PERFORMANCE-BASED EVALUATION OF CASSAVA STARCH AND *MAKUBA* MATRIX FOR THE STABILISATION OF COMPRESSED EARTH BRICKS

BY

ISMA'IL MUHAMMAD KHALIL

DEPARTMENT OF BUILDING
FACULTY OF ENVIRONMENTAL DESIGN
AHMADU BELLO UNIVERSITY,
ZARIA, NIGERIA

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Isma'il Muhammad KHALIL
B. Sc BUILDING (UNI. JOS 1992), M. Sc Const. Tech (UNI. JOS 2005)
(PhD/ENV-DESIGN/7836/2009-2010)

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FACULTY OF ENVIRONMENTAL DESIGN
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JUNE, 2017

Declaration

I declare that the work in this Thesis entitled Performance-Based Evaluation of Cassava Starch and *Makuba* Matrix for the Stabilisation of Compressed Earth Brickshas been carried out by me in the Department of Building. The information derived from the literature has been duly acknowledged in the text and in the list of references provided. No part of the Thesis was previously presented for another degree or diploma at this or any other Institution.

Isma'il Muhammad KHALIL	______________________	___________
Name of Student	Signature	Date

Certification

This ThesisentitledPERFORMANCE-BASED EVALUATION OF CASSAVA STARCH AND *MAKUBA* MATRIX FOR THE STABILISATION OF COMPRESSED EARTH BRICKSby Isma'il Muhammad KHALIL meets the regulations governing the award of the degree of PhDin Construction Technology of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. I. K. Zubairu Chairman Supervisory Committee	Signature	Date
Prof. O. G. Okoli Member Supervisory Committee	Signature	Date
Prof. M. M. Garba Member Supervisory Committee	Signature	Date
Dr. K. Dikko Head of Department	Signature	Date
Prof. S. Z. Abubakar Dean, School of Postgraduate Studies	Signature	Date

Dedication

This Thesis is specifically dedicated to the following:

My father, Mallam MuhammadKhalil Hadejia;

My siblings, Aminatu, Halimatu and Abubakar

Acknowledgment

My profound gratitude goes to Almighty Allah (SWT) for His divine guidance and protection throughout my life. Alhamdulillah, wassaalatu wassaalaamu alan-Nabiyul Kareem.

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Abbreviations

ASME = American Society of Mechanical Engineers

BS = British Standards

CEB = Compressed Earth Bricks

CSEB = Compressed Stabilised Earth Bricks

CSM = Cassava Starch and *Makuba*

CSMBs = Cassava Starch/*Makuba Bricks*

CPM = Cooked Paste Mix

C_s = Compressive Strength

C_t = Capillarity

C_w = cold water

DDM = Delayed Dry MixElectron Microscopy

EM = Electron Micrograph

EMC = Equilibrium Moisture Content

ESEM = Environmental Scanning Electron Microscopy

FAO = Food and Agriculture Organization

H_w = hot water

IITA = International Institute of Tropical Agriculture

IDM = Instant Dry Mix

L = Laterite

L_{sl} = Solid Limit

L_{sk} = Shrinkage Limit

LI = Liquidity Index

LL = Liquid Limit

L_S = light slurry

MDD = Maximum Dry Density

M = *Makuba*

MI = Microscopic Image

ML = *Makuba* /Laterite

M_s = strength model

MUSRL = Multi-User Science Research Laboratory

NBRRI = Nigerian Building and Road Research Institute

OMC = Optimum moisture content

PDF = Powder Diffraction File

PI = Plasticity Index

PL = Plastic Limit

PH = Pore Histogram

P_s = Practical strength

P_t = Permeability

R_a = Abrasion resistance

S = Starch(Cassava)

SEM = Scanning Electron Microscope

Sg = Specific Gravity

SML = Starch/*Makuba*/Laterite

SL = Starch/Laterite

S_p = Starch Powder

S_s = Standard Strength

T_s = Theoretical strength

U_{CP} = Uniform clear paste

UNCHS = United Nations Centre for Human Settlement

UNESCO = United Nations Educational Scientific and Cultural Organisation

USGS = United States Geological Survey

W_a = Water Absorption

XRD = X-ray powder diffraction

XRF = X–Ray Fluorescent

Abstract

Although the major material(soil) for the production of Adobe or earth bricks isreadily available and affordable which,could provide a lasting solution to the need for affordable housing,it is not without some inherent problems.The problems associated with soil has led to drawback in the use of earth as a building material. These are lack of durability and need for frequent maintenance. Stabilising the earth with certain materials such as cement has helped a little however, many of these materials like lime and chemical stabilisers are limited in quantity some of them hazardous.Cementproduction highlycontributes to carbon dioxide emission, (a global concern) and it is majorly unaffordable to the common man. Cassava starch and *makuba* (CSM), are both applied for soil stabilisation in traditional building construction but no record of their usage exist in conventional construction. This Thesisexploresways to improve the strength and durability properties of Earth Bricks by utilising these locally available and affordable materials, CSM,to stabilise laterite soil. The work examined different techniques for soil stabilisation with CSM and various curing methods. Brick specimens with 0 to 20% content of CSM spaced at 5% intervalsas binder of laterite soil were produced. The specimens were subjected to tests of compressive strength, densification, abrasion resistance, moisture movements, elevated temperatures and a further confirmatory investigation in the form ofScanning Electron Microscopy. CSM Bricks (CSMBs) have shown improvements up to 64% in compressive strength beyond the minimum requirement of NBRRI and over 100% increased durability properties above un-stabilised laterite bricks. CSMBs could be utilised for application in building construction such as load bearing walls, partition walls, composite walls; parapets and for esthetic finishes as facing bricks since the surfaces of the bricks may not require finishing in the form of plastering, cladding or painting. This is due to the natural texture of laterite which is not altered by cassava starch paste but given additional red brownish tint by *makuba*.

CHAPTER 1

INTRODUCTION

1.1 Background to the Study

Soil is the most abundant of all building materials found almost everywhere on this planet.This explains why majority of the population in the developing world live in Earth (mud) buildings and according to (Namango, 2006), will continue to do so out of necessity. Consequently, it has become a subject of concern to develop ways and means of improving the engineering properties of soil to enhanceEarth buildings.This involves improvement of building materials which, according to (HABITAT, 1998),are limited to basic ones such as those for walling, roof-cladding and low-strength binders.

