Technology Incubation (NBTI) and National Office for Technology Acquisition and Promotion (NOTAP) have the responsibility of managing the intellectual property rights and technology transfer issues in Nigeria and hence facilitate the process of commercialization [38]. Less than 2% of Research & Development (R&D) in Nigeria has been commercialized. This led Siyanbola et al. [39] to recommend a change in commercialization strategy in Nigeria through networking and collaboration among key stakeholders in the commercialization process. Onwualu [40] identified the steps and actions required for taking a project from initiation to commercialization which includes idea generation, screening of ideas, research and development, business analysis, prototypes development, test marketing and commercialization. A framework for commercialization was presented by Ugonna and Onwualu [35].

2.2.2 The Role of Research and Innovation in Overcoming the Obstacles to Sustainable Housing in Nigeria

The obstacles identified above can be eliminated through research and innovation. These include the formulation of good policies, development of new materials, the improvement on the efficiency of local materials, job creation, better understanding of population dynamics, evolution of the integrated approach to housing and urban development, and new functional designs for housing and urban infrastructure.

a) Formulation of Good Policies and their Implementation

The outcome of research in the housing and urban development sector can be harnessed and used by policymakers in the formulation of good policies that will help in the advancement of housing and urban development sector in Nigeria. Hence, creating a database for the storage of research findings will make it easy for policymakers to easily access the research findings and utilize them in formulating well-informed policies for sustainable housing and urban development. According to Lawal [41], most comprehensive housing policy should address the role of government which may vary from the planning and control of all aspects of housing production – land, investment, construction and occupancy – to intervention only at certain levels or when solutions are needed for specific problems involving such matters as land use plans and controls, credit and financial aids, subsidies to low-income groups, rent control, slum clearance and relocation. There is also a need for an innovation policy framework that will produce researchers with entrepreneurship skills. Therefore, a major role of research and innovation can play in this area include a comprehensive study of the policies, development of new policies, the study of the implementation of existing and past policies, and study of best global practices.

b) Development of New Building Materials

Product-driven research will surely give birth to new building materials that can be commercialized. When new materials are produced via research, they will compete with the conventional materials and will help to check the hike in the prices of the conventional materials [42]. This type of competition will result in the availability of affordable and sustainable materials for housing and urban development. Both government and private-owned manufacturing firms should support productive research and innovation to develop new products and processes that would enhance competitiveness. New frontiers in building materials research include: nanotechnology, natural fibre reinforcement, use of agro-wastes in making bricks, thermal envelop materials, composite, materials with acoustics, energy-efficient construction, lightweight materials, smart materials, green building, biocomposites, modelling of materials, nanocomposite materials, hybrid materials, green pave and advanced materials.

c) Improvement in the Efficiency of Local Building Materials

The use of research to make local building materials better is important in overcoming the challenges of housing and urban development in Nigeria. Applying research findings aimed at improving the strength, durability and efficiency of local materials will enable them to compete favourably with foreign ones. Oni [43] pointed out that it will be difficult to produce affordable housing without making use of locally sourced materials obtained through research and innovation. Research and innovation tasks in this area include making materials serve longer terms as well as withstand extreme weather conditions.

d) Job Creation

Research is like a business. Research leads to innovation which leads to new material and new method of construction through start-ups and clusters. The commercialization of research findings creates many entrepreneurs. These entrepreneurs can come together as clusters to establish cottage industries to solve the needs of society while making money. There is a need for key institutions that are responsible for linking knowledge to innovative entrepreneurship and growth to step up their game to see that the wealth of knowledge emanating from research findings are turned to useful products [44]. They should also assist in overcoming the challenges of providing an institutional framework that connects knowledge and entrepreneurship in promoting housing and urban development in Nigeria. A good example is the promotion of technology-based start-ups in the building industry. These start-ups can focus on service delivery, connecting professionals and businesses in the industry and providing cost-effective linkages to consumers.

e) Better Understanding of Population Dynamics

The continuous population increase in Nigeria demands a better understanding of population dynamics in order to cope with the challenges associated with population growth. Uncontrolled population growth has huge implications such as inadequate power supply, poor waste disposal, inadequate housing, and growth of slums, traffic congestion, and shortage of water [45]. The role of research in providing a better understanding of the population dynamics and infrastructural development is key to developing a functional housing policy for the provision of housing and urban infrastructure. Research focus in this area includes the study of rural-urban migration, settlement of indigenes population, housing needs and requirements, as well as the socio-economic status of consumers in the housing sector.

f) Evolution of Integrated Approach to Housing and Urban Development

Nigeria must begin to add action to the talk regarding her infrastructural development to prevent the country from experiencing a serious crisis in the near future. Therefore, there is a need for a more functional integrated approach to housing and urban development to forestall the imminent crisis in housing and urban infrastructural sector. The integrated approach of Public-Private Partnership (PPP) is key to achieving the desired infrastructural development in Nigeria. PPP basically involves the provision of land by the government to interested private developers who are able and willing to utilize their resources to develop real estate for sale to members of the public including institutions. Nigerian government at all levels can partner with the private sector to provide affordable infrastructure to Nigerians. Good models of PPP can be obtained through research. Research focus in this area includes the study of successful PPP schemes in other countries, the study of the existing PPP projects in the sector in Nigeria and evolving new PPP models to suit the Nigerian environment.

g) New Functional Designs for Housing and Urban Infrastructure

The government has been unsuccessful in its approach to achieving the goal of the National Housing Policy and its institutional framework. Therefore, incisive research to develop new functional designs for housing and urban infrastructure is a necessity for providing affordable housing and urban infrastructure in Nigeria. A comprehensive housing and urban infrastructural need assessment based on reliable data obtained via research especially of demographic parameters such as population growth and urbanization trends have to be thoroughly done [46]. These assessments will be very instrumental in developing new functional designs and policies for the desired development in the housing and urban infrastructural sector.

This can be done on a regional basis which can lead to regional housing and infrastructure development plans.

2.3 Sustainable Building Materials

The future of sustainable and affordable housing in Nigeria and Africa as a whole lies in the beneficiation of the abundant local building materials. The problems of the high cost of cement and other conventional building materials have necessitated the increase in the demand for sustainable and affordable construction projects in Nigeria and other developing countries [47]. Sustainable building materials can be classified as building materials that have the capacity of meeting the needs of the present generation without compromising the ability for future generations to meet their own needs [48]. Most of these sustainable building materials have good insulating properties and are cheaper to produce when compared to conventional materials. Utilization of the locally available building materials has the benefit of reducing the cost of construction cost as well as providing buildings that are suitable for the local environmental conditions. These environment-friendly building materials require less energy to produce and impacts more sustainability to buildings [49]. The major characteristics of sustainable building materials are shown in Figure 2.1.

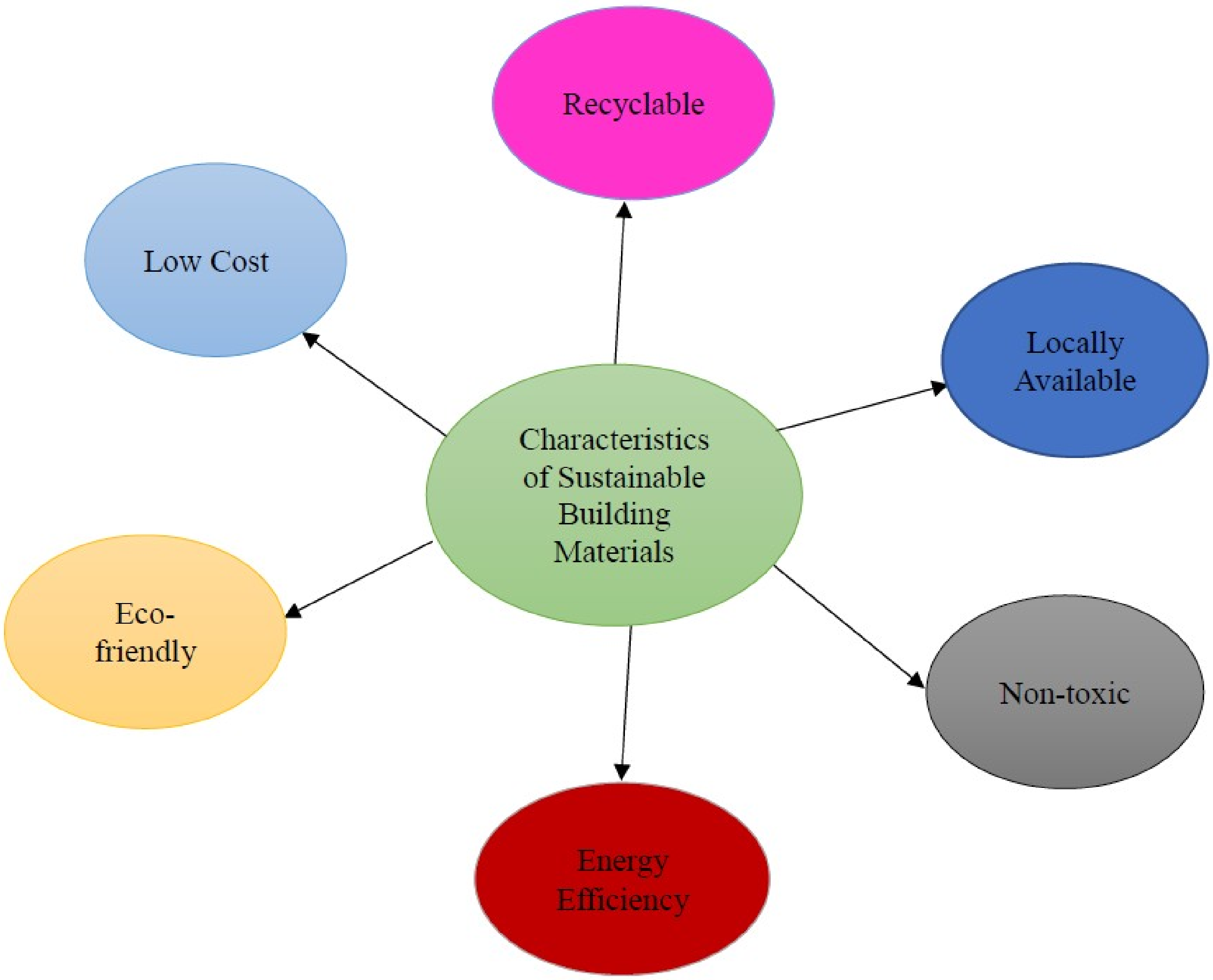

Figure 2.1: Major Characteristics of Sustainable Building Materials

2.3.1 Lateritic Soil as a Sustainable Building Material

Sustainable building materials are those materials that have the capacity of meeting the building needs of the present generation without having a negative effect on the capability of future generations to meet their own needs [50]. Lateritic soil is regarded as a sustainable building material because it can be recovered 100% when recycled or deconstructed. Although the advantages of sustainable building materials are well known, the use of conventional and high-impact building materials such as cement is still on the rise [51]. In order to achieve sustainable construction, efforts must be targeted at improving local building materials production processes, materials recycling/reuse, materials substitution, as well as the utilization of eco-friendly and innovative materials.

2.3.2 Lateritic Bricks versus Sandcrete Blocks

Although the cement block is currently the conventional building material, bricks made from lateritic soils have been used for the building of houses and edifices since ancient times. The major advantages of lateritic bricks over sandcrete blocks is the low cost of production as a result of the small quantity of cement or stabilizer needed to produce lateritic bricks with adequate compressive strengths [52]. The densities of lateritic bricks are greater than that of sandcrete blocks which implies that they are expected to be more solid and durable when used as a walling unit in buildings [53]. The greater densities of lateritic bricks are attributed to the texture of lateritic soil which reduces the voids in the brick as a result of a wide range of particle sizes being able to bind closely together. There is high porosity in sandcrete blocks when compared to the lateritic bricks and this results in the lateritic bricks having greater compressive strength at cement content less than 10% [52].

2.4 Agro-waste Ash as Soil Stabilizer

Environmental pollution from heaps of agro-wastes littered in the streets has been a nuisance to the society. Efforts have been made on how to either recycle or re-use these wastes to reduce their implications and health hazards [54]. One of the diverse ways of managing agro-wastes is its use in the construction industry. Several researchers have used agro-wastes in the form of ash or fibre as a soil stabilizer or an admixture to improve the geotechnical and mechanical properties of soil. Ayininuola and Sogunro [55] worked on the effects of bone ash (BA) stabilization on shear strength of lateritic soil and found out that all tested samples attained maximum shear strengths at 7% bone ash stabilization. The impact of bone ash on the consolidation/ settlement of lateritic soil carried out by Ayininuola and Akinniyi [56] discovered that addition of about 7 to 10% of bone ash to the lateritic soils will significantly reduce their settlement potential and increase their stability. The use of corn cob ash (CCA) as a pozzolan in stabilizing lateritic soils for road pavement construction in a sub-tropical region was investigated by Apampa [57]. The study showed that ordinary portland cement-corn cob ash blends in the ratio of 1:1 used at optimization levels reduced the overall Ordinary Portland Cement (OPC) consumption by up to 26.8% and could result in a corresponding reduction in net CO_2 contribution to the environment. He suggested the promotion of the use of appropriate blends of OPC: CCA, rather than OPC alone for the stabilization of soils for road works because it helps not only in CO_2 emission control but also in getting economically rid of corn cob waste. Recent works on the geotechnical properties of Lateritic Soil stabilized with CCA by Nnochiri and Adetayo [58] obtained that corn cobs ash (CCA) reduced the Maximum dry density (MDD) from 1345kg/m3 at 0% CCA to 1284kg/m3 at 10% CCA and increased the optimum moisture content from 14.9% at 0% CCA to 20.20% at 10% CCA. Akinwumi and Aidomojie [59] explored the engineering properties of lateritic soil stabilized with cement -corncob ash and found out that the addition of cement -corncob ash to the lateritic soil generally reduced its plasticity, swell potential and permeability. The study on the stabilization potential of Nanosized palm bunch ash (NPBA) was carried out by Onyelowe [60] and it was shown that the optimum moisture content increased at 12 and 15% by weight of NPBA compared to the 0% NPBA proportion and that NPBA also increased the California bearing ratio (CBR) of the lateritic soil while MDD decreases. Deboch [61] reviewed previous work done on the stabilization of lateritic soils. In the research conducted by Aguwa [62], the compressive strength of laterite-cement blocks was found to have increased steadily with increase in the cement content percentages up to 20% but decreased when the cement contents are above 20%. Influence of bone ash on soil California Bearing Ratio (CBR) was conducted by Ayininuola and Denloye [63]. The bone ash (BA) was added in proportions of 0, 3, 5, 7, 10, 15 and 20% by weight and they found out that on the addition of BA, the CBR increased as a percentage of BA increased up to 7%, after which it decreased. This implies that BA of up to 7% can be used to enhance soil CBR for subgrade or road base material. The use of bone ash as an admixture to the kaolin-stabilized lateritic soil was carried out by Onyelowe [64] and he discovered that the addition of various percentages of bone ash increased the maximum dry density and reduced the optimum moisture content. Otunyo and Chukuigwe [65] worked on the potential of palm bunch ash to stabilize lateritic soil and found out that Palm bunch ash of between 20-25% can be used to stabilize lateritic soil.

Some representative studies on the use of agro-waste ash for stabilization of earth-based materials are shown in Table 2.2. It is evident that each of the agro-waste ash used in the previous studies shown in Table 1 improved the geotechnical and mechanical properties of soil. This indicates that agro-waste ash is a viable material for the stabilization of soil for building applications.

Table 2.2

Previous studies on the use of agro-waste for stabilization of earth-based materials

Reference	Agro-waste type	% Content of stabilization	Curing age	Type of earth-based materials	Properties of soil improved
Akinwumi & Aidomojie [59]	Corncob ash	0 - 12%	1day and 28 days	Lateritic soil	Geotechnical properties
Ayininuola & Sogunro [55]	Bone ash	3%, 5%, 7%, 10%, 15% and 20%	-	Sandy & Clayey soil	Shear strength

Okonkwo et al. [66]	Bagasse ash	from 0% to 20% at 2% intervals	7 days	Lateritic soil	Compressive strength and California bearing ratio
James [67]	Saw-dust or wood ash	5%, 10% and 20%	2 hours, 7, 14 and 28 days	Expansive soil	Unconfined compression strength (UCS)
Beigh & Lone [68]	Bone ash	2%, 4%, 6%, 8% and 10%	-	Clayey soil	Shear strength
Ayininuola & Denloye [63]	Bone ash	0, 3, 5, 7, 10, 15 and 20%	-	Sandy & Clayey soil	California bearing ratio

2.5 Production of Bone and Palm Bunch Ash

Cattle bones obtained from meat vendors were washed and sun-dried for two weeks after which they were burnt in an electric furnace at a temperature of 650°C. The burnt cattle bones were ground with a Jaw Crusher and then passed through 75μm mesh sieve to obtain a fine particle of BA as shown in Figure 2.2(a). Conversely, the collected palm bunches were sun-dried for one week after which they were burnt in the open air and allowed to cool before passing the resulting PBA through a 75μm mesh sieve to obtain a fine particle of PBA as represented in Figure 2.2(b). The chemical compositions of BA and PBA analysed using Thermo Scientific X-ray Fluorescence (XRF) Epsilon Spectrometer are shown in Tables 2.3 and 2.4 respectively. XRF analysis was done using the standard method with Montana soil SRM 2710 as a Thermo Fisher Scientific standard reference material. The result of the chemical composition analysis indicates the presence of oxide of calcium in both BA and PBA needed for the pozzolanic reaction with the lateritic soil is present both in the BA and PBA. The main oxides present in Portland cement which include CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO and K_2O were also present in BA and PBA as shown in the chemical composition of the BA and PBA represented in Tables 2.3 and 2.4. Soil stabilization can be achieved by the pozzolanic reaction between the CaO present in the stabilizers and the soil particles [69]. This implies that the addition of BA and PBA to the lateritic soil in the presence of water will produce a cementitious material containing C-S-H (calcium silicate hydrate) which is the main product of the hydration of Portland cement that is responsible for the strength in cement-based materials [70,71].

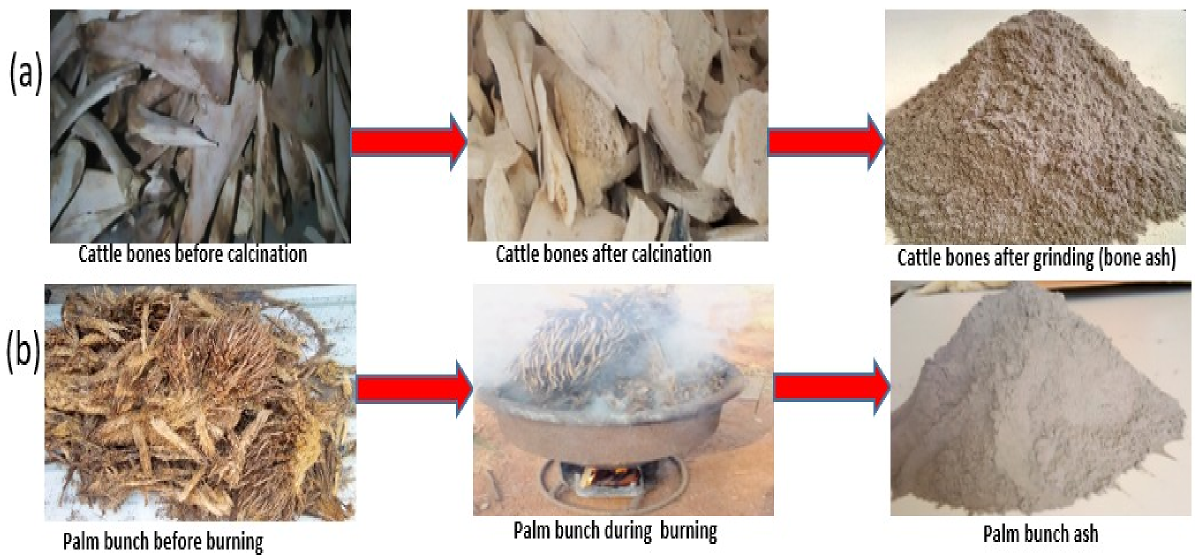

Figure 2.2. Production processes of (a) BA and (b) PBA

Table 2.3

Chemical composition of the palm bunch ash

Oxides	SiO_2	K_2O	MgO	CaO	P_2O_5	Al_2O_3	SrO	Fe_2O_3	MnO	ZnO	TiO_2
%	34.396	27.251	9.264	5.803	5.752	2.755	0.953	0.656	0.175	0.100	0.073

Table 2.4

Chemical composition of the bone ash [69]

Oxides	CaO	P_2O_5	MgO	Na_2O	SrO	Al_2O_3	K_2O	Fe_2O_3	ZnO
%	52.20	48.08	2.08	1.33	0.87	0.61	0.09	0.03	0.01

2.6 Mechanism of Strength Improvement of Lateritic Soil Stabilized with Agro-waste Ash

Lateritic soil is a commonly used local building material which is pozzolanic in nature. The likely reactions resulting in the strength improvement of lateritic soil stabilized with agro-waste ash include pozzolanic reaction, aggregation and carbonation [72]. Pozzolans are siliceous and aluminous materials that possess little or no cementitious value but which will, in finely divided form and in the presence of moisture will react with calcium hydroxide at ordinary temperature to form possessing cementitious compounds [73]. The ability of a pozzolan to react with calcium hydroxide and water is given by measuring its pozzolanic activity [74]. According to the ASTM C618 [75] recommendation, a material can be classified as pozzolanic if the sum of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 70%. Lateritic soil being rich in SiO_2, Fe_2O_3 and Al_2O_3 will react with calcium hydroxide in the presence of moisture at room temperature to form calcium silicate gel (cementitious materials) that binds the soil particles together [76]. Thus, the compressive strength improvement in stabilized lateritic bricks is as a result of the reaction between the pozzolanic materials and calcium hydroxide in the presence of moisture and shown below.

$Ca^{+} + 2(OH)^{-} + SiO_2$ (soil silica) $\rightarrow$ $CaO.\ SiO_2\ .H_2O$

$Ca^{+} + 2(OH)^{-} + Al_2O_3$ (soil alumina) $\rightarrow$ $CaO.\ Al_2O_3.\ H_2O$

The aggregation or flocculation of the soil particles is likely as a result of the exchange of cations or the flocking of additional cations to the clay component of the lateritic soil which cause the strength improvement of the stabilized soil [77]. Carbonation can occur when the carbon dioxide from the atmosphere reacts with oxides or hydroxides of calcium to form calcium carbonate [78].

The compressive strength is the most important strength improvement properties when compared to other mechanical properties of bricks with respect to brick walls. Research on stabilized lateritic bricks has shown that the compressive strength of stabilized bricks depends on curing temperature, soil properties, amount and type of stabilizers, mix design, moisture/water content, level of compaction and curing age [79-84].

2.7 Prediction Linking Lateritic Brick Mix Design to Compressive Strength Methods

Selected existing studies on prediction of compressive strength of stabilized lateritic bricks using different regression models are represented in Table 2.5. Some of the input variables used in the models represented in Table 2.5 include age, cement content, index properties (consistency and Atterberg's limit), field density, moisture content, specific gravity, sand, particle size, and laterite. These input variables were used to successfully predict the strength of lateritic bricks to a certain extent depending on the model and type of input variables employed.

Table 2.5

Previous studies on compressive strength prediction of the lateritic brick using regression models

Reference	Input variables	Curing age	Adopted model	Achieved R^2
Jafer et al. [85]	Age and Ordinary Portland Cement (OPC).	1, 3, 7, 14, 28 and 90 days	Non-linear multi-regression model	0.8534
Attoh-Okine & Fekpe [86]	Index properties, field density and moisture content.	-	Adaptive neural networks model	-
Iyeke et al. [87]	plasticity index, percentage of particles passing sieve No.200, specific gravity, liquid limit and plastic limit	-	Artificial neural network model	-
Ezeh & Anya [88]	Water, cement, sand and laterite	28 days	Scheffe's simplex model	-
Jaritngam et al. [89]	Cement content and curing time	3, 7, 14 and 28 days	Multiple regression models	0.97

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3.0 CHAPTER THREE: MECHANICAL BEHAVIOUR OF LATERITIC SOIL STABILIZED WITH BONE ASH AND HYDRATED LIME FOR SUSTAINABLE BUILDING APPLICATIONS

3.1 Introduction

The choice of building materials in the society has been influenced by availability and cost [1]. As a result of the high cost of conventional construction materials in most developing countries, owning a house is relatively difficult for the large proportion of low-income citizens. The Managing Director of Federal Mortgage Bank of Nigeria (FMBN) asserted that the housing shortfall is evaluated to be between 17–20 million housing units, growing yearly by 900 000 units, with a possible expense of N6 trillion, that is, US$16 billion [2]. In order to solve this problem, it is necessary to explore new ways of producing building materials from locally available materials at low cost. Over the years, the construction industry has moved from using local building materials to conventional building materials. However, issues of cost and availability have necessitated interest in earth-based materials in recent times. Lateritic soils are environmentally friendly materials [3,4]. Buildings constructed with earth-based materials are the most affordable since earth materials are available and are cheaper. Nigeria is blessed with these and other natural materials for construction [5]. Lateritic soil is used as a building material for the moulding of bricks and plastering in Nigeria [6]. It is a group of highly weathered soils formed by the concentration of hydrated oxides of iron and aluminium [7]. Lateritic soil as a locally available material looks promising as a better alternative to conventional building materials except for a few problems. It contains high plastic clay [8]. The high plasticity may result in cracks in construction projects [9]. In order to address this, there is a need for stabilization of lateritic soil. According to the American Society for Testing and Materials (ASTM), the reasons of soil stabilization include: increasing the strength of existing soil to enhance its load-bearing capacity, permeability improvement and enhancement of soil resistance to the process of weathering and traffic usage among others [10]. Stabilization of lateritic soil prevents future problems like swelling and damping which could lead to failure of the structure built with untreated lateritic soil [11]. It also aids the long-lasting of roads and buildings built with lateritic soil thereby saving the cost of maintenance [4]. It is therefore important, to understand the mechanical behaviour of lateritic soil and thus Figure out the techniques of its stabilization. Research on recycling of waste polyethene (PE) and using it as reinforcement in lateritic bricks for sustainable building materials indicates that the composite containing 20 vol. % of PE had the best combination of flexural/ compressive strength and fracture toughness [12]. The result also indicates that beyond 20 vol. % of PE, the compressive/flexural strengths as well as the fracture toughness values decrease. Due to the potential of geopolymer to fill spaces that exist between soil particles, Aziz and Mukri [13] worked on how to determine the best percentage of geopolymer that is suitable to improve the compaction parameter of lateritic soil and found that the lateritic soil mix with 15% of geopolymer gave the best value of dry density and moisture content of the soil with the heavy and standard compaction effort. Mustapha [14] worked on natural fibre (straw) reinforced lateritic soil and the result indicated improved mechanical properties such as compressive strength, flexural strength, and fracture toughness. A new liquid polymer soil stabilizer, which was developed for use as a means of stabilization treatment of soil known as SS299, was examined by Marto, *et al.* [15] and the results indicated that SS299 soil stabilizer was able to significantly increase the unconfined compressive strength and shear strength of lateritic soil. The influence of bone ash on the shear strength of soil was investigated by Ayininuola and Shogunro [16] and the results showed that bone ash played a fascinating role in increasing the shear strength of the soil. The geotechnical properties of lateritic soil stabilized with liquid soil stabilizers, canlite (SS 299) was analyzed by Mohd Yunus et al. [9] and it was observed that the SS 299 soil stabilizer was able to improve the geotechnical properties of the lateritic soil such that the unconfined compression strength increased with the curing period, the variation mainly occurring in the first 28 days. Achampong et al. [17] worked on the chemical stabilization of lateritic soils for road construction by looking at a case study of the lateritic soil and the result showed that only 6% lime addition was the most suitable for stabilizing the soil. Previous works done on the use of bone ash for stabilization of lateritic soils were focused on shear strength and consolidation [16]. There is, therefore, the need to focus on the morphology and compressive strength of stabilized lateritic soil. The specific objectives of the present study were to: characterize both the lateritic soil samples and the bone ash; determine appropriate mix proportions of stabilized lateritic soil using hydrated lime and bone ash as stabilization agents; determine the effects of hydrated lime and bone ash on the compressive strength of stabilized lateritic bricks; determine the effects of hydrated lime and bone ash on the morphology of stabilized lateritic bricks and determine the effect of different methods of curing on the compressive strength of stabilized lateritic bricks.

3.2 Materials and Methods

3.2.1 Sampling and sample preparation

The study location is Abuja, Nigeria (with GPS coordinates of 9° 4' 20.1504" N and 7° 29' 28.6872" E and an elevation of 491 meters). The bone ash was produced from the cattle bones obtained at no cost from the meat vendor shop in Gosa, Abuja. The raw lateritic soil sample, hydrated lime, and cattle bone ash are shown in Figures 3.1(a), (b) and (c) respectively. Nigerian lateritic soil samples were chosen for this research because they are abundantly available and are used in many geotechnical engineering works in Nigeria. Lateritic soil was obtained from a depth of 1–2 m below the ground surface. The two samples were obtained from Gosa (LSS1) and Sauka (LSS2), Federal Capital Territory, Nigeria. The lateritic materials were collected, room-dried and ground to fine particles (<2.36mm) using mortar. The choice of the particle size is based on previous work [18]. Commercially available hydrated lime, as well as bone ash obtained from calcined cattle bones, were used to stabilize the lateritic materials respectively.

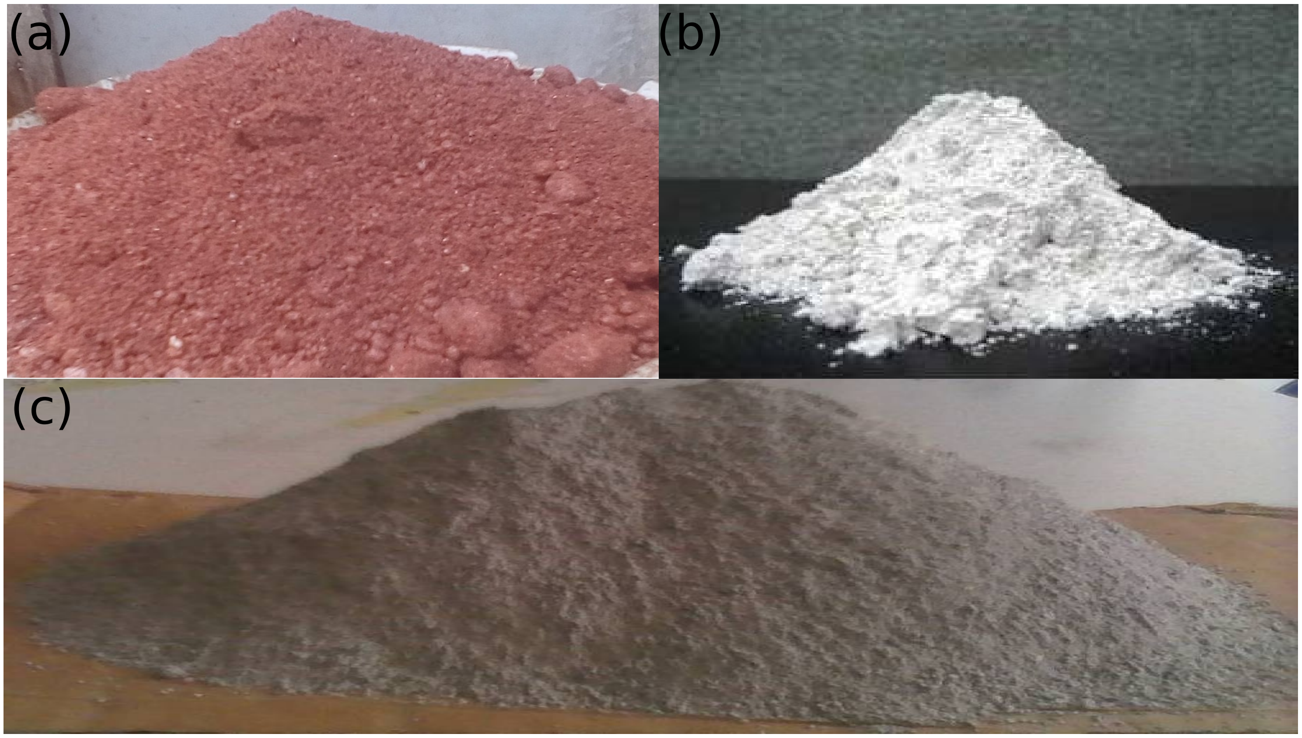


Figure 3.1. (a) Raw Lateritic Soil (b) Hydrated Lime (c) Cattle bone ash after calcination and grinding

3.2.2 Research Design

Different percentages of hydrated lime (3%, 9% and 15%) and bone ash (5%, 10%, 15% and 20%) were used in the stabilization of lateritic soil. Different curing methods (room-dried, sun-dried and oven-dried) and different levels of stabilizers were chosen based on previous works [6, 16]. The cattle bones were washed and dried for two weeks before calcination at 900^{o}C in an electric furnace. The calcined bones were crushed with a grinder and passed through No. 200 sieve (75μm) before usage. The choice of the particle size for the bone ash was based on previous work [19]. The hydrated lime was also passed through No. 200 sieve before usage. The lateritic bricks samples of different material matrices and compositions were produced (Figure 3.2). The effect of bone ash treated lateritic soil sample 2 (BAT2), lime treated lateritic soil sample 1 (LT1) and lime treated lateritic soil sample 2 (LT2) on the compressive strength of the soil were compared to that of untreated lateritic soil sample 1 (UL1) and untreated lateritic soil sample 2 (UL2) respectively.