The advantages of many alternative building materials such as furnace slag, rice-husk ash, carbide waste, and plant extracts are yet to be fully harnessed in Nigeria, and little is known of their conventional utilisation beyond laboratory tests. Some of the plant extracts are cassava starch and *makuba,* which are abundant and environmentally friendly additives that are in use as soil stabilisers in mud walls (adobe) and mud roof construction locally in some areas of this country. The starch from cassava, which is mainly used for laundry, is a by-product extracted from cassava tubers during the processing of cassava flour, *alibo* and *gari*.Khalil(2005), asserted that in Akwanga and Wamba towns in Nasarawa state, Nigeria, cassava starch is used in the manufacture of conical mud balls (local walling units) called '*tubali'*, and also in wall rendering as stabiliser.*Makuba* is a local building material also used in stabilising mud for wall rendering, mud decking and roof construction with a good water proofing property in many parts of Northern Nigeria. According to Abejide (2007),the aqueous solution of the empty pods of the African locust bean, (*Parkia biglobosa*), sometimes including the bark, was used in hardening the surfaces of Earth rammed floors and the sides of indigo pits. The extract, called *makuba*, is also appliedin pottery as gloss paint after firing.

Soil is stabilised for various purposes such as road and wall constructions. This is done to improve the engineering properties of soilsuch as Atterberg limits which is due to the extreme variability of its constituent minerals. According to Geotechnical-Manual (2001), the main components of soil are mineral/organic matters, moisture and air which differ in their proportions.Geotechnical Engineers according to Onunkwo, Uzoije, & Onyekuru (2014), have classified soils in terms of their engineering properties which determines the ability of the soils to function as support for foundations of structures or as building materials such as bricks. Terzaghi and Peck (1995) in (Onunkwo, Uzoije, & Onyekuru, 2014), asserted that laboratory analyses are important steps in evaluating the engineering properties of soils.

Soil stabilisation which is the alteration of any property of a soil in order to improve its engineering performances can be in form of physical, mechanical, chemical or a combination of two or more of these techniques. According to Matawal (1990), compaction of soil, usually by mechanical means, reduces air voids and subsequently controls moisture content changes; increases unit weight by densification; enhances shear strength of soil; reduces permeability; and makes soil less susceptible to settlement under load. On the other hand, compaction alone may be inadequate because according to Matawal & Tomorin (1996), the best soil for construction often falls short of required standards of strength for stable and strong structures. To improve the soil characteristics to the minimum standard requires a certain amount of stabilisation. Some research works on soil as a building material or component have confirmed that,using soil without stabilisation with additives for the construction of structures give low compressive strength and are less resistant to environmental factors, (Balami & Izam, 1998). The properties of stabilised soils vary not only with changes in soil types, but also with the type and quality of stabilising material. Subsequently, studies into the utilisation of soil as construction material such as (Matawal & Tomorin, 1996) and (Balami & Izam, 1998), have centered on examining the suitability of stabilising agents and soil types for different purposes.

In stabilising soil for producing building elements, cement is commonly used, (Matawal & Tomorin, 1996). Its high cost owing partly to transportation, especially to rural areas has prompted researches into the use of alternative materials to partially or fully replace it. Other reasons include high demand for energy in its production and itsgreenhouse effects. According to Khalil(2005), some research works geared towards developing affordable means of stabilising soils using locally sourced materials have yielded certain levels of strength reasonable for construction. Examples include: Strength Properties of Compressed Earth Bricks (CEB) using Earthworm Cast as Stabiliser by Kamang (1998);Unconfined Compressive strength and durability of Lime-Clay Soil for Building Construction by Okoli (1998); Properties of Compressed Earth Bricks Stabilised with Termite Mound Material by Olaoye & Anigbogu(2000); and Performance of Soilcrete Blocks with Plant Extract Additive by Abejide (2007). These works established that the stabilisers have resulted in increased strengths ranging from 0.9N/mm^2 to 2.55 N/mm^2 for use in low rise buildings. Other works by Dahiru & Zubairu(2007); and Dalziel 1948 in Abejide(2007)for example, have applied other alternative materialsdue to their abundance or in the recycling of wastes as soil stabilisersor replacements for cement. These are furnace slag, bitumen, rice-husk ash, carbide waste, dye waste, horse hair, gum Arabic, plant extracts and starches from grains/tubers. Cassava starch and *makuba* (CSM), apart from being used locally in mud buildings, have been individually put to laboratory tests with results indicating increase in compressive strengths of cassava starch stabilised soil as high as 3.55N/mm^2. However, cassava starch stabilised soil specimens turned out to be weak in terms of resistance to water penetration, (Khalil, 2005). On the other hand, *makuba* was reported by Abejide (2007), to possess higher resistance to water absorption. Even though *makuba* also improved the strengths of soil up to 2.04N/mm^2,(Ibrahim, 2010), the specimens were observed to be brittle hence, failure of *makuba* stabilised specimens under compression could be instant without any form of warning. The combination of cassava starch and *makuba* could be a great advantage because the shortfall of one could be compensated by the other.

Earth construction provides comfortable living environment due to its high thermal and heat insulation values. It also offers other important factors that contribute to the achievement of good planning, design and construction solutions for the provision of shelter, (Marwan & Nasim, 2016).Itcan also provide employment opportunities and savings in the funding of projects as all materials (laterite and CSM), with the exception of tools, may be readily available without high need for transportation, especially in rural areas.

1.2 Problem Statement

Majority of developing countries are faced with the issues of providing adequate, affordable and sufficient shelter with the conditions getting worse due to scarcity of resources, (Kerali, 2001). The fundamental need for shelteris a concept that is as old as the recorded history of mankind and it has been universally accepted as the second most important human need after food,Daniel *et al*(2010);Onuoha (2013).In the year 2007, the World Bank identified 152 developing countries Nigeria inclusive, where one in every three people is without adequate shelter, (HABITAT, 2008). This Organisation is working towards lowering the statistics through the provision of low-cost, sustainable building materials and technologies. According to theUnited Nations Centre for Human Settlements,UNCHS(2000) in Danjuma(2010), political independence has influenced the rate of urbanisation in Africa, which is the fastest in the world. Migration from rural to urban centers in search of education and/or greener pastures is a contributory factor to the scarcity of shelter in urban centers.Housing delivery is a major problem confronting the underdeveloped world with several housing policies put in place but without housing delivery. Not only is the population growth rate higher than the rate of housing provision, the actual housing delivery processes are more often than not over-ambitious hence, not sustainable, (Daramola et al, 2013). If developmental activities such as Earth Brick production are encouraged in rural areas, this trend may change directions and influx to urban cities may reduce.