Figure 3.2. Lateritic brick samples

3.2.3 Characterization of the Samples

Various tests were used to determine the compositions of the samples used and to ascertain the effectiveness of the hydrated lime and bone ash stabilizers on lateritic soil samples. The mineralogical compositions of the lateritic soil samples used for this research were analysed using X-ray Diffraction (XRD) test. The XRD test was carried out by using the Rigaku Miniflex 600 XRD machine with range 10-70 at a rate of 2 degrees/min and Cu K radiation. The chemical compositions of lateritic soil and bone ash were obtained using Thermo Scientific X-ray Fluorescence (XRF) Epsilon Spectrometer. XRF analysis was done using the standard method with Montana soil SRM 2710 as a Thermo Fisher Scientific standard reference material. Thermo Scientific Fourier-transform infrared spectroscopy (FTIR) Nicolet is5 Spectrometer was used in the characterization of the bone ash. The morphology and chemical composition of the samples was obtained using the Evo/LS10 ZEISS Scanning Electron Microscope (SEM). Tests were conducted on the natural lateritic soil samples to obtain their engineering properties. These tests included Sieve analysis (particle size distribution) and Atterberg limits tests. The particle size distribution and classification for the two lateritic soil samples were determined using British Standards (BS). The Atterberg limits and classification for the two lateritic soil samples were determined using BS 1377-*2* [20].

3.2.4 Compressive Strength Tests

Compressive strength of each of the samples was determined using the TIRA test model 2810, Thuringia, Germany of the Universal Mechanical Testing Machine (Figure 3.3) after 28days of curing. The compressive strengths and dimensions of the lateritic bricks were determined in accordance with BS 3921 [21]. A pair of Vernier callipers was used to measure the actual dimensions of the specimens before testing with the Universal machine. The compressive strength tests were done under displacement control mode at a displacement rate of 0.02 mm/s. The specimens were deformed monotonically to failure at a loading rate of 24 kN/s. Load measurements were taken at the point of failure of the lateritic brick samples. The Eq. (1) was used to calculate the maximum compressive stress in the lateritic bricks at failure:

$$\sigma = P / A \tag{1}$$

Where: σ = calculated normal stress (MPa); P = measured applied load (N); A = net area of the surface on which the load is applied (m^2).

The effect of the different percentages of the hydrated lime and bone ash stabilizers on compressive strengths were determined.

Figure 3.3: Experimental Set-up for Compressive Strength Test

3.3 Results and Discussion

3.3.1 Physical Chemical and Mineralogical Composition

The chemical composition of the hydrated lime and bone ash used for the study are shown in Table 3.1 and 3.2 respectively while Table 3.3 and 3.4 give the chemical composition and physical properties of the natural lateritic soil samples used respectively. The major constituent of both the hydrated lime and bone ash is calcium. The chemical composition of the different lateritic soil samples indicates that lateritic soil contains silicon and aluminum predominantly as shown in Table 3.3.

Table 3.1

Chemical composition of hydrated lime used for the study.

Constituents	(%) Percentages
Calcium Oxide [CaO]	95.0%
Chloride (Cl)	0.04%
Sulfate (SO_4)	0.4%
Iron (Fe)	0.1%
Heavy metals (as Pb)	0.005%
Substances not precipitated by Ammonium oxalate (as Sulfate)	2.5%
Loss on ignition	1.955%

Table 3.2

Chemical composition of bone ash used for the study.

Chemical compositions	(%) Percentages
Calcium Oxide (CaO)	52.2020
Magnesium Oxide (MgO)	2.0770
Aluminium Oxide (Al_2O_3)	0.6130
Phosphorus Oxide (P_2O_5)	48.0770
Sodium Oxide (Na_2O)	1.3290
Potassium Oxide (K_2O)	0.0907
Strontium Oxide (SrO)	0.8670
Iron Oxide (Fe_2O_3)	0.0303
Zinc Oxide (ZnO)	0.0069
Sulphur(S)	0.2124

Chloride (Cl)	0.3400
Chromium Oxide (Cr_2O_3)	0.0011
Nickel Oxide (Ni_2O)	0.0003
Manganese Oxide (MnO)	0.0002

Table 3.3

Chemical composition of raw lateritic soil samples used for the study.

Chemical compositions	Weight (%) of LSS1	Weight (%) of LSS2
Silicon Oxide (SiO_2)	68.1210	49.3740
Aluminium Oxide (Al_2O_3)	19.5280	27.0870
Phosphorus Oxide (P_2O_5)	0.3837	0.2384
Barium Oxide (BaO)	0.1014	0.0894
Iron Oxide (Fe_2O_3)	5.8743	10.8140
Sodium Oxide (Na_2O)	0.3680	0.2570
Strontium Oxide (SrO)	0.1254	-
Zirconium Oxide (ZrO_2)	0.2545	0.0758
Magnesium Oxide (MgO)	1.2590	0.6640
Copper Oxide (CuO)	0.0013	0.0043
Potassium Oxide (K_2O)	1.8219	1.0928
Nickel Oxide (Ni_2O)	0.0014	0.0028
Calcium Oxide (CaO)	0.1109	0.0305

Titanium Oxide (TiO_2)	1.1620	0.9968
Zinc Oxide (ZnO)	0.0045	0.0032
Chromium Oxide (Cr_2O_3)	0.0041	0.0158
Vanadium Oxide (V_2O_5)	0. 0243	0.0296
Cerium Oxide (CeO_2)	0.0240	0.0291
Tantalum Oxide (Ta_2O_5)	0.0042	0.0084
Manganese Oxide (MnO)	0. 0906	0.0601
Rubidium Oxide (Rb_2O)	0.0072	0.0038
Yttrium Oxide (Y_2O_3)	0.0027	0.0034
Lead Oxide (PbO)	0.0046	0.0075
Nobium Oxide (Nb_2O_5)	0.0002	0.0020
Gallium Oxide (Ga_2O_3)	0.0018	0.0032
Thorium Oxide (ThO_2)	0.0012	0.0033
Chloride (Cl)	-	0.0310
Sulphur (S)	0. 1134	0.0949

Table 3.4

Physical Properties of Natural Lateritic Soil Samples.

Engineering properties	**LSS1**	**LSS2**
Liquid limit (%)	43.90	31.00

Plastic limit (%)	24.39	21.41
Plasticity index (%)	19.50	9.59
Plasticity Chart Classification	Silt with high plasticity	Silt with medium plasticity
Linear Shrinkage (%)	8.91	6.40
Moisture content (%)	24.39	21.41

The lateritic soil's richness in silicon and aluminium was confirmed by the EDS microanalysis as shown in Figure 3.4(a) and (b). The result of the EDS analysis on the bone ash in Figure 3.4 (c) shows that calcium is the major constituent, which explains the improved compressive strength obtained as a result of the pozzolanic reactions that took place when bone ash was mixed with lateritic soil and water. The calcium oxide present in bone ash reacts with water to form calcium hydroxide: $\{CaO\ (s) + H_2O\ (l) \rightarrow Ca\ (OH)_2\ (s)\}$. The lateritic soils used for the study contain mainly siliceous and aluminous materials and can be referred to as pozzolans [22]. Also, the results show that the soil sample possesses no cementitious value due to the absence of calcium. The soil being a pozzolan contains mainly siliceous and aluminous materials which in finely divided form chemically reacted with calcium hydroxide in the presence of water to form cementitious compounds resulting in the improved compressive strength.

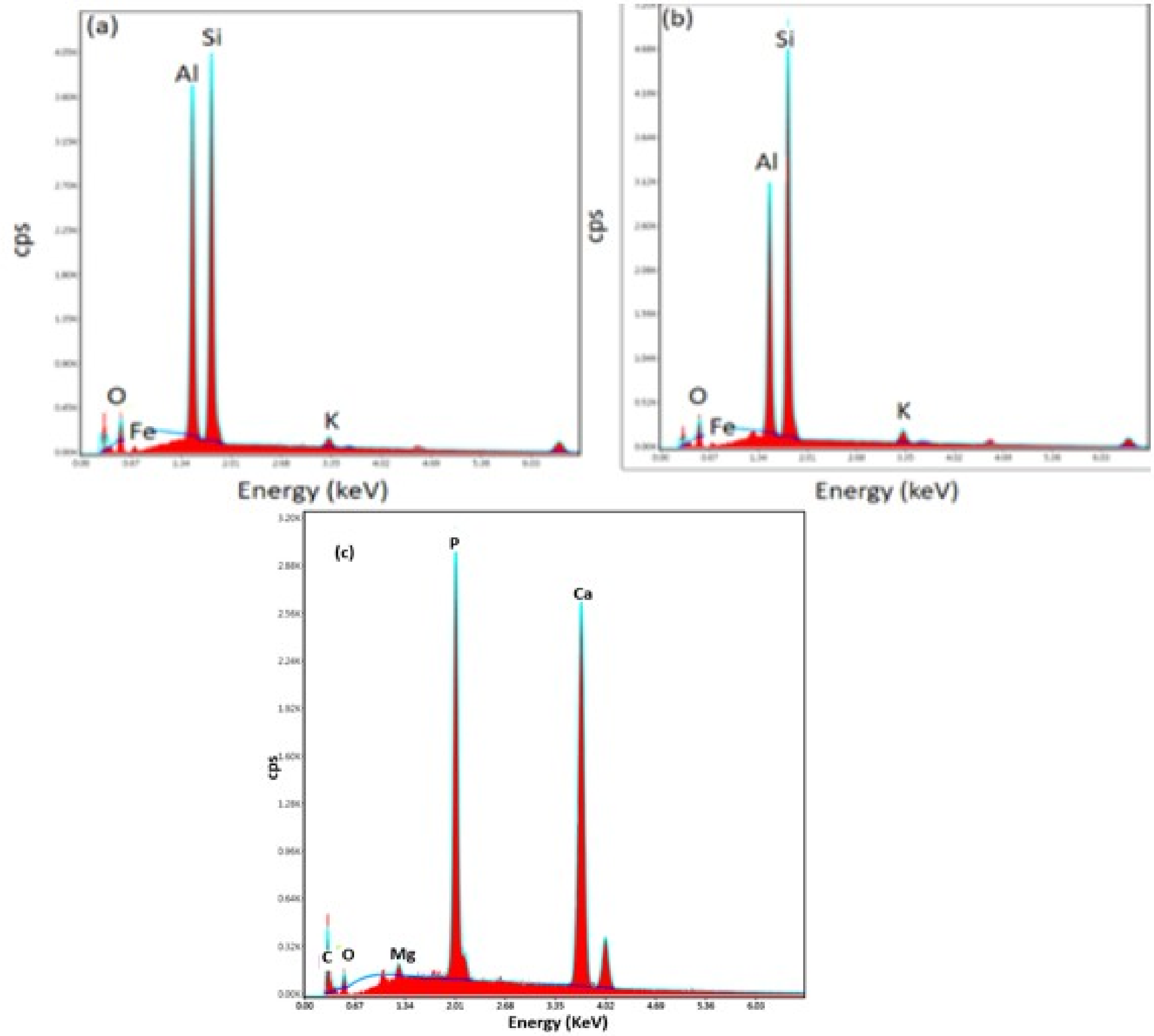
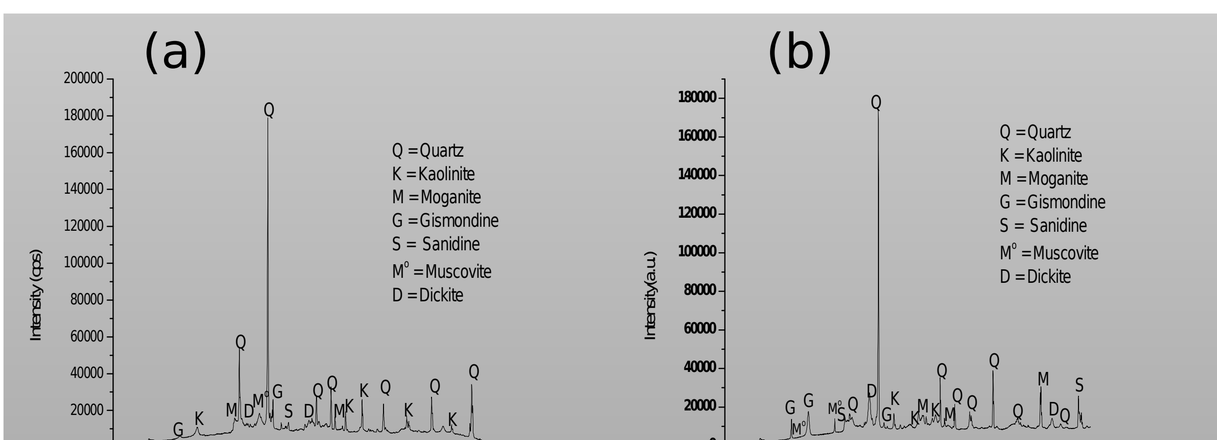


Figure 3.4. (a)EDS microanalysis of lateritic soil sample 1 (LSS1); (b) EDS microanalysis of lateritic soil sample 2; (LSS2) (c) EDS microanalysis of bone ash**.**

3.3.2. Characterization of Lateritic soils

The phase composition of the two lateritic soil samples presented by mineralogical analysis diffractograms are shown in Figure 3.5(a) and 3.5(b). From the XRD patterns, quartz is



durability. This further depicts lateritic soil as a promising material for construction because quartz is durable.

Figure 3.5. (a) XRD pattern for lateritic soil sample 1(b) XRD pattern for lateritic soil sample 2

3.3.3 Characterization of Bone Ash

The FTIR results (Figure 3.6) identified the mineral as a poorly crystalline, CO_3^{2-}-containing apatite, presenting bands typically described in hydroxyapatite. The chemical groups found in the spectra of bone ash used for the study are PO_4^{3-}, CO_3^{2-}, OH^- and –NCS. The $\nu_3PO_4^{3-}$ (1200-900 cm^{-1}) appeared as broadbands with a discrete shoulder having a strong peak at 1200cm^{-1}. The $\nu_1PO_4^{3-}$ (980-940 cm^{-1}) band was generally overlapped with the $\nu_3PO_4^{3-}$ whereas, the $\nu_4PO_4^{3-}$ (650-500 cm^{-1}) was partially resolved into two broad peaks. These shapes of the PO_4^{3-} bands depict the low crystallinity of the minerals. The presence of CO_3^{2-} was as a result of the clear bands of the $\nu_3CO_3^{2-}$ (1600-1350 cm^{-1}). Peaks of the ν_1OH^- (3572 cm^{-1}) and ν_2OH^- (3572 cm^{-1}) were observed to overlap each other as shown in Figure 3.6. The OH^- and CO_3^{2-} functional groups are important for the pozzolanic reaction between the lateritic soil and bone ash which resulted in improved compressive strength of stabilized lateritic soil due to the formation of C-S-

H (Calcium Silicate Hydrate). A peak of $\nu_L OH^-$ (630 cm^{-1}) was not seen in the FTIR spectra. The presence of Isothiocyanate (2000 cm^{-1}) was also observed.

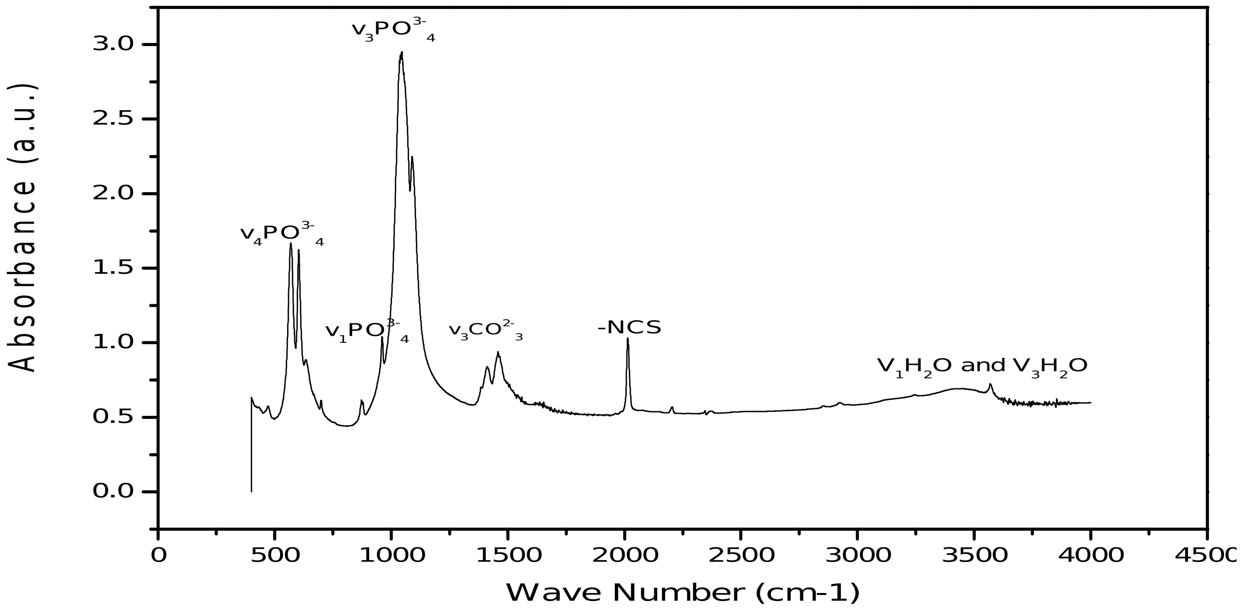


Figure 3.6. FTIR Spectra of Bone Ash used for the Study

3.3.4 Mechanical Behavior

Mechanical properties [Figures 3.7(a) and (b)] were influenced by different methods of curing and this agrees with the study by Kubba et al. [23]. The samples cured using room-dried method gave the highest increase in their compressive strengths followed by those cured using the sun-dried method and this is line with the findings of [24]. Those cured using the oven-dried method gave the lowest compressive strengths. The lower strengths observed for the samples cured using the oven-dried method could be because of the quick setting caused by the high temperature of the oven that resulted in visible cracks. The higher compressive strength recorded for the sample cured using the room-dried method might be because of the presence of oxygen, which controlled the early hardening period and hence prevented the quick setting of the stabilized bricks. Figure 3.7 (a) and (b) indicate that the compressive strengths of the samples cured using the room-dried method increased optimally at 9% hydrated lime stabilization after which there was a decline in compressive strength. This agrees with the earlier work of Achampong et al. [17]. Interestingly, all the bricks produced from a mixture of lateritic soil and lime as well as the mixture of lateritic soil and bone ash met the minimum compressive strength requirement of 1.65 N/mm^2 (1.65 MPa) specified by the Nigerian Building and Road Research Institute (NBRRI) for building construction as reported in Raheem et al. [25].

The compressive strength of lateritic soils stabilized with lime and bone ash indicated a significant improvement when compared to the compressive strength of the raw lateritic soil. The compressive strength results showed that the addition of 9% of hydrated lime gave the highest compressive strength for the stabilized lateritic bricks after 28 days. The improved compressive strength of the stabilized bricks likely occurred as a result of the reaction between calcium from the bone ash and silica from the lateritic soil in the presence of water to form materials similar to those found in Portland cement. Thus, the chemical reaction between the siliceous and alumina components in the lateritic soil samples, calcium hydroxide and water accounted for the improved strength due to the formation of denser and cementitious materials as shown in Figure 3.7 (a) and (b). There was a significant increase in the compressive strength of BAT2 (bone ash treated lateritic soil sample 2) as compared to the compressive strength of the UL2 (Untreated Lateritic soil sample 2) as shown in Figure 3.7 (c). This can be attributed to the reaction between Calcium Oxide (CaO) from the bone ash and the water of mixture resulting in the formation of lime [$Ca(OH)_2$]. It was also observed that the compressive strength of the stabilized samples increased with an increase in the amount of calcium and vice versa. The optimum composition that gave the highest experimental compressive strength for the bone ash treated LSS2 was the 5% BAT2. It is noted from the results obtained that only a small percentage

(5%) of bone ash was required to improve the mechanical properties of LSS2. This agrees with the earlier works done on the effect of bone ash on the shear strength of soil by Ayininuola and Shogunro [16] and the one done by Ayininuola and Akinniyi [26] on the influence of bone ash on soil consolidation. Hence, bone ash could serve as a better and sustainable alternative to lime for stabilization of soils.

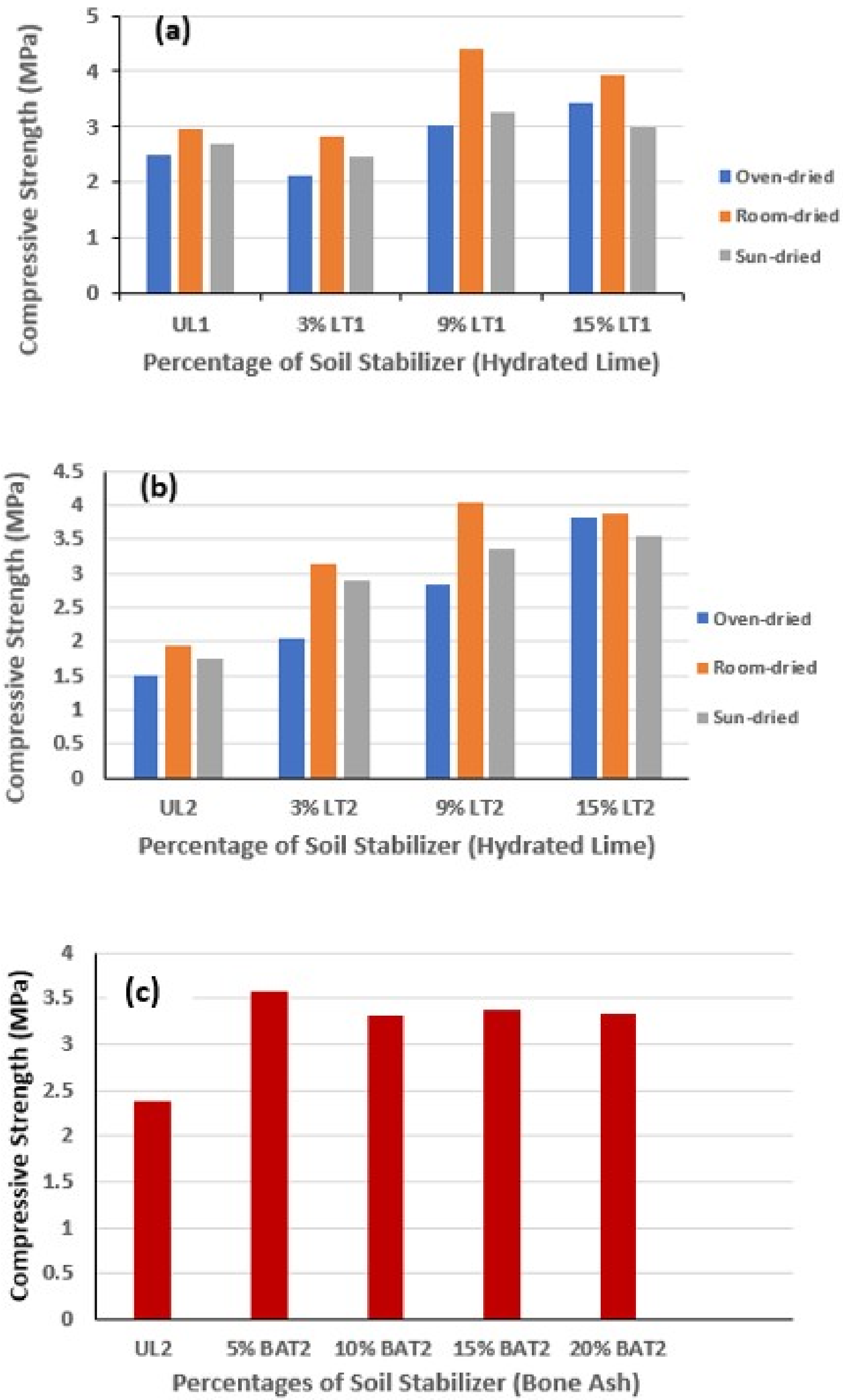


Figure 3.7: (a) Effect of Different % of Lime-Stabilized LSS1 **(b)** Effect of Different % of Lime-Stabilized LSS2 **(c)** Influence of Bone Ash on Compressive Strength of LSS2.

3.3.5 The Microstructure of the Samples

Morphology of LSS1, LSS2 and bone ash are shown in Figure 3.8 (a), (b) and (c) respectively. The presence of pores was observed in the morphology of LSS1 and LSS2 as represented in Figure 3.8 (a) and (b) respectively. Figure 3.8 (b) indicates the presence of a shiny silicate mineral called mica which could improve the thermal properties of bricks [27] produced with LSS2.

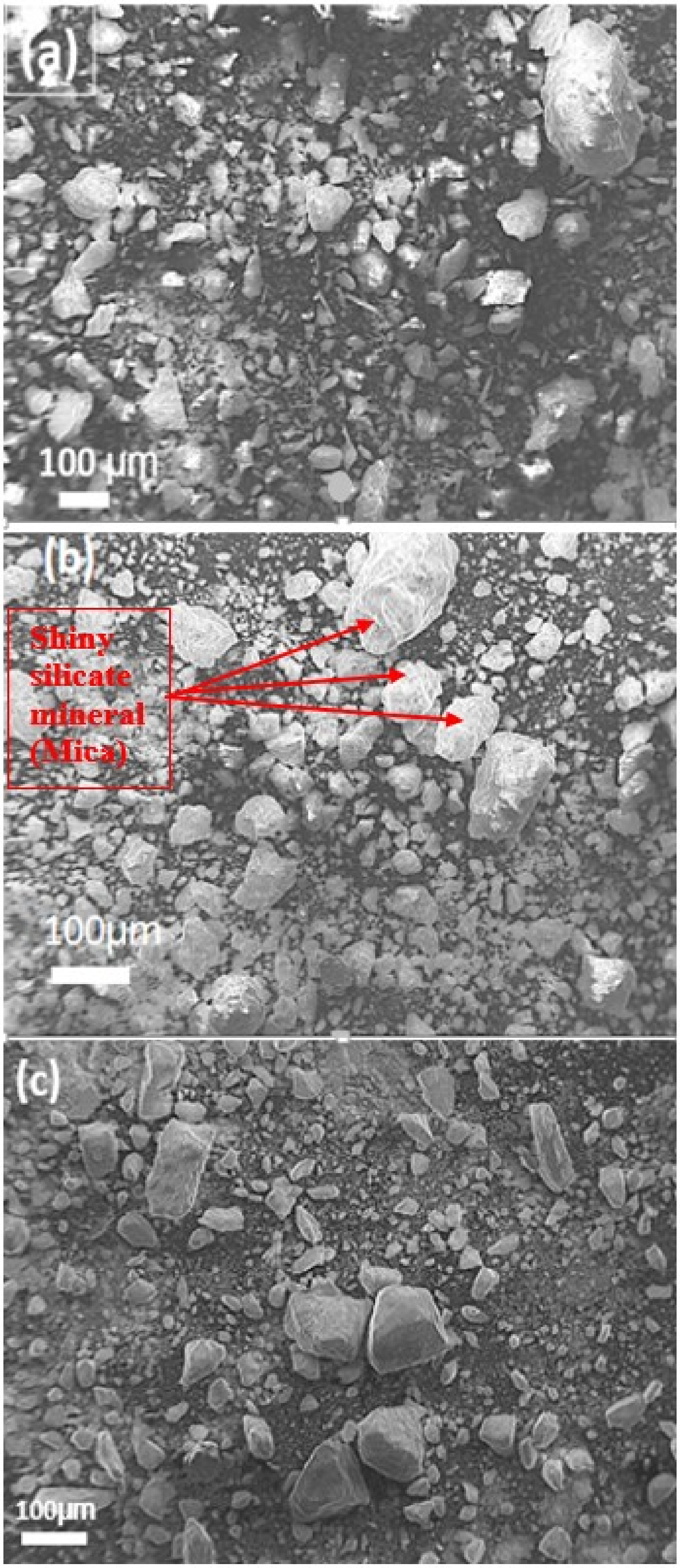


Figure 3.8: (a) Morphology of LSS1; **(b)** Morphology of LSS2; **(c)** Morphology of Bone Ash.

3.3.6 Effects of Hydrated Lime and Bone Ash Soil Stabilizers on Lateritic Soil

The microstructural analysis using Scanning Electron Microscopy (SEM) indicates denser materials which resulted in reduced porosity for the stabilized lateritic soil samples as shown in Figure 3.9(a) and (b). The particles of these denser materials have closer contact and stronger bonding due to the pozzolanic reactions between the soil stabilizers and the soil which will ultimately result in reduced porosity. Increase in the density, as well as a decrease in the porosity, increased the compressive strength of the stabilized lateritic soil [28]. The SEM image of lateritic soil stabilized with 10% bone ash shown indicates the presence of fibrous materials and this accounts for the reduced compressive strength [29] observed in Figure 3.7 (c). The microanalysis presented in Figure 3.9(d), (e) and (f) indicates the presence of silicon, aluminium, calcium and oxygen which means that there is the possibility of pozzolanic reaction occurring in the presence of water. This gave a possible explanation for an improvement in the strength of stabilized lateritic soil samples. It was also observed that the strength of the stabilized samples increases with increase in the content of calcium present in hydrated lime and bone ash (BA) as shown in Figure 3.9 (d), (e) and (f). This resulted in the variation that was observed in the SEM results in Figure 3.9 (a), (b), and (c) where the smaller amount of calcium resulted in a less dense material shown in Figure 3.9 (c) compared to Figure 3.9 (b) where the larger amount calcium resulted in a denser material.

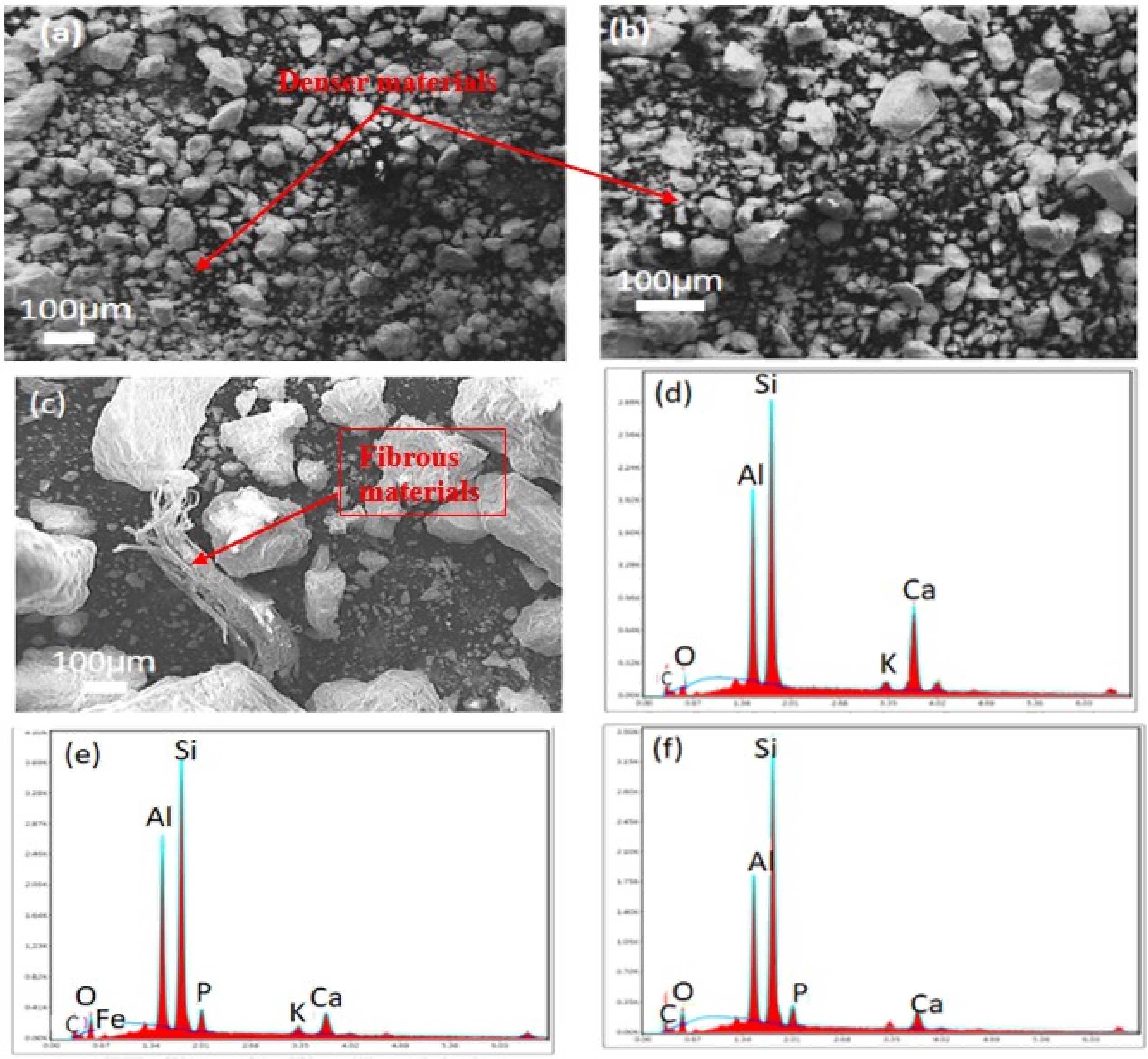


Figure 3.9. Morphology of: **(a)** LSS2 containing 9% Hydrated Lime **(b)** LSS2 containing 5% Bone Ash **(c)** LSS2 stabilized containing 10% Bone Ash; EDS microanalysis of: **(d)** LSS2 containing 9% Hydrated Lime **(e)** LSS2 containing 5% BA **(f)** LSS2 containing 10% BA

3.4 Summary and Concluding Remarks

The conclusions from this study are:

- Lateritic bricks cured using room-drying method gave the highest compressive strength compared to the bricks cured using the oven-drying and sun-drying method;
- The optimum composition that had the highest experimental compressive strength for the bone ash treated LSS2 was the 5%BAT2;

- The use of 9% by weight of the hydrated lime additive and 5% by weight of bone ash additive was found to be the optimum amounts for the stabilization of the soil;
- The morphology of the stabilized samples indicates denser materials which resulted in reduced porosity that gave rise to improved compressive strength;
- Further work is in progress to develop statistical and stochastic models for predicting the compressive strength of stabilized soils.