Since the mid-1980s, Nigeria has been going through series of economic crises such as hike in the cost of common commodities and services. These crises have devastating effects on the cost of building materials and housing supply in the country alongside the escalation of house rents. The major factors responsible for this development are the low financial standing of people, and low level of awareness in the use ofcheaper and energy conserving construction materials such as CSEBs which serve as alternative to the Sandcrete/Concrete blocks used all over the country, (Daramola, 2005).

Cement production requires a great amount of energy, so finding materials that can favourably substitute for it will make appropriate environmental sense. The Environmental Building News,Environmental (2009), reported that the production of Portland cement used in the United State of America (U. S. A.), leads toemission of greenhouse gasinto the atmosphere, which is comparable to operating 22 million cars. In addition, the U. S. A. imports about 20% of the 100 million metric tons of cement it uses annually, leading to additional cost burden and energywastage. Cement situation in Nigeria is far worse than that of the U. S. A. Cement production in Kogi, Gombe and Sokoto states for example, are resulting in the devastation of land in the process of raw materials acquisition, (gypsum, limestone, shale and clay). Reclamation is an additional cost burden thus; farm lands around these areas are fast thinning out. Another major constraint in the manufacture of cement in Nigeria is power. The erratic power supply apart from crumbling small scale cement producers, has heightened the price of cement beyond the reach of the rural and urban poor, (Fiakpa, 2008).

There are some inherent problems associated with Earth buildings which includes drawback of earth as a building material due to its lack of durability (low resistance to water penetration) and need for frequent maintenance; problem of earth construction leading to high shrinkage, cracking and low strength; unstable nature of earth when used for the construction of houses above two stories.Even at that, walls of ground floor need to be thicker than those for upper floors in the same building.

1.3 Justification for the Study

Although the techniques of producing CSEBs using variety of stabilisers are widely practiced, the combination of cassava starch and *makuba* to produce cassava starch/*makuba* bricks (CSMBs) is new. Among studies in stabilising soils for all construction, cement remains outstanding as indicated in the works carried out by Matawal (1990); Ufford (1990); Matawal& Tomorin(1996); and Daramola(2005). These works utilised cement to measure the responses of different lateritic soils to stabilisation. Unfortunately, cement is relatively expensive compared to some soil stabilisers like lime, furnace slag and other industrial wastes. According to Ufford(1990), theNigerianconstruction industry in the 1980s suffered a depression as a result of the continual increase in the cost of construction materials. Cement, one of the most widely used is the most expensive construction material. Thus study into the development and utilisation of locally available raw materials which can partially or wholly replace cement in order to reduce its quantity in construction works has become imperative.The rising cost of conventional building materials in Nigeriahas necessitated intensification in the search for alternative building materials of simple and cheap construction techniques to be developed, (Taiwo & Adeboye, 2013). The negative impact of the problems facing housing delivery in Nigeria may be reduced to some extent where locally sourced materials are tested for possible application inbuilding construction works. This, in a way, may contribute to reducing the effect of the scarcity and hence high cost of cement and other construction materials as well as conserving Nigeria's foreign reserve spent on the importation of these materials. When the technologies of utilising local materials are articulated, it may not only reduce the overdependence on conventional building materials, but can also contribute to the reduction in environment pollution arising from agricultural and industrial wastes.

Earth-based housing may provide a lasting solution to the need for affordable housing throughout the developing world,(James, et al., 2016). Adobe construction (using sun-dried earthen bricks) has been an ecologically sound, affordable building technique in many parts of the world for thousands of years. Historical and current use of adobe in the southwestern part of the United States for example, which is based on economic; social; and environmental considerations, indicate that in that region, adobe is truly an ‘appropriate’ technology: it is long-lasting, conserves energy, uses local building materials, creates jobs, requires little capital, and ‘fits’ culturally, as documented by (Villagearth, 2010).

Before the advent of cement and its subsequent use in the production of blocks, earth bricks/blocks were the main walling materials but characterised with low qualities especially, compressive strength and resistance to water penetration and fire. With the introduction of regulated amount of cement to local mud bricks, CSEBs evolved. The quantity of cement in CSEB is minimal compared to that used in sandcrete blocks. This is because with large quantity of cement in soil,shrinkage may be high in the soil bricks and the consequences of eventual hydration of isolated cement grains may result in the formation of cracks and destabilisation of wall components.The controlled and regulated amount of cement in soil only improves strength and retards moisture movement to a certain degree within minimum requirements, hence the need to conventionally put to test, locally available raw materials with convincing local history of application to produce more durable and affordable Earth bricks.

According to the International Institute of Tropical Agriculture, IITA/Crops (2004),cassava has taken an economic role in the world in that the starch from it is used as binding agent in the production of paper and textile in south-east Asia and Latin America. In a research work by (Khalil, 2005), five soil types (sandy, clayey, loamy, laterite and gravelly soils), were stabilised with cassava starch. Laterite soil yielded outstanding improvements in strength and durability properties like abrasion resistance and resistance to impact loading. Compressive strength was improvedup to 3.55N/mm^2 at 20% starch content at 28 days. This is an indication of the likelihood that cassava starch could take up the place of cement even if partially, in the stabilisation of laterite soils for the production of earth bricks. The only observed shortcoming of cassava starch as a soil stabiliser is its affinity for water. The water absorption of stabilised specimens had no significant differences when compared to the control specimens, although absorption rate was slowed down with increase in starch content, (Khalil, 2005). This is where *makuba* may come in as it has been in use from time immemorial in local mud roof construction as a stabiliser. A research work that stabilised laterite with *makuba* and cement byAbejide(2007), discovered that the water absorption rate of blocks produced with laterite and *makuba* was 10% less than the water absorbed by those produced with laterite and cement.