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4.0 CHAPTER FOUR: MULTIVARIATE REGRESSION MODELS FOR PREDICTING THE COMPRESSIVE STRENGTH OF BONE ASH STABILIZED LATERITIC SOIL FOR SUSTAINABLE BUILDING

4.1 Introduction

Lateritic soils are among the topmost local building materials used in the construction industry in Nigeria for the provision of sustainable and affordable housing and other infrastructure [1]. The high cost of conventional building materials such as cement and asphalt which has resulted in housing deficits in Nigeria has led researchers to seek how to utilize the abundant local materials such as lateritic soil in the country by improving its strength to make it more suitable for sustainable housing materials. Recent research works in construction materials are focused on finding a sustainable alternative capable of reducing the consumption of cement and concrete in the construction industry [2, 3, 4, and 5]. Lateritic bricks have been used since ancient times for the provision of affordable housing and other infrastructure such as roads, dams and monuments [6]. However, a structure constructed with lateritic soil has lower compressive strength compared to that of cement and concrete resulting in low load bearing capacity and durability [7].

Conversely, there have been several tons of agro-wastes generated [8] due to the consistent increase in population with its attendant socio-economic activities. Cattle bone is one of the major agro-wastes from meat production [9]. In the quest to turn wastes to wealth, different ways of utilization of these wastes in many economic sectors especially the construction industries are of paramount importance. This will not only add economic value to the wastes but will also provide new job opportunities for individuals who may be involved in waste collection and utilization.

In order to strengthen lateritic soil for sustainable building applications, researchers have been exploring different waste materials including agro-wastes materials as admixtures or soil stabilizers for improving the mechanical properties of lateritic soil [10]. Obianyo et al. [11] explored the possibility of using bone ash in place of hydrated lime in stabilizing lateritic soil for sustainable buildings. It was found that the bone ash improved the compressive strength of the lateritic soil significantly after 28 days of curing. An adequate understanding of the soil compressive strength is crucial in construction projects such as buildings, earth dams, and road and railway embankments [12].

However, a substantial amount of time, financial resources and energy are required to run tests in the laboratory to obtain the compressive strength of lateritic soil. Therefore, the application of mathematical or statistical models in predicting the strength of earth-based materials such as lateritic soil is crucial. Presently, there is limited systematic data on the properties and multivariate regression models for strength prediction of stabilized lateritic bricks. Jin et al. [13] expressed the need for using multiple independent variables (IVs) in a proper data analytical method for predicting the targeted response random variable (RRV) of cementitious materials. Artificial Neural Network (ANN) and linear regression method have been used by various researchers to predict the properties of stabilized earth-based materials [14, 15]. There is no empirical model available for predicting the compressive strength of bricks made from lateritic soil stabilized with bone ash.

This study aimed to develop multivariate stochastic models for predicting the compressive strength of bricks made from lateritic soils stabilized with bone ash for sustainable building purposes. The statistical models were used to predict the compressive strength of stabilized lateritic soil. The implication of the formulated models on the effects of bone ah stabilizer, curing age and curing temperature on the compressive strength of stabilized lateritic soil was quantitatively demonstrated in this work. Also, the application of these proposed statistical models has the potential of reducing the cost and time in acquiring experimental data.

4.2 Materials and Methods

4.2.1 Materials

In this study, the sustainable building material used is lateritic soil and it was obtained from Tunga-Maje, Gwagwalada Area Council, Abuja. The study area, Abuja in Nigeria with Global Positioning System (GPS) coordinates of 9° 4' 20.1504" N and 7° 29' 28.6872" E is in the subtropics with seasonal heavy rainfalls that promote laterization which is a process that widely occurs in the middle Niger, Benue and Upper Benue areas [30]. The cattle bones for the production of bone ash used shown in Figure 4.1 was obtained from a meat vendor shop. The chemical compositions of the lateritic soil sample (LSS) and bone ash are shown in Table 4.1 and 4.2 respectively were obtained via XRF analysis using Thermo Scientific X-ray Fluorescence (XRF) Epsilon Spectrometer. The summation of the oxides percentage of SiO_2, Al_2O_3 and Fe_2O_3 for the LSS is greater than 70% and this implies that the soil sample is pozzolanic [31]. The chemical composition of bone ash indicates that it contains predominantly oxides of calcium and phosphorus. Clean tap water that is free from contamination and good for drinking was used for the mixing of the raw materials as specified in BS EN 1008 [32]. The particle size distribution of the lateritic soil sample used for this study was obtained using Sieve analysis as presented in Figure 4.2. The distribution curve indicated that the soil sample mainly contains silt.

Figure 4.1. Cattle bones used for the production of bone ash used for the study [1:127]

Table 4.1
Chemical composition of lateritic soil samples used for the study

Oxides	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	TiO_2	Na_2O	P_2O_5	CaO	BaO	MnO
%Conten t	67.9	20.1	6.6	1.9	1.1	1.0	0.4	0.4	0.2	0.1	0.1

Table 4.2
Chemical composition of bone ash used for the study [11]

Oxides	CaO	P_2O_5	MgO	Na_2O	SrO	Al_2O_3	K_2O	Fe_2O_3	ZnO
%Content	52.20	48.08	2.08	1.33	0.87	0.61	0.09	0.03	0.01

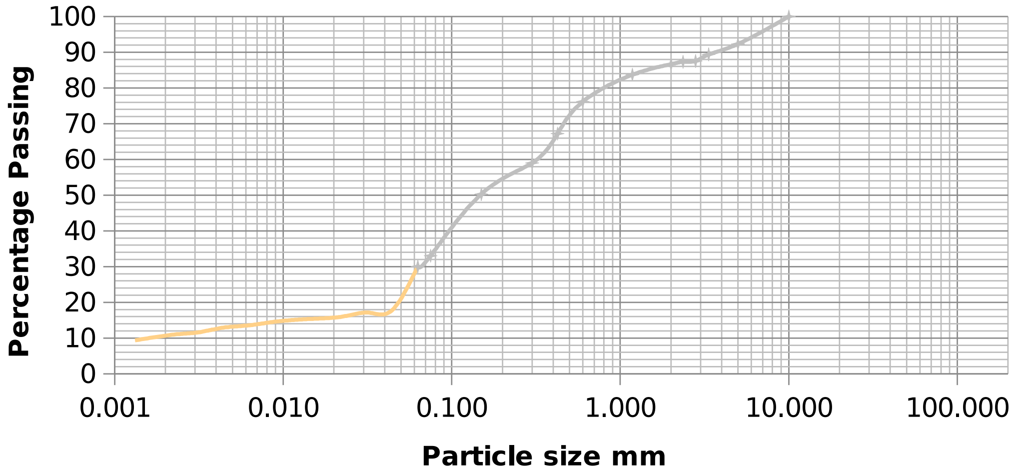


Figure 4.2. Particle size distribution of lateritic soil.

4.2.2 Experimental design

The lateritic soil samples (LSS) were collected and air-dried for two weeks at the AfDB laboratory of African University of Science and Technology, Abuja. The bone ash (BA) used for the soil stabilization was obtained from the cattle bones, which were washed, sun-dried, calcined at 650°C, crushed and passed through a 75μm sieve. The experimental mix design for the lateritic brick used consisted of four different matrices with bone ash content of 0, 3, 6 and 9% of the weight of lateritic soil. The water used for the mix design was 20% of the weight of the combination of bone ash and lateritic soil contents for the four matrices. Each of the matrices was made up of a three-component composite obtained by mixing lateritic soil, bone ash and water. These constituents were mixed in varying proportions aimed at achieving a desired compressive strength of the stabilized bricks. Both the bone ash and lateritic soil were first mixed with respect to the mix design before adding the required calculated amount of water. A homogenous mixture of lateritic soil, bone ash and water were then placed in a 50mm × 50mm × 50mm mould after which the moulded bricks were cured for 3, 14 and 28 days using room-drying, sun-drying and oven-drying methods at temperatures of 23±2°C, 37±2°C and 600°C respectively. Compressive strength tests were conducted on the cured lateritic bricks and the results were presented in Table 4.4. The effects of curing age and curing temperature on each of the design mixes were analyzed with respect to compressive strength (CS). The independent variables (IVs) employed in predicting the response random variable (RRV) are X_1, X_2, and X_3 denoting percentage of bone ash, curing age and curing temperature respectively.

4.2.3 Defining IVs in estimating the behaviour of stabilized lateritic bricks

The various IVs for predicting the targeted RRV (CS) is defined in Table 4.3. Comprehensive experimental data of the compressive strength data and the potential IVs that could influence the RRV are shown in Table 4.4. The CS was determined based on monitoring of the force or load at the point of failure and the initial cross-sectional surface area during the compressive strength tests. These IVs were chosen according to their effects on the compressive strength of stabilized lateritic soil in previous studies [11]. In order to clearly understand the effects of bone ash content, curing age and curing temperature on the compressive strength of bone ash stabilized lateritic soil, bar graphs of comparison of the compressive strength of these parameters are shown in Figure 4.3. It was observed from Figure 4.3 that the samples containing 6% bone ash cured at a temperature of 23°C for 28days gave the best compressive strength. Samples cured using the oven-drying method at a temperature of 600°C were found to have lower compressive strength compared to those cured using room-drying and sun-drying methods.

Table 4.3
Definitions of RRV and IVs for the system

Variables	Symbols	Definitions
Y_1	f_{cs}(MPa)	CS (MPa): Compressive Strength of Lateritic Bricks (LB)
X_1	W_{ba} (%)	Different Percentage of Bone Ash (BA)

X_2	t_{ca} (days)	Curing age
X_3	T_c (ºC)	Curing temperature

Table 4.4
Average Results of the tested lateritic bricks

No. of speci-mens	W_{ba} (%)	t_{ca} (days)	T_c (ºC)	f_{cs}(MPa)
3	0	3	23	1.941
3	3	3	23	2.320
3	6	3	23	3.131
3	9	3	23	2.807
3	0	14	23	2.147
3	3	14	23	2.399
3	6	14	23	3.391
3	9	14	23	3.002
3	0	28	23	2.333
3	3	28	23	2.846
3	6	28	23	3.572
3	9	28	23	3.338
3	0	3	37	1.794
3	3	3	37	2.270
3	6	3	37	3.057
3	9	3	37	2.772
3	0	14	37	2.029
3	3	14	37	2.310
3	6	14	37	3.271
3	9	14	37	2.937
3	0	28	37	2.306
3	3	28	37	2.800
3	6	28	37	3.612
3	9	28	37	3.209
3	0	3	600	1.684
3	3	3	600	2.105
3	6	3	600	2.948
3	9	3	600	2.655
3	0	14	600	1.621
3	3	14	600	1.932
3	6	14	600	2.896
3	9	14	600	2.575
3	0	28	600	1.542
3	3	28	600	1.868

3	6	28	600	2.702
3	9	28	600	2.511

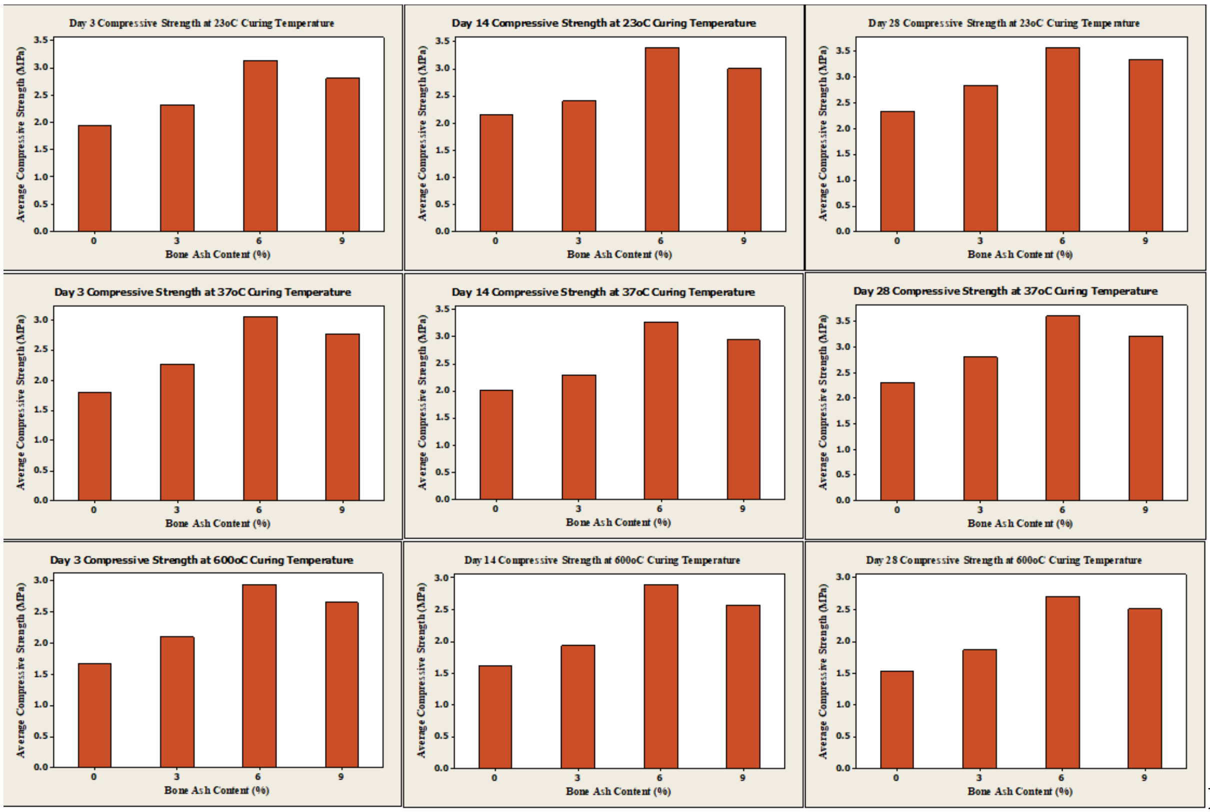


Figure 4.3. Comparison of compressive strength of different parameters

4.2.4 Development of Non-linear and Mixed Regression Models for Predicting the Behaviour of Stabilized Lateritic brick

The use of statistical models to examine the possible relationship between the strength of stabilized lateritic brick and input variables (i.e. curing temperature, curing age and bone ash content) were carried out. Different potential regression models were applied and their accuracies in predicting the RRV of stabilized lateritic brick were assessed. The model I described in Eq. (1) is from the conventional linear regression model whereas the non-linear and mixed models which are represented in Eqs. (2) - (5) were initiated [33].

Model I: *Multivariate linear regression analysis*

$$Y_i = \alpha + \sum_{j=1}^{k} \beta_j X_{ij}, i = 1, \ldots, n (1)$$

Model II: A non-linear model involving natural logarithms

$$\ln Y_i = \alpha + \sum_{j=1}^{k} \beta_j X_{ij}, i = 1, \ldots, n (2)$$

Model III: The second type of non-linear model involving natural logarithms

$$\ln Y_i = \alpha + \sum_{j=1}^{k} \beta_j \ln X_{ij}, i = 1, \ldots, n (3)$$

Mixed models from (3) to (k + 3)

$$\frac{X_{ij}}{Y_i} = \alpha + \sum_{l=1}^{k} \beta_l X_{il}, i = 1, \ldots, n; j = 1, \ldots, k (4)$$

Mixed models from (k + 4) to (2k + 3)

$$\frac{\ln X_{ij}}{Y_i} = \alpha + \sum_{l=1}^{k} \beta_l \ln X_{il}, i = 1, \ldots, n; j = 1, \ldots, k (5)$$

where *k* IVs such as curing temperature and age are represented by X_{ij}, and the response random variables (RRV) which is CS is denoted by Y_1, and α, $\beta_1 \ldots \beta_k$ are constants associated with the jth IV.

All the models proposed for the RRVs are (2k+3) models. The analysis of each of the (2k+3) models was performed using Minitab statistical software. In order to compare the accuracy of these models in predicting the target RRVs, the values of the residual standard deviation (RSD) and R^2 were generated from the regression analysis. Analysis of Variance (ANOVA) was used to generate the *F* and *p* values from the data samples which were used to test the significance of the selected regression models at a 95% significance level. The null hypothesis to be tested was that the target RRV with the chosen IVs cannot be predicted using the selected models. When the *p*-value was less than 0.05, the null hypothesis would be rejected and this indicated that the selected regression model fitted the data. Conversely, if the *p*-value was greater than 0.05, the null hypothesis would be accepted and this indicated that the selected regression model does not fit the data. According to Durbin-Watson statistical analysis which is based on the null hypothesis, residuals from a least-squares regression are not autocorrelated. The value of the Durbin-Watson varies from 0 to 4. An ideal Durbin-Watson value ranges from 1.5 to 2.5 [34] whereas, a value less than 2 indicates positive serial correlation; a value equals 2 indicates non-autocorrelation and a value greater 2 indicates negative correlation [35].

In order to study the differences between the predicted RRV and experimental data, the residual analysis was also conducted using Minitab software to obtain the values and distribution of residuals. Some of the *k* IVs will certainly have more significant effects on the target RRV than others. To test the significance of the effect of each independent variable (IV) on the RRV, t-test of correlation analysis was conducted. Each IV has a *p*-value corresponding to each *t* value. A *p*-value less than 0.05 at 95% level of confidence implies that the selected IV significantly contributed to the RRV while *p* values greater than 0.05 indicate that the IVs do not contribute to the RRV significantly. The redundancies caused by the internal correlations among IVs resulted in some IVs having higher significance than others. This implies that the regression analysis could be repeated by eliminating the redundant IVs which will automatically shorten the regression equation by including only the significant IVs.

4.3 Results and Discussion

The evaluation of the performance of the different models used in predicting the compressive strength of lateritic bricks was carried out to ascertain their accuracies in predicting the RRV. A total of 9 multivariate models were evaluated in this study. The best-fit model was obtained by conducting a residual analysis. The effects of the individual factors (IVs) on the RRV were also analyzed. The regression analysis was conducted in such a way that the internally correlated IV among the shortlisted IVs was automatically removed before the analysis.

4.3.1 Comparison of the Different Models

The nine (9) different statistical models used for the multivariate regression analysis for predicting the RRV with their prediction performance measured by R^2 values are summarized in Table 4.5. Non- linear models performed better than the linear model whereas numerous mixed models outperformed both linear and non-linear models as shown in Table 4.5. Models 4, 6, and 9 were found to be superior with higher R^2 values in predicting the RRV. The multivariate regression equations of Model 4, which exhibits superior performance compared to other models explored, is presented in Eq. (6). All the mixed models performed better with R^2 above 90%. The Eqs. of models 6 and 9 are shown in Eqs. (7) and (8).

$$W_{ba}/f_{cs} = 0.0500114 + 0.336052\ W_{ba} - 0.00477305\ t_{ca} + 0.000485692\ T_c \qquad (6)$$

$$T_c/f_{cs} = 20.4685 - 6.063\ W_{ba} + 0.275179\ t_{ca} + 0.47155\ T_c \qquad (7)$$

$$\ln(T_c)/f_{cs} = 160.631 - 2.39097\ \ln(W_{ba}) - 34.5628\ \ln(W_{ls}) - 0.0201418\ \ln(t_{ca}) + 0.492081\ \ln(T_c) \qquad (8)$$

The Durbin-Watson statistical test result was incorporated in Table 4.5. Durbin-Watson value of the majority of the 9 statistical models fell within the ideal value range except for Models 3, 5, and 7. It was observed that the Durbin-Watson values for Models 1, 2, 4, and 9 were greater than

2, which indicated negative correlation whereas that of Models 6 and 8 were less than 2, which indicated positive serial correlation.

Table 4.5

Multivariate regression results in predicting the compressive strength of lateritic bricks

Model type	Model Number	RRV	R^2	Durbin-Watson value
Linear	1	f_{cs}	0.733	2.29527
Non- linear	2	$\ln(f_{cs})$	0.756	2.19061
Non- linear	3	$\ln(f_{cs})$	0.883	1.21519
Mixed models	4	W_{ba}/f_{cs}	0.969*	2.57512
Mixed models	5	t_{ca}/f_{cs}	0.911	1.27837
Mixed models	6	T_c/f_{cs}	0.945*	1.90797
Mixed models	7	$\ln(W_{ba})/f_{cs}$	0.944	0.72111
Mixed models	8	$\ln(t_{ca})/f_{cs}$	0.928	1.49368
Mixed models	9	$\ln(T_c)/f_{cs}$	0.953*	2.43035

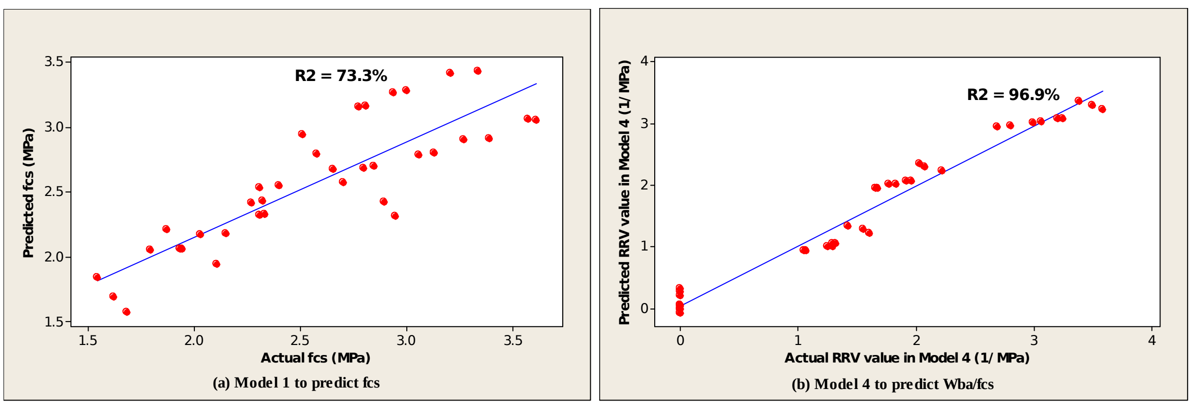
*Models that achieved the best R^2 are highlighted.

4.3.2 Regression Analysis using the Best-fit Model

According to Table 4.5, the obtained best-fit model (Model 4) was further analyzed with respect to the experimental and predicted values from the multivariate regression analysis. Model 1 and Model 4 were used to establish the linear correlation between the experimental and modelled RRV values as shown in Figure 4:4. Model 1's regression equation is represented in Eq. 9.

$$f_{cs} = 2.05029 + 0.122063\, W_{ba} + 0.0106128\, t_{ca} - 0.000843747\, T_c \quad (9)$$

The conventional linear regression as represented in Model 1 was compared with the best-fit model (Model 4) in Figure 4.4. Model 4 was found outperforming Model 1 for the predicted RRV. In addition to the comparison of R^2 value between Model 1 and Model 4, a residual analysis was conducted as shown in Figure 4.5 and 4.6. The linear regression model (Model 1) in Figure 4.5 indicated normally distributed residual values. However, its residual values were not uniformly or symmetrically distributed around the neutral line representing the zero residuals. Mixed model (Model 4) shown in Figure 4.6 indicated a significantly higher frequency of residuals at 0 when compared to Model 1. The Fitted Value and Observation Order of the two distribution plots in Figure 4.5 and 4.6 further showed that Model 4 has a better distribution of residual values which are more uniformly and symmetrically distributed around the neutral line.



(a) Model 1 to predict fcs

(b) Model 4 to predict Wba/fcs

Figure 4.4. Comparison between the predicted RRV and experimental data using Model 1 and Model 4.

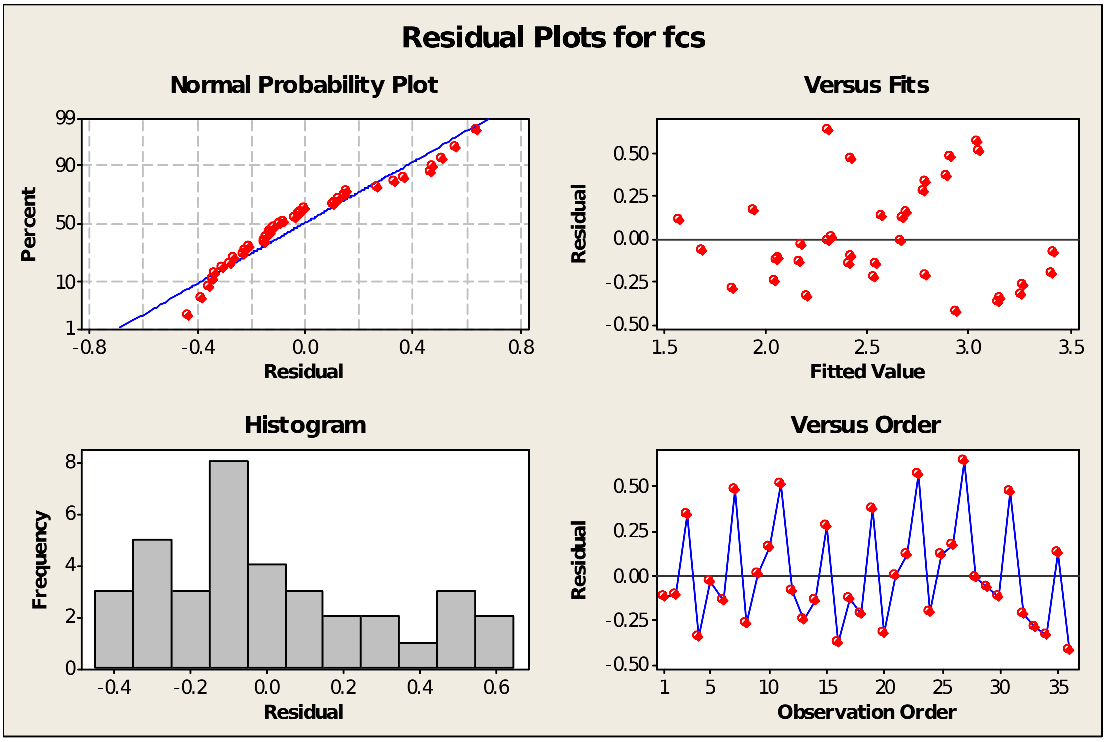


Figure 4.5. Residual analysis of Model 1 in predicting f_{cs}.

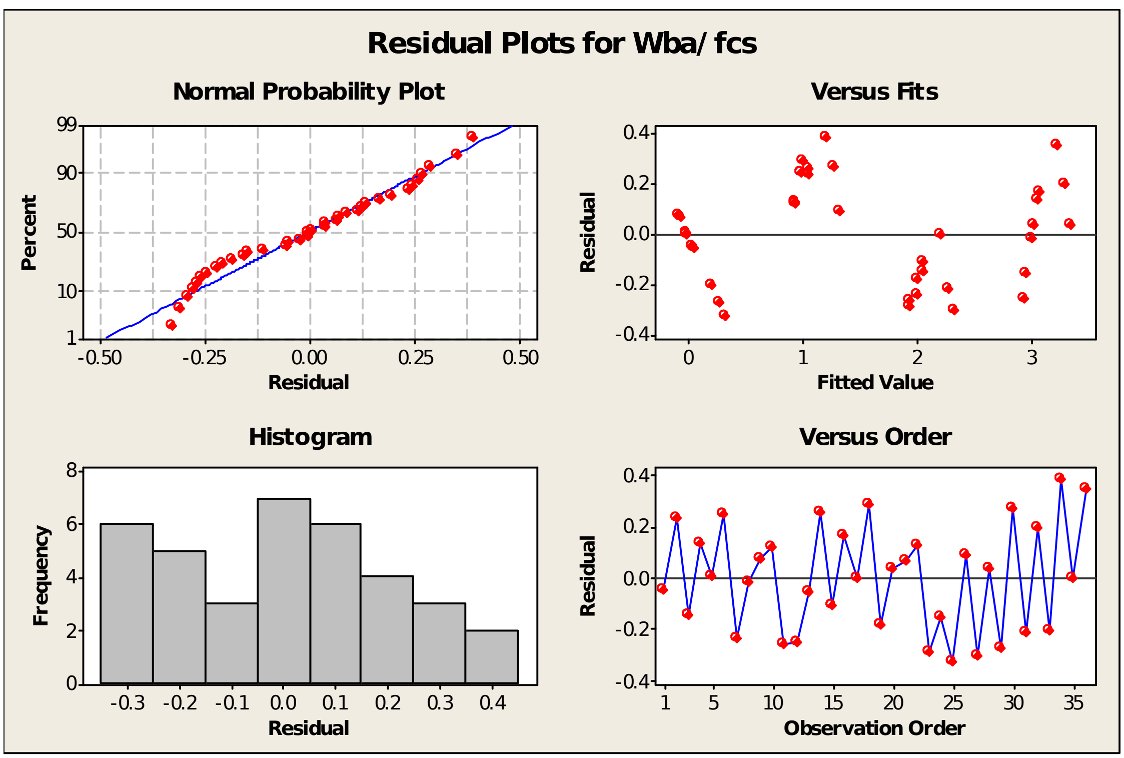


Figure 4.6. Residual analysis of Model 4 in predicting W_{ba}/f_{cs}

4.3.3 Individual Factor Analysis

The assessment and the interpretation of the effects of the different parameters measured from the 108 mixes require the use of statistical techniques. Two-way ANOVA and regression analysis were used to analyze the data using Minitab software developed by Minitab Incorporation [36]. Statistical models presented have a confidence limit of 95%. Individual effects of each of the IV on the targeted RRV (compressive strength) based on the linear regression model (Model 1) were represented in Table 4.6. The correlational relationship and the level of significance of the effects of the IVs (factors) are shown by the t-values and p-values in Table 4.6. The bone ash content (X_1 or W_{ba}) had the highest positive significant effect (t-value = 6.22; p-value = 0.00), followed by curing temperature (X_3 or T_c) with t-value of -2.58 and p-value of 0.014. These effects were as a result of the cementitious content (CaO) of bone ash that facilitated the pozzolanic reaction that occurred in the stabilized lateritic soil which further led to the observed improved compressive strength due to the cementitious compounds formed. However, bone ash content had a significant positive impact on the compressive strength of the bone ash stabilized lateritic soil whereas curing temperature had a negative effect. The negative effect of curing temperature identified by the regression models could be attributed to the lower improvement in compressive strength gain of lateritic soil with respect to curing temperature. Curing age (X_2 or t_{ca}) had the least effect on compressive strength with t-value of 1.15 and p-value of 0.258. This implies that the effects of curing age on the compressive strength of the samples were not strong enough compared to that of the bone ash content and curing temperature. This could be as a result of lower compressive strength gain of lateritic soil with respect to curing age compared to that of cement and concrete [3].

Table 4.6

Individual factor analysis of the RRV based on Model 1

IVs	IV symbols	t value	p-value
X_1	W_{ba}	6.22	0.000
X_2	t_{ca}	1.15	0.258
X_3	T_c	-2.58	0.014

* X_1=bone ash content; X_2=curing age; X_3=Curing temperature

4.3.4 Discussions of findings from statistical modelling

The prediction performance of all the 9 different models for the RRV (compressive strength) indicated that the mixed models generally performed better than the conventional linear regression method. The non- linear regression models also performed better than the linear regression model. The introduction of the non-linear and mixed regression models yielded prediction accuracy nearly 88% and 97% respectively. The effect of the individual factor on the compressive strength was further measured using the individual factor analysis obtained from the multivariate regression analysis. The result of the individual factor analysis indicated that the bone ash content had the most significant effect on the compressive strength of RRV. This was as a result of the pozzolanic reaction that took place when the lateritic soil was mixed with bone ash and water. The stabilization mechanisms of bone ash on lateritic soil with respect to its mechanical properties, microstructural analysis and pozzolanic reaction had been comprehensively presented in previous work [11]. However, the curing age did not contribute to the improved strength of the lateritic bricks significantly as much as bone ash content and curing temperature. The statistical regression approaches used in this study can be used as a prediction tool to estimate the compressive strength of lateritic bricks for sustainable building. The proposed mixed model (Model 4) could be adopted as an alternative to other complementary methods such as artificial neural network model, Scheffe's simplex model, and adaptive neural networks model in predicting the compressive strength of lateritic bricks. This adopted statistical model has the advantages of being cost-effective and less time-consuming.

4.4 Practical implications

The practical implications of the proposed model to the construction industry would depend on the amount of time and financial resources required as well as the ability of the model to meet the requirements recommended for lateritic bricks in terms of compressive strength which is a function of optimum bone ash content, curing age and curing temperature. Based on the experimental data of this study, the optimum bone ash content that gave the best compressive strength of 3.572MPa was 6% cured at room temperature (23±2^{o}C) for 28days. Room temperature which is the optimum curing temperature has positive implications for low energy demand in producing the bricks. The optimum compressive strength obtained in this study met the specifications for laterite bricks of compressive strength of 1.65MPa by the Nigerian Building and Road Research Institute (NBRRI) [37]. Although the compositions of soil could vary from one location to another, lateritic soil used for moulding the brick samples has similar oxides present irrespective of the locations they were obtained. In other words, lateritic soil being a pozzolana contains oxides of silicon, aluminium and iron (SiO_2, Al_2O_3 and Fe_2O_3) up to 70% recommended by ASTM C618 [38] and will always react with the cementitious content (CaO) of bone ash in the presence of water to improve the strength of the composite (brick) formed. Hence, the model would be relevant to all lateritic soil and other pozzolanic soils.

4.5 Summary and Concluding Remarks

This study successfully used newly developed multivariate regression models in predicting the compressive strength of the bone ash stabilized lateritic bricks. Linear, non-linear and mixed models were applied in predicting the compressive strength of stabilized lateritic bricks based on the experimental results of 108 mixes. The prediction performance of the proposed multivariate models, as well as the effects of the individual factors, were compared. It was found that the non-linear models performed better than the linear model whereas the mixed models generally performed better than both the linear and non-linear models with respect to higher accuracy and symmetrical distribution of residual values. Also, the bone ash content among other predictors was found to have the most significant positive effects on the compressive strength of the lateritic bricks. However, curing age was found to have a less significant effect on the compressive strength of the samples. The usefulness of the models is limited to the range of variables used but for a more universal application, wider ranges of variables can be explored. Therefore, the proposed mixed model from this study could be further developed for the prediction of the mechanical behaviour of stabilized lateritic bricks for sustainable practical applications of housing materials in Nigeria and other developing economies.