This research work utilised a matrix composed of these agricultural products (CSM), which are both abundant all over the tropical regions of the world,(Olanipekun, 2012); (Lawal, 2012), in stabilising laterite to produce CSMBs. The study into the possibility of using CSM matrix in stabilising laterite soil is justifiedowing to the fact that buildings, out of necessity are going green. In green construction, energy wastage is minimised by avoiding the generation of heat or reducing it in the production of building materials.At the same time green building provides several advantages observed by Kasai & Jabbour(2014), such as appreciation in the value of the property, reduction in water and energy consumption as well as reduction in waste generation. Apart from the escalating cost of cement, some alternative materials to cement such as (rice husk ash and bitumen) for example, require high heat in transforming to ash or melting to required viscosity before application. After the application of these synthesised materials, environmental pollution may not be avoided and emission of harmful gasses from walls and other elements may continue due to reactions with other materials. Therefore, local materials with binding effects requiring little or no heating will be favourable to the production of green buildings. The significance of this study is further informed by some other reasons. Among them are, energy saving in buildings; aesthetic values as CSMBs may require little or no finishing as a result of the natural colour of laterite and beauty when pointed; ease of construction and socio-economic benefits that will be derived by both rural and urban populace through generation of employments; increase in the cultivation of these plants, which will retard desert encroachment; and wealth derivation by bricks production. The choice of laterite soil instead of clay is because the latter is expansive and that is one reason for the need to fire clay bricks at high temperatures. This is not necessary with laterite, thus making it anappropriate building material.

1.4. Aim and Objectives

1.4.1 Aim

This research work is aimed at investigating the performance of Cassava Starch and *Makuba* matrix in stabilising laterite soil with a view to maximizing their utilisation as alternative materials to cement in building construction.

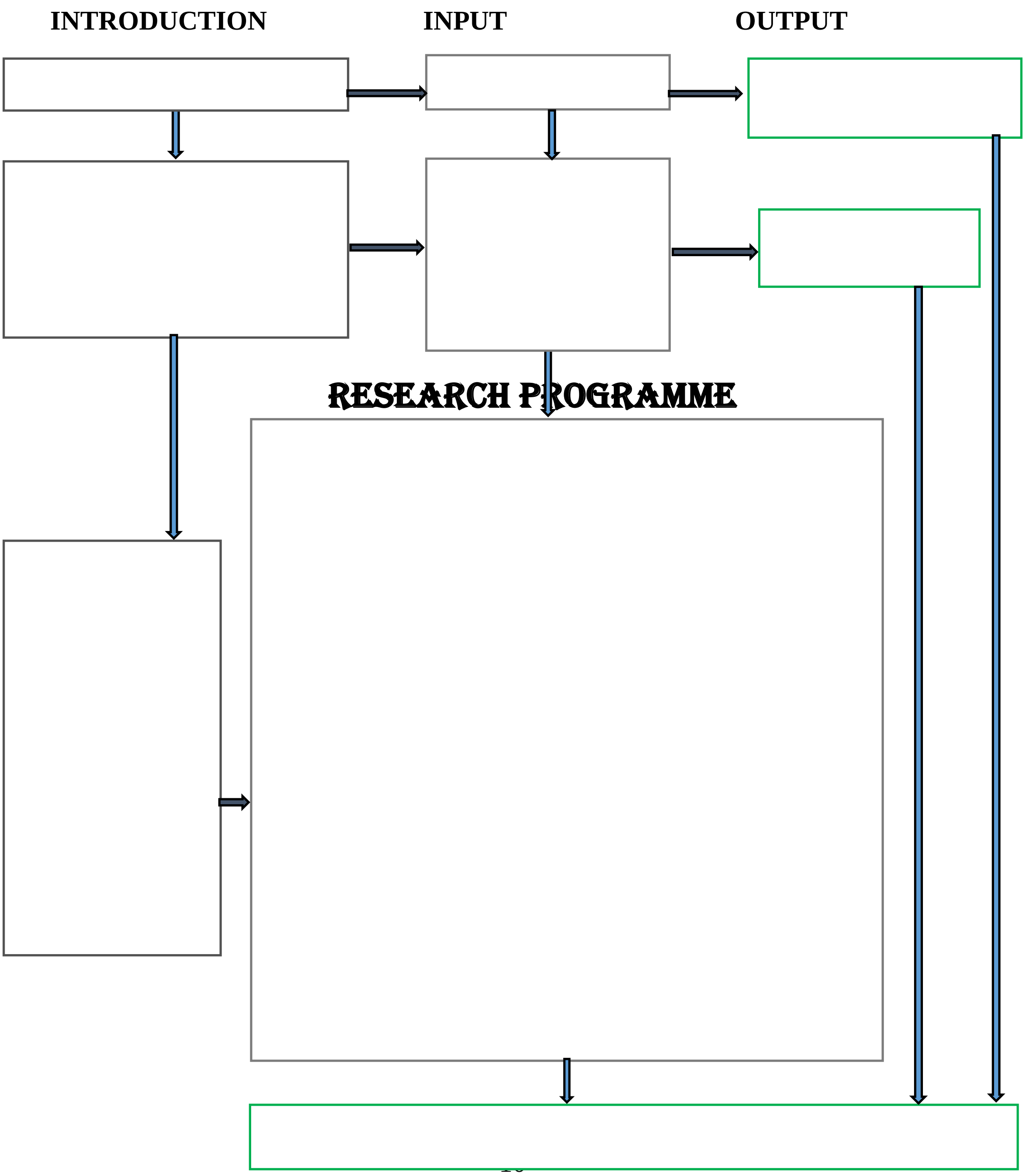
1.4.2 Objectives

The specific objectives are to:

1. Investigate engineering properties of the research materialsprior to designing matrix mixes.
2. Establish optimum percentage levels of CSMmatrix in brick samples.
3. Determine durability properties of CSMBs within 28 days of curing.
4. Assess strength characteristics of the different mixes of CSMBs.
5. Evaluate the performance of CSMBs as walling units under elevated temperatures.
6. Examine the morphology of CSMBs through Scanning Electron Microscopy.
7. Develop analytical models for the prediction of CSMB strength characteristics.

1.5 Research Design

The research carried out in this Thesis was designed in three stages as displayed in figure 1.1. The introductory stage consists of the formation of the research topic and giving it a proper tittle; highlighting the problem statement of the research; drafting of the aim and objectives of the Thesis and scoping the work. The input stage comprised of the main body of the work were the objectives were treated through laboratory experiments. The third stage is made up of discussion and interpretation of the research findings that lead to the conclusions.



[Adapted from Abdul-Azeez, 2012]

Figure 1.1: Research Design

1.6 Scope and Delimitation

1.6.1 Scope

Although laterite is used in the production of roof slates, rammed floors, tiles, cast walls etc., this work extensively focused on Compressed Stabilised Earth Bricks (CSEBs). Preliminary laboratory tests of strength and durability were maintained within 28 days of curing while strength tests were extended to 360 days.

1.6.2 Delimitation

An attempt was made for a detailed study for confirmation of the suitability of cassava starch and *makuba* as potential soil stabilisers. It was expected that the water proofing property of *makuba* would complement the stickiness effect of cassava starch for the production of appropriate walling units. However, the economic viability of using CSMBs may not be feasible as at now due to the fact that as a first attempt at combining local alternative materials not as replacements to cement to produce earth bricks, all efforts were directed at establishing durability properties and strength characteristics only.

CHAPTER 2

LITRATURE REVIEW

2.1 Theoretical Framework

Enhancing the Building material sector, which requires the integration of locally available alternative materials into construction technology, is central to this research work. Theories associated with search for soil stabilisers include(Matawal & Tomorin, 1996), (Balami & Izam, 1998), (Kamang, 1998), (Okoli, 1998), (Olaoye & Anigbogu, 2000),(Adam & Agib, 2001), (Kerali, 2001), (Heebink & Hassett, 2001), (Lime, 2001), (Daramola, 2005),(Khalil, 2005),(Namango, 2006),(Abejide, 2007), (Ramson, 2011), (Riza, Abdul-Rahman, & Zaidi, 2011), (Wayne, 2011) and (Oskam, 2013).These research works haveestablished the binding properties of some locally available materials including cassava starch,on soils.Other theories, (Abejide, 2007) and (Ibrahim, 2010),are on the capabilities of the aqueous solution of the African Locust bean pod to bind soil particles as well as resist water penetration.

According to HABITAT(1989),studies that address the context of building materials choice and preference have foundthat the most urgent task is to address the needs of the urban and rural poor whose most pressing needs is basic shelter. Thus, the decision for applying alternative construction materials as substitutes for costly conventional ones such as cement must satisfy certain criteria such as availability, affordability and standards.

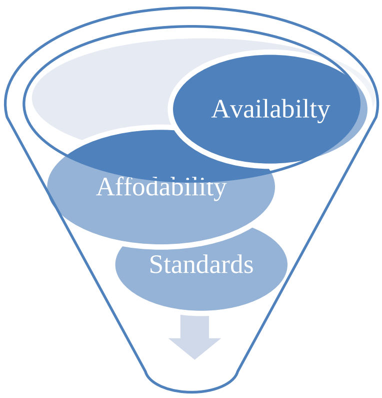


Figure 2.1: Decision cone for selection of appropriate alternative construction materials

It is not enough to establish the availability of alternative materials in large quantities. As seen in figure 2.1, the decision for selection of alternative construction materials requires that the acquisition, processing and transportation of the materials must be relatively affordable. Again, the materials have to pass minimum requirements stipulated by relevant standards such as the British Standards; American Standards, Nigerian Building Code and others. By working simultaneously on these criteria, appropriate building construction materials are more likely to be developed.

2.2 Housing Delivery

Housing delivery is a major problem confronting the underdeveloped world with several housing policies put in place but without housing delivery. Not only is the population growth rate higher than the rate of housing provision, the actual housing delivery processes are more often than not over-ambitious hence, not sustainable, (Daramola, Alagbe, Aduwo, & Ogbiye, 2013).

Challenges of housing in terms of quality and quantity as observed by (Ibimilua, 2011), seem to be the same all over the world. The poor have less access to housing while the rich have upper hand in accessing housing. In rural areas of Nigeria, housing is generally inadequate in terms of quality, while in urban areas the major problem is that of quantity. Enhancing the quality of buildings in rural areas requires the upgrading of rural building materials such as Earth and local binders like *makuba* for example. In urban areas where shortage in quantity is experienced, developing cheaper but quality materials such as CSEBs would go a long way to ease the problem.

2.3 Building Construction Technology

Towards the end of the 20th century, as the world was striving for a better quality of life, the poorpopulation was fighting for life itself and as at then more than 600 million people in cities and towns throughout the world were homeless or lived in dilapidated houses.

(HABITAT, 1989),posited that unless a revolution in solving the shelter problem takes place, this shocking statistic will triple by the year 2025. Provision of decent shelter for this large number of people will no doubt be the major challenge of the construction sector in the 21^{st} century. Traditionally, technological development in the construction industry has always influenced social and economic development, including development of human settlements. Technological advancement has contributed to greater productivity and lesser construction cost and has even reduced the adverse effects of construction on the environment in many countries. But developing countries are far fromthe benefits of technology to meet the increasing demand of shelter for even the low-income population.

The United Nations Centre for Human Settlements (UNCHS)(HABITAT, 2008), over the past decades, has been promoting the development of appropriate, energy-efficient and environmentally-sound construction technologies, which heavily relies on locally available resources. The construction industry is said to be the backbone of national economic and social development as revealed by several studies such as(HABITAT, 1989); (Kerali, 2001) and (Namango., 2006). This is evident during the periods of national economic growth where construction activities grow more rapidly than the economy as a whole. In developed economies, gross inadequacies in shelter are the basic indicators of underdevelopment related to low infrastructure and amenity delivery systems which result from the constraints of the construction sector. Despite the strategic relevance of the construction sector, it still operates with major inadequacies especially in developing countries. For example, construction costs are relatively high, basic inputs, particularly building materials are scarce and expensive, yet the sector heavily relies on importation amidst availability of unexploited indigenous resources. Thus, the outputs of the construction sector is farfrommeeting the demands for shelter and infrastructure especially the demands of low-income population. The fundamental reasons for this anomaly are among others, lack of good planning; lack of policy implementations if any; poor financing; and use of inappropriate and outdated technologies which are not suitable for local conditions, and are wasteful in terms of energy inputs.

The rapid pace of technological changes has radically impacted on the nature and practices of construction in developed countries and this has brought about technology-related issues in the forefront in all developmental sectors, the building materials industriesinclusive. Changing technological needs of the construction sector necessitates that developing countries rectify past deficiencies and enhance capacities to meet new challenges,(HABITAT, 1989). HABITAT further stressed the importance of improving energy efficiency and the application of low-energy, environmentally-sound and safe technologies in Building Construction. This can be achieved by adopting not only environmentally-sound and safe technologies but by the use and adoption of environmentally friendly building materials.

2.4 Building Materials

The building materials sector has been acclaimed by the (HABITAT, 1989)as the backbone of successful shelter strategies. Some previous reports of the UNCHS have outlined the significance of small-scale building-materials production within the framework of shelter improvement. The fundamental principle which the Centre has been promoting, both in its research efforts and in field implementation projects, is that small-scale technologies, in general, are suited to the resource limitations of developing countries. Besides, (Marwan & Nasim, 2016), have observed that recent interest in theapplication of natural materials is due to the increasing demand for housing caused by rapid population growth and the need to reduce energy consumption in the building industry. Earth construction offers a very high resistance to fire if well treated, and provides comfortable living environment due to its high thermal and heat insulation values. It also offers other important factors that contribute to the achievement of good planning, design and construction solutions for the provision of shelter.