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5.0 CHAPTER FIVE: PERFORMANCE OF LATERITIC SOIL STABILIZED WITH COMBINATION OF BONE AND PALM BUNCH ASH FOR SUSTAINABLE BUILDING APPLICATIONS

5.1 Introduction

Affordable building for mass housing is the panacea for the housing deficit affecting the increasing population of the African continent especially Nigeria. Harnessing the abundant local building materials present in African is key for making adequate houses affordable for the populace. Lateritic soil is an earth-based building material [1] that is among the topmost available local building materials abundantly deposited in Nigeria and other tropical countries [2]. Earth building materials are cheaper than cement, non-toxic and eco-friendly [3]. The lateritic soil is composed mainly of quartz, iron–magnesium–manganese (amphibole group) and kaolinite [4]. Soils having a ratio of silica to sesquioxide [$SiO_2/(Fe_2O_3 + Al_2 O_3)$] which are less than 1.33 are classified as laterites whereas the ones between 1.33 and 2.00 are classified as lateritic soil, and those above 2.00 are classified as non-lateritic soils [5]. Lateritic soil can easily be recycled and that makes it a sustainable building material [6]. However, due to their lower compressive strength, water absorption and dimensional stability compared to cementitious materials, lateritic blocks are considered as non-durable buildings materials. A wide range of chemical stabilization techniques such as the use of cement, lime, agro-waste ash and plastic waste have been investigated to improve the physical, chemical and mechanical properties of earth-based materials [7-14].

Stabilization of earth materials has been employed in the construction industry in order to improve the strength of structures constructed with these materials [15]. The effectiveness of using hydrated lime for the stabilization of lateritic soil had been established by various researchers. However, hydrated lime is more expensive than cement in Nigeria, as the cost of 50 Kg of cement can only purchase 12.5kg of hydrated lime [16]. This high cost of hydrated lime has made it a non-viable material for the construction of sustainable buildings. Hence, the need to seek an alternative to lime for stabilization of soil. Agro-waste ash is a promising alternative to lime as agro–wastes are produced in hundreds of metric tonnes yearly in Nigeria [17]. The utilization of agro-waste for soil stabilization will result in value addition to the agro-wastes as well as clean up the environment from pollution caused by the agro-wastes.

The valorization of agro-wastes in the field of civil engineering is a profitable alternative to cement for sustainable construction applications and have been investigated by various researchers [18-20]. Previous work done on lateritic soils by Obianyo et al. [21] indicated the effective stabilization of lateritic soil using bone ash in place of hydrated lime. However, the embodied energy required for the production of the bone ash is still an issue of concern. Hence the need to find alternative agro-waste ash for possible partial replacement of bone ash for lateritic soil stabilization. Oil palm bunch is abundantly available in Nigeria and it is usually discarded as waste after removal of the palm fruit. Besides the production of palm bunch ash requires considerably less energy than bone ash. Hence, palm bunch ash was used for partial replacement of the bone ash in the stabilization of lateritic soils. This study investigates the effective utilization and stabilization of lateritic soils using agro-waste ash (bone ash and palm bunch ash) for sustainable and affordable construction applications. The effects of curing temperature, curing age, water content, the weight percentage of stabilizers (BA and PBA) and size effect of the samples on the compressive strength of lateritic bricks were also explored in this work. The understanding of how these factors influence the compressive strength of stabilized lateritic soil will enhance the production of an improved and more durable lateritic bricks for sustainable buildings.

5.2 Materials and Methods

5.2.1 Materials

The lateritic soil used in this study was obtained from Galadimawa, Airport Road, Abuja, Nigeria. The cattle bones used for the production of BA were sourced from Gosa Market, Airport Road, Abuja whereas the palm bunches used for the production of the PBA were obtained from Oba, Anambra State, Nigeria. The chemical composition and particle size distribution of the lateritic soil used in the study are presented in Table 5.1 and Figure 5.1 respectively. The ratio of silica to sesquioxide [SiO2/ (Fe2O3 + Al2 O3)] for the soil sample used for the study is 1.546. This ratio of silica to sesquioxide falls between 1.33 and 2.00 and hence it is lateritic soil [5]. From XRF results of Table 5.1, It can be seen that the summation of the SiO_2, Al_2O_3 and Fe_2O_3 is 81.361% and the value is greater than 70% recommended by ASTM C618 [22] for a material to be classified as pozzolanic material. Hence, the lateritic soil sample used for the study is pozzolanic which implies that it possesses little or no cementitious value but in finely divided form and the presence of water will react chemically with calcium hydroxide at ordinary temperature to form compounds having cementitious properties [21]. The particle size distribution curve observed in Figure 5.1 represents a well-graded soil that contains silt predominantly, according to BS 1377: Part 2: 1990: 4.3 classification.

Table 5.1

Chemical composition of the lateritic soil sample

Oxides	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	TiO_2	P_2O_5	ZrO_2	Na_2O	MnO	CaO
%	49.404	23.424	8.533	1.884	1.617	0.996	0.248	0.143	0.115	0.103	0.085

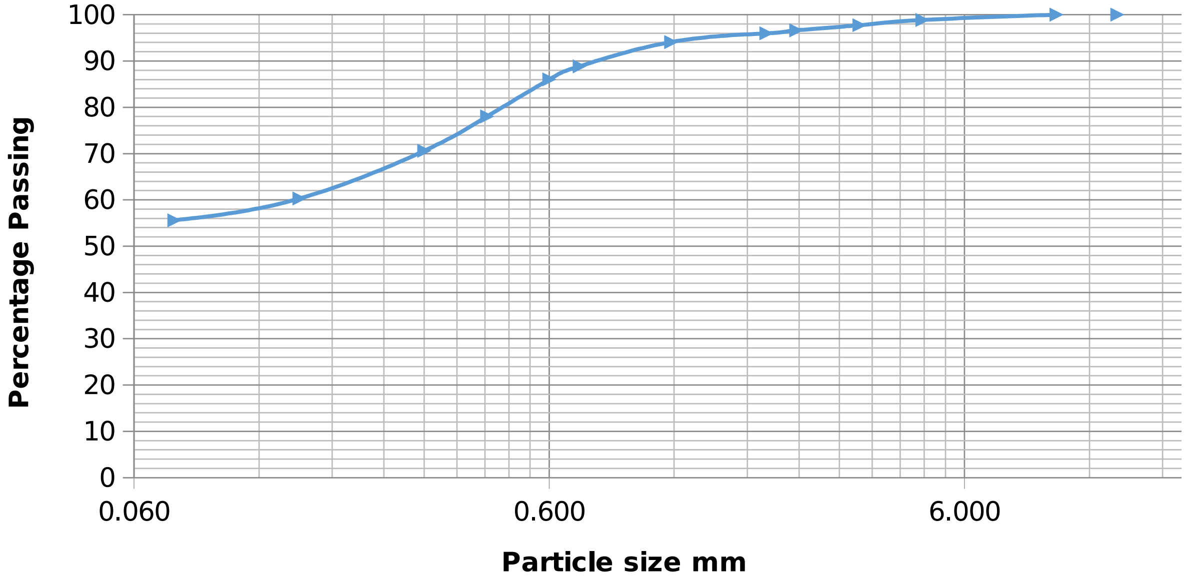


Figure 5.1. Particle size distribution of the lateritic soil

5.2.2. Materials characterization

Characterization of the soil sample and the agro-waste ash using specific tests will aid the proper understanding of the properties of the materials as well as their mechanical behaviours. Nicolet is5 Thermo Scientific FTIR spectrometer was used in the characterization of the powdered samples of lateritic soil, BA and PBA. The mineralogical compositions of the laterite samples used for this research were analyzed using a Rigaku Miniflex 600 XRD machine with range 10-70° at a rate of 2°/min and Cu K alpha radiation. Energy Dispersive X-ray Spectroscopy (EDS) maps and scanning electron micrographs were obtained with the use of the Evo/LS10 ZEISS Scanning Electron Microscope (SEM).

5.2.3 Sample preparation and research design

Samples of BA and PBA were used as soil stabilizers to improve the strength of lateritic soil obtained from Galadimawa in Abuja, Nigeria. The soil samples were obtained from a depth of 1.5m to 2.0m below the ground surface using the method of disturbed sampling. The soil sample was air-dried at room temperature for two weeks at the AfDB laboratory at African University of Science and Technology and was ground to fine particles. The cattle bones were washed and dried for two weeks. The BA was obtained by calcination of cattle bones at 650^oC in an electric furnace. Palm bunch were dried thoroughly under the sun for 1 week, cut into smaller sizes and burnt for about an hour using open-air burning. The resulting BA and PBA were passed through No. 200 sieve (75µm) before usage to obtain finer particles.

Preliminary laboratory tests on soil sample for the purpose of characterization, which include natural moisture content, particle size distribution and Atterberg limits were carried out in order to understand the properties and behaviour of the soil sample used. Also, XRF, XRD and FTIR tests were carried out on the soil sample, BA and PBA to obtain their chemical compositions, mineralogical compositions and the functional groups present. The BA and PBA were added to the soil sample in equal proportion at a varying proportion of 0%, 2%, 4% and 6% by weight of the soil and mixed thoroughly before adding a calculated amount of water. Different water content of 18%, 24% and 30% were used in the mix design to determine the effects of water content on the mechanical properties of the stabilized bricks. The homogenized mixture of the raw materials (lateritic soil, BA, PBA and water) were used to mould lateritic bricks samples of different material matrices and compositions. The lateritic bricks were obtained with the aid of a locally made mould of 50×50×50 mm^3; 70×70×70 mm^3; and 100×100×100 mm^3 sizes which were constructed to correspond to the shape and sizes of the samples to be made. The freshly moulded lateritic bricks were carefully extruded in good shape after 24 hours on a clean, hard and flat surface to prevent the development of cracks. The moulded samples were cured for 7days, 14days and 28days before testing. Also, different methods of curing (air-drying, sun-drying and oven-drying methods) were adopted to cure the bricks. Various tests including compressive strength, XRD, dry density, EDS and SEM were carried out on the lateritic bricks to measure the mechanical properties of agro-waste stabilized lateritic bricks.

5.2.4 Compressive strength of lateritic bricks

The compressive strengths of the lateritic bricks were determined in accordance with BS 3921 [25] using Model 70-S12V02 Universal Testing Machine Controls. Load measurements were taken during testing at a displacement rate of 0.02 mm/s and a loading rate of 24 kN/s until lateritic brick failure occurred as shown in Figure 5.2. Equation 1 was used to calculate the maximum compressive stress in the lateritic bricks at failure:

$$\sigma = \frac{P}{A} \tag{1}$$

where: σ = calculated normal stress (MPa); P = measured applied load (N); A = net area of the surface on which the load was applied (m^2).

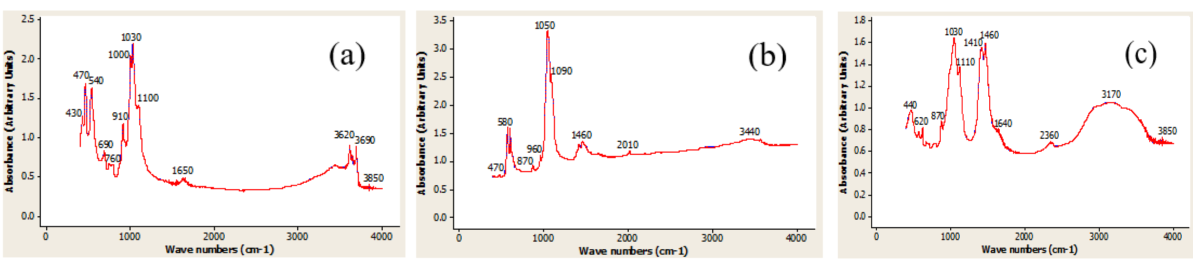
Figure 5.2. Failure pattern of the lateritic brick indicating delamination of the outer surface

During the compressive strength test, care was taken to ensure that the lateritic bricks were properly positioned and aligned with the axis of the thrust of the compression machine to ensure uniform loading on the lateritic bricks [26]. The results of the compressive strength tests were used to evaluate the effect of different levels of stabilizers (BA and PBA), curing age, water content, curing temperature and size effects of the sample on compressive strength of the lateritic bricks.

5.3 Results and Discussion

5.3.1 Infrared (IR) spectra of lateritic soil, BA and PBA

In order to properly understand the reactions and bonding types responsible for the strength improvement in the stabilized lateritic bricks, FTIR spectra of lateritic soil, BA and PBA were obtained as shown in Figures. 5.3. (a), (b) and (c) respectively. The IR spectra of lateritic soil and PBA are dominated by Si-O-Al band at 1030 cm^{-1} whereas the dominant band of BA had a sharp peak with higher intensity at a higher wave number of 1050 cm^{-1}. The infrared spectra presented in Figure 5.3. (c) indicated a broad absorbance at 2800–3850 cm^{-1} assigned to vibration of O-H due to the presence of chemically bound water [27]. Figure 5.3. (a) indicates the typical bands of the hydroxyl stretch of kaolinite at 3620 cm^{-1} and 3690 cm^{-1} [28,29].



Figures 5.3. Infrared spectra of (a) Lateritic soil (b) BA and (c) PBA

5.3.2 Microstructure of the materials and lateritic bricks

The polished products of BA, PBA, non-stabilized and stabilized lateritic bricks were analysed by the Scanning Electron Microscopy and are shown in Figures. 5.4 (a-f). The morphology of BA in Figure 5.4a indicate the presence of ligament and spongy-like materials. The presence of flake-shaped particles was observed in the morphology of PBA as shown in Figure 5.4b and these could improve the tensile strength of the lateritic brick stabilized with PBA by acting as a fibre. The morphologies of both non-stabilized and stabilized lateritic bricks shown in Figures. 5.4 (c-f) are similar at higher magnification, indicating the predominant presence of quartz particles. However, the non-stabilized lateritic brick contains porous materials as shown in Figure 5.4c. Agglomerated morphology due to the accumulation of cementitious materials was observed for the stabilized lateritic soil as shown in Figures. 5.4 (d,e). Quartz was found to be present in the morphology of the sample stabilized with 4% stabilizers (2%BA and 2%PBA) as represented in Figure 5.4e and this accounts for the best compressive strength obtained for sample stabilized with 4% stabilizers.

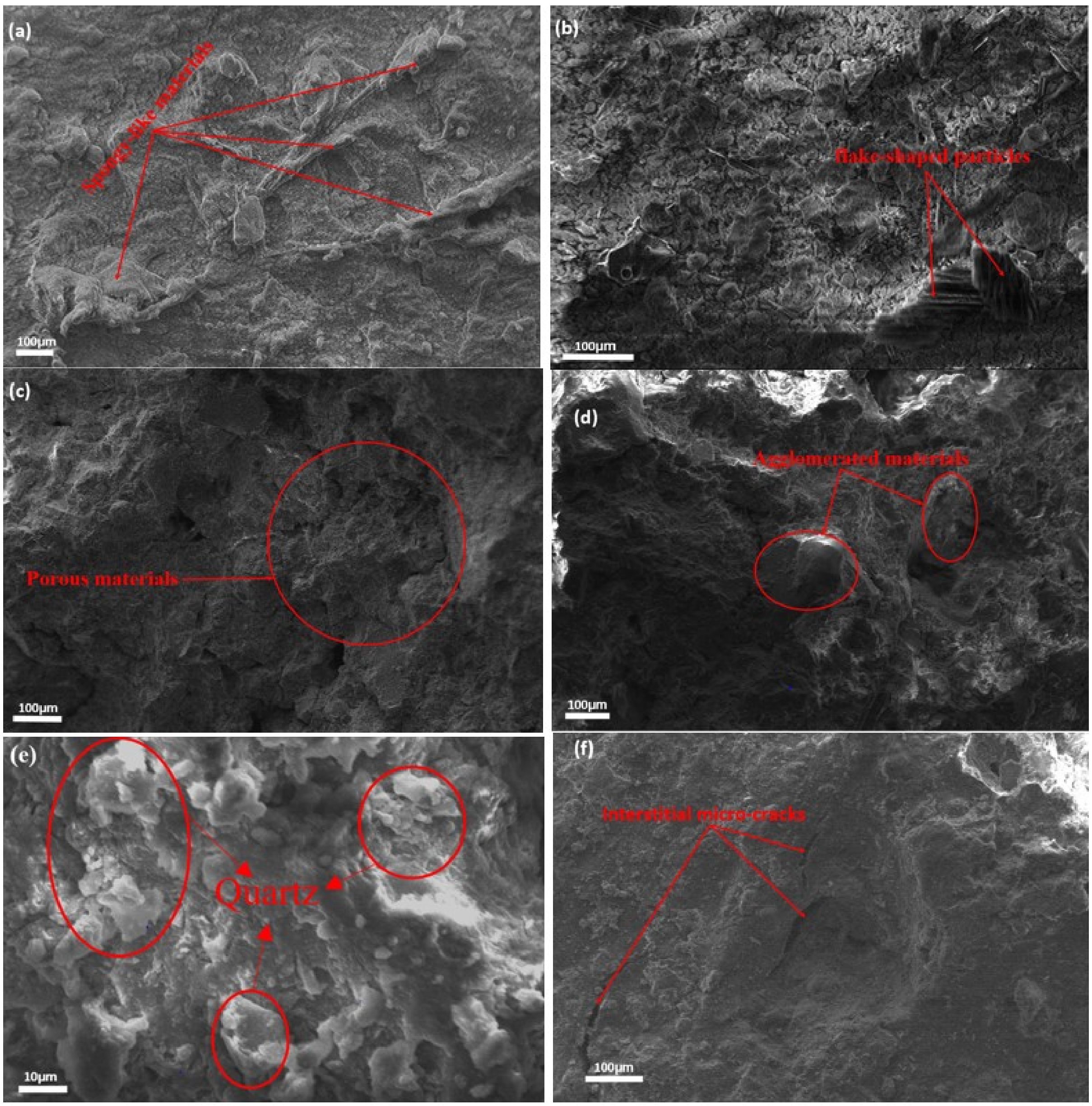


Figure 5.4. Morphologies of (a) BA (b) PBA (c) Non-Stabilized Lateritic Brick (d) 2% Stabilized Lateritic Brick (e) 4% Stabilized Lateritic Brick (f) 6% Stabilized Lateritic Brick

Presence of interstitial micro-cracks was observed in Figure 5.4f and this could be attributed to the lower compressive strength obtained for this sample compared to that obtained for samples stabilized with 2% and 4% proportions of stabilizers.