In searching for solutions to improve the building-materials sector in developing countries, the most urgent task opined by the(HABITAT, 1989), is to address the needs of the majority of the population, usually the urban and rural poor among whose most important needs is shelter. In this respect, developing countries are said to have some degree of consolation in that the range of materials required is limited to basic ones such as those for walling, roof-cladding and low-strength binders. At the same time, the materials which are viable for the low-income population, such as soil blocks, fired-clay bricks and tiles, building lime, micro-concrete roofing tiles and improved thatch roofing, can all be produced at good quality using rudimentary technologies, consistent with what developing countries can sustain, (HABITAT, 1989).

According to HABITAT(1989), the availability of raw materials in large quantity and of suitable quality, is a major factor in decision making for the establishment of building-material production plants, regardless of the scale of production. The size of raw-material deposits is an important consideration in the choice of the scale of production. Small-scale plants have the advantage of using smaller deposits. Confirmation of the suitability of raw materials for the production of quality building materials is of utmost importance and is undertaken both in the field and in the laboratory.

(HABITAT, 1998), identified the most required building materials as those for walling, roof-cladding and low-strength binders. This Thesis dealt extensively with materials for walling and low-strength binders excluding roof-cladding.

2.5 Wall

A wall as defined by the English-Dictionary (2016), is a building component which is continuous, vertical and thin relative to its height and length. Walls are categorised in accordance with their function and position in a building. They range from external walls that provide shelter from the environment there by protecting the interior from external vagaries such as wind, rain and variation in temperature to internal ones that divide the space in buildings into partitions, rooms and compartments. Walls, according to Abhinav *et al*(2014), are categorised in terms of load as load bearing and non-load bearing; based on construction as solid, veneered, reinforced and cavity walls.

The basic function of the envelope or enclosure of a building or structure elicited by Daniel *et al*(2010), is to protect the covered or otherwise conditioned interior spaces from the surrounding external environment. Wall systems generally, have to be able to control massive energy, and particulate flows both within and across the system. These include, heat, air, moisture, smoke, odour, fire, blast, birds, insects and so on, (Daniel *et al*, 2010). For a wall to be functional, it has to satisfy specific requirements such as strength and stability; resistant to moisture movements, insulation against thermal movements; free from frequent maintenance; fire safety and give adequate security with certain degree of aesthetic values. Basically,Yasir(2013) and Constructor (2017), have pointed out that masonry wall is a form of construction the durability of which is generally affected by the quality of materials used and the workmanship employed during construction. Materials for wall construction varied widely from one region of the world to another. In the United Kingdom (UK) and Ireland, traditional walls are constructed of stone, brick, timber and earth, (Morgan, 2008). In Nigeria, the basic traditional wall construction material is earth. Enhancing the properties of earth walling materials in Nigeria is therefore highly required since earth has so many advantages such as availability, affordability, and adaptability.

2.5.1 Strength and Stability of Walls

Exterior walls must be capable of withstanding all applied internal and external forces, (Daniel *et al*, 2010). Majority of these forces are structural loading which include both static and dynamic loading including, but not limited to, dead load, live loads, wind loads, earthquake loads and possible blast loads. The walls have to be properly supported to resist and transfer the loads appropriately. The strength of a wall depends on the strength characteristics of the materials from which it is made, that is, the materials must be able to resist compressive, tensile and to some extent, flexural stresses as well as the technique of assembling the walling materials to erect the wall. Masonry wall opined by Smith (2017), is good in resisting compressive stress but is limited in flexural and tensile strength. CSEBs are equally good in taking compression and depending on the degree of compaction applied in pressing the bricks and stabilising materials, these bricks could be enhanced in resisting flexural and tensile stresses.

2.5.2 Resistance of Walls to Moisture Movements

Most physical and chemical properties of soil elements, wall inclusive, vary with moisture content. Measurement of moisture content asserted by Alberta (2016), is needed in every type of soil study. Hydrology, agrology, plant science building and civil engineering all require soil moisture data. The information on moisture required by the building and civil engineering professions are used in determining solutions to moisture movements in structural elements that would be detrimental to the elements if left unchecked.As observed by Daniel *et al*(2010)**,** moisture transfer can occur in walls through multiple mechanisms. Wetting can occur as a result of direct or indirect exposure of walls to rainwater penetration, as well as due to diffusive or convective vapor flow across an exterior wall system or assembly that results in condensation inside the wall system. Once a wall gets wet, capillary transfer within, or between, layers of the exterior assembly can also occur, and can be further exacerbated by moisture loads inherent to an exterior wall product or material shortly after initial installation. CSEBs stabilised with *makuba* have good resistance to moisture movements, (Abejide, 2007).

2.5.3 Insulation Properties of Walls

Walls should be able to serve as good barriers against the transmission of heat and sound to enclosed spaces. The rate at which heat is conducted through a wall depends on how dense the wall is. The denser the wall the higher its rate of heat conduction but the less its sound transmission, (Emmitt & Gorse, 2010).There must be a striking balance between these functions in the design of walls to regulate and insulate both heat and sound transfer within enclosures. Earth walls are such that alterations in thicknesses of walls and the incorporation of additives could solve insulation problems.

2.5.4 Maintenance of Walls

Maintenance is a yard stick for measuring the durability of a wall. The less the frequency of maintenance of a wall, the more durable the wall is. Emmitt & Gorse(2010), have stated that where there are agreed minimum functional requirements for example, exclusion of rain and thermal properties, durability could be measured by comparing the cost of maintenance of different walls over a number of years.Un-rendered, un-stabilised Earth walls require frequent maintenance for example, on yearly bases. Cassava starch stabilised brick walls may extend to two years or more before maintenance is required. This is because the starch according to Khalil (2005), slows the ingress of water which might take longer to penetrate to the interior of the wall and cause any serious damages. *Makuba* stabilised walls mayrequire minimal maintenance due to good resistance to water penetration, (Abejide, 2007).

2.5.5 Fire Safety of Walls

According to (Zaib, 2013),masonry wall functional requirements besides adequate strength to support imposed loads; sufficient water tightness; sufficient visual privacy and sound transmission; also include appropriate fire resistance and the ability to accommodate heating as well as air conditioning.The materials used in constructing a wall,opined byEmmitt & Gorse(2010), determine the resistivity of the wall to fire. The walls combined with doors and windows must provide adequate protection against fire and its spread to other building elements. It is observed by Ranjan (2013), that with good quality workmanship, earth brick walls possess good fire resistance.

2.5.6 Security of Walls

Walls play a primary function along with doors and windows against forced entry into buildings.Forexample, ram raiding of especially commercial premises,(Emmitt & Gorse, 2010). CSMBs as walling units can provideequal security as other walling units such as burnt bricks, depending on the quality of wall construction.

2.5.7 Aesthetic values of Walls

Barry, according to Emmitt & Gorse(2010), stated that walls are important visually and are vital components in the design of a building that make major contributions to the character of the building. Aesthetic values vary from one individual to another thus, standards of acceptable appearance depends on the individuals choice and preference. The choice of materials here rely on satisfying the other functional requirements mentioned earlier. CSMBs can fit into various wall designs and patterns like Flemish and basket weave bonds. They can also accommodate pointing and jointing like other brick types and with good textured and coloured laterite, the aesthetic values of CSMB walls may have no bounds.

2.5.8 Walling Materials

Popular walling materials in use today include but not limited to stone; bricks and blocks; timber; concrete; steel; glass and adobe, (wiseGEEK, 2017). Emmitt & Gorse(2010), also observed that some other materials used and abandoned a long time ago are becoming popular once again as a result of environmental concerns. Their utilization is now being revisited adopting both ancient and modern technologies. These are adobe, straw bale construction and more especially, CEBs.

2.6 Earth Construction

Earth, as Gernot (2007), posited, is a naturally available material which is easy to use even with low craft skills; absorbs and desorbs humidity faster to a higher extent than any other material; produces hardly any environmental waste; and balances indoor climate and moisture movements creating a healthy environment. Earth according to Nagaraj*et al*(2014), being abundantly available, has invariably been the major construction material for proving housing and other structures around the world. Globally it is estimated that one third of the world's population live in earth buildings acclaimedLittle & Morton(2001), while Hawthorn(2012), declared that approximately one-quarter of the world's population live in homes made of earth, majority of which are in the developing world. These are both modern and traditional buildings, which occur in most cultures and climates. In the United Kingdom alone there are estimated to be over 500,000 inhabited earth buildings. In Scottish construction, earth was the principal material used, until the 18th century and Scotland still retains a rich heritage of earth construction with much regional variety. Many surviving buildings today, are not recognised as being of earth construction and much work has been done on this in recent years by Historic Scotland and others, (Little & Morton, 2001). In Nigeria, the basic wall construction material in most traditional architecture asserted by Egenti, Khatib, & Oloke(2014), is earth, usually arranged in simple low-cost and self-help construction methods.

According to Pacheco-Torgal & Jalali(2012), earth construction has received an increased attention by the scientific community in the 1990s as illustrated by several published research articles when compared to decades before then. Earth construction has a major expression in developing countries and its importance can be seen in some of the environmental benefits associated with it such as economic issues; renewable resource; little waste generation; energy conservation; minimal carbon dioxide emissions; and proper indoor air quality. Little & Morton(2001), have established that the principal reason for using earth-based materials is the excellent sustainability characteristics exhibited by these materials. These include low carbon emissions, efficient use of finite resources, minimising pollution, waste, and use of benign materials, local sourcing and biodegradability.

The construction industry is recognised as currently being the major source of carbon emissions, pollution and waste production, thus within the context of national priorities, earth has a great potential to make a significant contribution towards reduction of the environmental impact of construction, (Little & Morton, 2001).

Several Earth Construction techniques are practiced around the world.Themost usual being: wattle and daub; cob; rammed earth (including earth projection); earth bricks (adobe) or compressed earth bricks/blocks (CEB), (Pacheco-Torgal & Jalali, 2012).

2.6.1 Adobe

Every low-cost housing project according toSidibe(1985), seeks to build the most durable house at the lowest possible cost. Common adobe, as it has been known for centuries, is simply a soil mixture with a clay content of at least 40 percent which becomes a sticky mud when mixed with water. This mix is used to produce building blocks in wooden moulds. Traditional adobe is an acceptable alternative to wood, masonry, cement, or steel walling. Adobe attracts moisture, which erodes its cohesiveness but an annual application of a firm coat of mud plaster will prevent block erosion. One coat is usually sufficient in regions with low rainfall. In humid rainier regions, two coats are required. Moisture degradation of adobe wall can be prevented by stabilisation. Improving traditional adobe as a building material focuses on soil selection and the proper methods for controlling moisture content of the material. These two factors influence the performance of un-stabilised adobe, and determine the success or failure of the stabilisation process. Example of known efficient stabilisers used with adobe are straws, cement, asphalt emulsion, and lime.

According to Sidibe (1985), an adobe wall can control heat transfer due to the thermal properties inherent in the massive walls typical in adobe construction. In temperate climates typified by heat in the day and cold in the night, the high thermal mass of adobe levels out the heat transfer through the wall to the living space. The massive walls require a large and relatively long input of radiation from the sun and convection from the surrounding air before getting warm through to the interior and begin to transfer heat to the living space. After sun set, temperature drops but the already warmed up wall will continue to transfer heat to the interior for several hours due to the effect of time lag. Thus, adobe wall of the appropriate design is very effective at controlling inside temperature through the wide daily fluctuations typical of desert climates, a factor which has contributed to its longevity as a building material.

In addition, external adobe walls can be covered with glass to increase heat collection which, in a passive solar home, are called Trombe walls. This practice according to Rogers(2016), is a construction that uses a combination of thermal mass and glazing to collect and store solar radiation for heating buildings.

2.6.2 Compressed Earth Bricks

Compressed earth block or brick (CEB) is the modernised form of the moulded adobe. The idea of compacting earth to improve the quality and performance of adobe is not new, and it was with wooden tamps that the first compressed earth blocks were produced. The first earth compressing machines for CEB probably dated from the 18th century starting from France, where Francois Cointeraux, inventor and fervent advocate of 'new pise' (rammed earth) designed the 'crecise', a device derived from a wine-press. But the first mechanical presses were designed in the beginning of the 20th century, using heavy lids forced down into moulds. Some of this kind of presses are even motor-driven. The fired brick industry were using static compression presses in which the earth is compressed between two converging plates. But the turning point in the use of presses and in the way in which CEBs were used for building and architectural purposes came only with effect from 1952, following the invention of the famous ClNVA-RAM press, plate I, designed by engineer Raul Ramirez at the CINVA Centre in Bogota, Columbia. In the 1970s and 1980s, new generations of manual, mechanical and motorised presses emerged, leading to a genuine market for the production and application of CEBs, (GTZ, 1995). TheCINVA-RAM asserted by Wayne (2011), is a simple, low-cost, portable machine for making CEBs and tiles from soil. The press has a mould box in which a hand operated piston compresses a slightly moistened mixture of soil and cement or lime. Blocks made with the CINVA-RAM are easier to make than sand Crete blocks, cost low, and can be made on a building site thus avoiding transportation costs.