5.3.3 Influence of curing temperatures and water content on the compressive strength of lateritic bricks

These physical-chemical reactions can be enhanced by controlling the curing temperatures [30]. Three different temperatures (23± 2°C; 37±2°C; 105°C) were used to cure the brick samples in this study. The results in Figure 5.5 indicated that the samples cured using the oven drying method (105°C) gave the best compressive strength compared to those cured at room temperature (23± 2°C) and sun drying temperature (37±2°C). This implies that using oven drying temperature as low as 105°C provides for better development of the compressive strength unlike using oven drying temperature as high as 650°C [21]. This trend of having lower strength development for samples cured at a higher temperature (650°C) could be as a result of the quick setting of the cementitious components of the stabilizers whereas the better development of the compressive strength for samples cured at lower oven drying temperature (105°C) could be attributed to the completion of the pozzolanic reactions between the soil particles and the soil stabilizers.

The pozzolanic reactions between the soil, soil stabilizers/additives and water had been identified by previous research as the major contributor to the improvement of the compressive strength of the stabilized soil [13,21]. Also, the behaviour of lateritic soil depends on the mineralogical constituents present in the soil as well as the amount of water in the soil [31]. The effects of water content on the compressive strength of lateritic brick samples are shown in Figure 5.5.

Among the different water contents (18%, 24% and 30%) explored in this study, brick samples mixed with 24% water content gave the best compressive strength. The better compressive strength obtained for 24% water content implies that the water content is adequate to ensure good workability of the composite (BA, PBA and lateritic soil). Brick samples mixed with 18% water content gave lower compressive strength compared to that of 24% and this could be attributed to the inability for the mixture to mix thoroughly resulting in micro-cracks and debonding in the stabilized bricks.

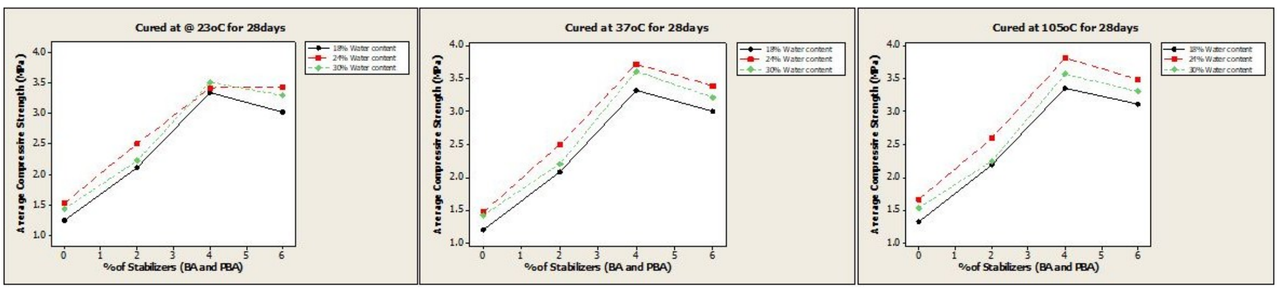


Figure 5.5. Influence of curing temperatures and water content on the compressive strength of lateritic bricks

5.3.4 Effect of weight percentage of the soil stabilizers and size effects of the specimens on the compressive strength of lateritic brick

The addition of the stabilizers (BA and PBA) influences the development of compressive strength of the lateritic bricks as shown in Figure 5.6. Increase in the compressive strength of the brick samples was observed up to 4% (2% BA and 2% PBA) after which it decreases. The increase in the compressive strength is due to the pozzolanic reactions between the lateritic soil and soil stabilizers resulting in the formation of cementitious materials (Calcium Silicate Hydrate), which accounts for the hardening and strengthening of the stabilized bricks [13,21,32]. The decrease in the compressive strength observed after the addition of 6% stabilizers could be attributed to the excess of BA and PBA that do not take part in the pozzolanic reactions between the soil and the stabilizers. These unreacted stabilizers occupy spaces within the soil structure forming defects and weak bonds between the cementitious compounds and soil particles resulting in a decrease in the compressive strength of the stabilized bricks. Also, the addition of the soil stabilizers more than the optimum value produces voids within the bricks that impact negatively on the mechanical properties of the brick samples resulting in reduced compressive strength obtained for the samples stabilized with 6% stabilizers (3% BA and 3% PBA) as shown in Figure 5.6. However, the compressive strength of all the stabilized samples was above 2.0 MPa and this conforms to the NBRRI compressive strength specifications of 1.65MPa for laterite bricks [33]. The best compressive strength result obtained for the tested samples is 3.818MPa and was obtained for the sample mixed with 24% water content and stabilized with 4% stabilizers, processed at 105°C for 24hours and cured for 28days.

The effects of the specimen size on the compressive strength of lateritic bricks are shown in Figure 5.6. For all the specimens with different water contents cured at different temperatures, the compressive strength increases as the size of the specimen gets smaller and vice versa. In other words, for bigger specimen sizes (10000mm^2 and 4900mm^2), lower compressive strength was obtained whereas for smaller specimen size (2500mm^2), higher compressive strength was obtained as represented in Figure 5.6.

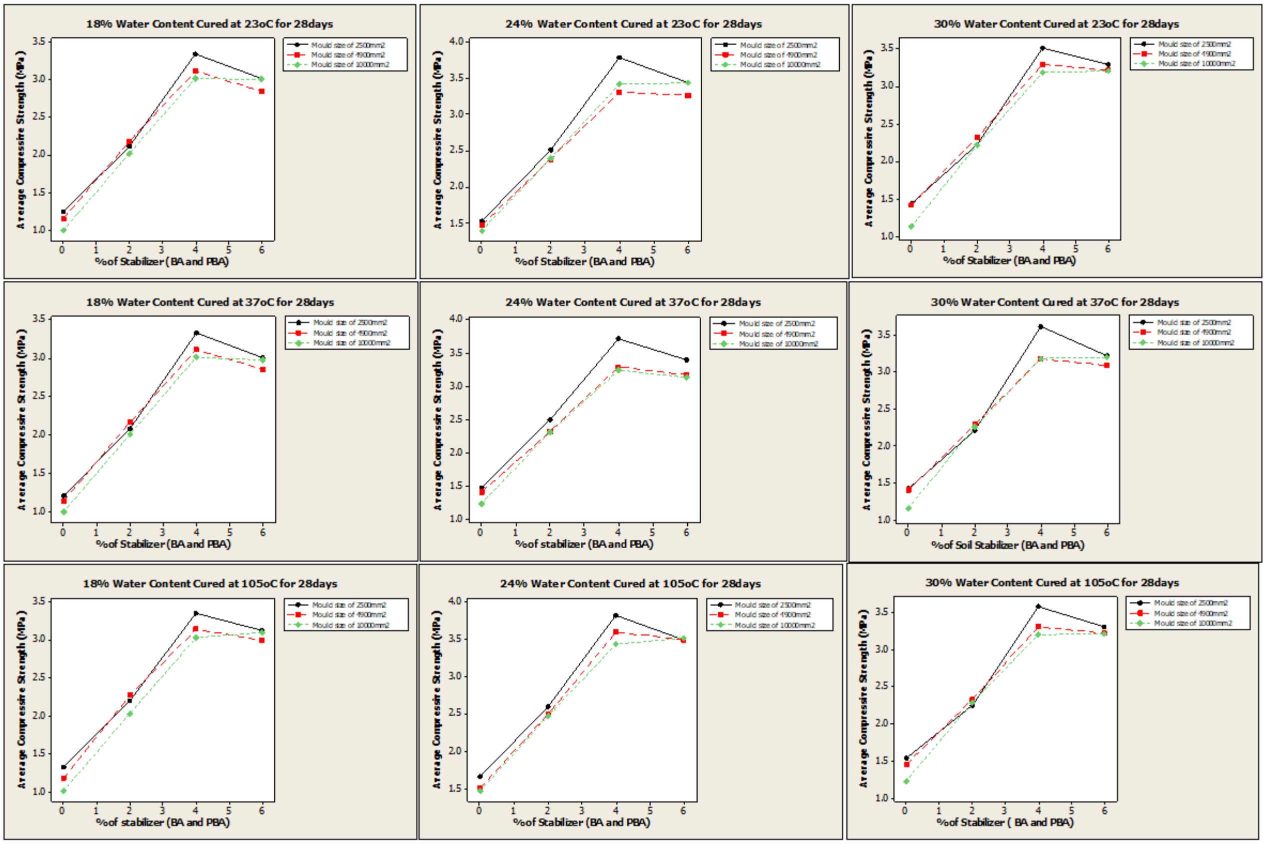


Figure 5.6. Effects of weight percentage of the soil stabilizers and size effects of the specimens on the compressive strength of lateritic bricks.

This lower compressive strength obtained for the bigger specimen size could be attributed to the increase in the number of defects as the surface area of the specimen becomes larger. Hence, the smaller the size of the specimen, the lesser the defects present and the better the compressive strength. The increase in the compressive strength of the bricks as the specimen sizes reduce is consistent with the trends obtained in previous studies [34-37].

5.3.5. Influence of curing age on the compressive strength of lateritic bricks

The effect of curing age on the compressive strength of earth-based materials has been studied [38,39]. The influences of curing age on the compressive strength of the lateritic brick sample are shown in Figure 5.7. It was observed that the compressive strength of the sample increases as the curing age increases and vice versa. Thus, brick samples cured for

28days gave the best compressive strength compared to those cured for 7 and 14days respectively as represented in Figure 5.7.

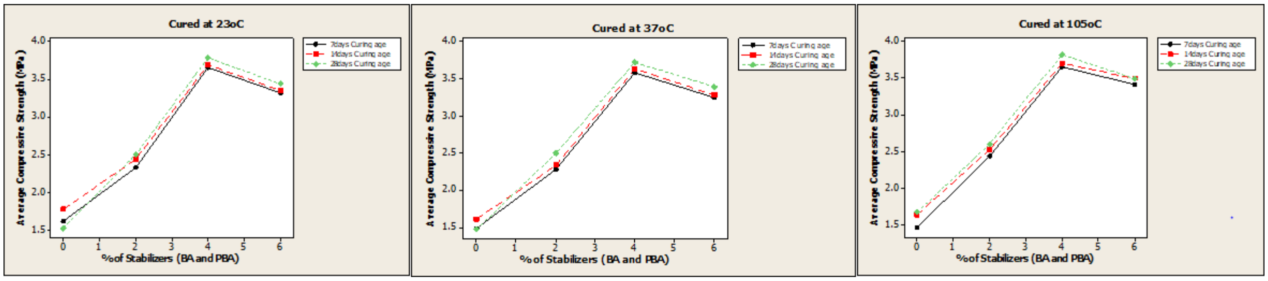


Figure 5.7. Effect of curing age on the compressive strength of lateritic bricks

These increase in the compressive strength with curing age is attributed to enough time provided for the complete pozzolanic reactions between the soil particles and the cementitious content of the soil stabilizers (BA and PBA) to take place.

5.4 Summary and Concluding Remarks

Agro-waste ash stabilization of lateritic soil could be used to manufacture affordable and eco-friendly building materials for the growing population of Nigeria. The best compressive strength result obtained for the tested samples is 3.818MPa and was obtained for the sample mixed with 24% water content and stabilized with 4% stabilizers, processed at 105°C for 24hours and cured for 28days. Hence, the addition of a combination of 4% stabilizers (BA and PBA) improved the compressive strength of lateritic soil by 129 %. Specimen produced with the smallest mould size (2500mm^2) and samples cured for 28days gave the best compressive strength. Also, the use of PBA for a partial replacement for BA reduces the embodied energy consumed in the production of BA since the PBA takes lesser embodied energy to produce. Therefore, eco-friendly and sustainable building materials can be obtained by agro-waste ash stabilization of lateritic soil.

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6.0 CHAPTER SIX: CONTRIBUTION TO KNOWLEDGE, CONCLUSION AND FUTURE WORK

6.1 Contribution to Knowledge

The following outstanding points have been summarized as the major contributions of this study to the existing body of knowledge:

i. Scientific explanation of the mechanical behaviour of lateritic soil stabilized with bone ash and hydrated lime for sustainable building applications;
ii. This study demonstrated that bone ash can be used in place of hydrated lime for the stabilization of lateritic soil for sustainable building applications;
iii. The study established the pozzolanic reactions between the lateritic soil and bone ash that led to the improved compressive strength of stabilized lateritic soil;
iv. Development of multivariate regression models for predicting the compressive strength of bone ash stabilized lateritic soil for sustainable building;
v. New knowledge on the performance of lateritic soil stabilized with combination of bone and palm bunch ash for sustainable building applications;
vi. This study demonstrated that palm bunch ash can be used for partial replacement of bone ash for lateritic soil stabilization and hence reducing the embodied energy consumed when only bone ash is used;
vii. The significance of water content, curing age and curing temperature on the compressive strength improvement of stabilized lateritic soil was established by this study;
viii. The study also demonstrated the size effects of the specimen on the compressive strength of stabilized lateritic bricks;

ix. Results of the study, when commercialized, can reduce the cost of making bricks, reduce environmental pollution from agro-waste and increase the use of earth based materials for building construction as alternative to cement.

6.2 Conclusions

Salient conclusions arising from the combined theoretical, experimental and statistical study are as follows:

a. Adequate utilization of the local building materials is of paramount importance to sustainable construction because of its availability, cost-effectiveness and ability to protect the environment.

b. The exploitation of the agro-waste ashes for soil stabilization will improve the economic values of the agro-wastes and will ensure a clean environment. Besides being cheaper and environment-friendly than cement stabilization, agro-waste ashes can potentially improve the geotechnical and mechanical properties of the soil for construction applications such as building bricks, subgrade of road pavement layer, embankment dam, etc.

c. Partial replacement of cement with agro-waste ash will reduce the consumption of cement in the construction industry and hence reduce global warming caused by the greenhouse effect/gases.

d. The dream of building sustainable African cities can be facilitated by the application of stabilized lateritic bricks for construction purposes.

e. Among the multivariate regression models explored, mixed model with R^2 of 97% was identified as the best-fit statistical models for predicting the compressive strength of stabilized lateritic soil followed by non-linear models. This model has practical application for the prediction of compressive strength of stabilized lateritic soil for sustainable housing construction in Nigeria;

f. Addition of a minimal percentage of BA (2%) and PBA (2%) improved the compressive strength of lateritic bricks by 129% compared to the natural lateritic soil.
g. Brick specimen produced with the smallest mould size (2500mm^2) gave higher compressive strength compared to larger mould size.
h. It was observed that the compressive strength of the sample increases as the curing age increases and vice versa.
i. The use of PBA for a partial replacement for BA reduces the embodied energy consumed in the production of BA since the PBA takes lesser embodied energy to produce.
j. The findings of this study confirm the potential of using lateritic soil stabilized with a minimal percentage of BA (2%) and PBA (2%) for sustainable building applications.

6.3 Future work

This study creates the need for further studies on mechanical properties of agro-waste stabilized lateritic soil for other constructions applications aside from building. California Bearing Ratio (CBR), fracture toughness and settlement behaviour of agro-waste stabilized lateritic soil with respect to road construction applications should be explored in further studies. The effect of using nano-sized agro-waste ash for the stabilization of lateritic soil was not considered in the present study. Also, further research is needed to test the durability of stabilized lateritic bricks under various weathering conditions. Future work will look at the real-life performance of buildings constructed with stabilized lateritic bricks. Studies comparing the greenhouse gases emitted and energy input (embodied energy) consumed in the production of different agro-waste ash and Portland cement will also be carried out.