Plate I: CINVA-RAM - The First Press for CEBs

Compressed earth block or brick are two terms used interchangeably to mean earth that has been compressed to make a building material, (MecoConcept, 2013). It is the material of choice in many cases such as Green Housing usedto build environmentally friendly houses with walls having high thermal inertia (radiant walls). It can also be added to straw bale and wood houses which are good insulators, but with low inertia.

At the inception in 1976 of HABITAT for Humanity International, a major provider of housing for the world's poor, (Wayne, 2011), offered that one of the first decisions made by the board of directors was to use locally-available materials as much as possible. This choice is the basis of a more sustainable building system, which is empowering to the people of the community, and better for the environment too. Compressed Earth Brick (CEB) is the name given to earthen bricks compressed with hand-operated or motorised hydraulic machines.In many areas of the world, proper materials are available for making CEB, thus this brick type may be a better choice than any other building material. The choice to use CEB greatly depends on several factors, including culture, labour force, and most importantly, the preference of the homeowner. Before Hand-operated presses that have been used for many decades and still today, blocks were produced by beating soil into a wooden mould with a stick. Rammed earth is a similar process, but a structure is made as one continuous mass of compressed earth. Modern equipment, with hydraulics driven by diesel, gas or electric motors, may be useful in urban areas or for large sites. However, the difficulty of using motor-driven equipment for smaller and more rural projects is hard to grasp in a remote village situation. The poor in these situations are often the ones that need the most help with improving their housing, and CEB can be one of the solutions to their building needs.

2.6.3 Compressed Earth Bricks Technology

CEB technology, as reviewed by GTZ(1995), is anchored in an initial concern to provide a new, economically and socially relevant response to housing production for the World's very poor. It has continued to focus on this concern as its area of application has developed. Hundreds of thousands of family or communal homes and educational and health facilities have indeed been developed since the early 1950s, when this building material emerged in its present form, at the CINVA Centre in Bogota, Colombia.

Plate II: Compressed Earth Brick Storey Building

Several building forms can be achieved using CEBs with ease as shown in plate II; CEB buildings are adaptable to any roof type. CEB walls can accommodate all door and window types and can stand without any finishing (plastering or rendering). CEB technology was a great means for worldwide renaissance and promotion of earth construction in the 20th century, (Auroville, 2016).

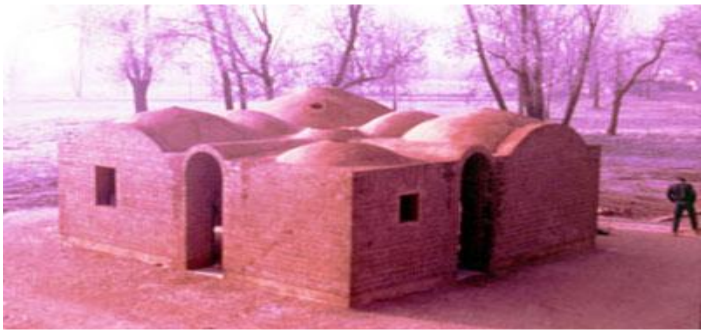


Plate III: Compressed Earth Brick Residential Building

Plate III shows a typical residential building with the superstructure completely made up of earth including the roofing. These buildings have gradually confirmed the appropriateness of CEB building technology, (GTZ, 1995). This simple building material, a direct descendant of the most ancient building traditions of unbaked earth brick and from fired brick, is capable of the same building and architectural subtlety and the same capacity for adaptation to the broad spectrum of factors, physical; ecological; social; economic and technical, which dictate the production of the built environment. As an appropriate building material, it has come to the fore by demonstrating its usefulness measured in technical, economic and also in human terms. From technical point of view, CEB technology is firmly propped up by a scientific body of knowledge equal to the knowledge developed for other building materials used in masonry. From economic point of view, the compressed earth block, has the advantage of being able to be locally produced and directly used. Today, it is comparable and sometimes more competitive to sandcrete blocks, depending on the context in which it is applied. As far as production and construction distribution chains are concerned, the technology generates employment opportunities across a wide range of jobs, from quarrying to brick-manufacturing, from builder to entrepreneur. In architectural terms, the CEB ensures high quality results and at the same time, given optimum conditions of use, enables foreign exchange and energy savings which are essential to its relevance from development point of view. At the human level, this technology provides concrete responses to the basic issue of improving the built environment and therefore the well-being of societies. Better quality construction and architecture, accessibility and replicability are the main criteria for evaluating this relevance from a human and economic point of view. But this relevance is only possible if the scientific and technical body of knowledge and practical skills are well mastered.

Furthermore, GTZ (1995), affirms that CEB technology has not only achieved a level of industrial potential with production methods suited to the formal production sector, but also been able to remain on the scale of craft production and safeguard a degree of usefulness which is relevant to informal sector applications. This dual advantage can serve a wide range of constructional applications in the field of both housing and public facilities. The success of contemporary cases, notably the example of applications on the Island of Mayotte (Comoro) and other developing countries like Sudan, Burkina Faso and Morocco (for example), confirms this dual advantages placed at the service of development ensuring economic and social spin-offs for the local population. This ratification needed to be confirmed by building up a body of knowledge and skill capable of being transmitted appropriately, starting from high quality architectural examples. The CEB technology is intended as much for land-use decision-makers, architects, engineers or entrepreneurs. It is meant to boost confidence and supply the practical tools which is indispensable particularly to disseminate knowledge and skill towards a wider area of application most especially towards housing and public facilities. This applies to local communities who have no choice but to use earth as a basic building material and who have a legitimate desire to benefit from modern technology. Such is CEB technology, at crossroads between traditional earth building customs and modern masonry building practices, a technology which offers an alternative whilst remaining within a range of high quality architectural and construction applications.

2.6.4 Moisture Content of Compressed Earth Brick soil mix

One of the most unique things about making CEB is the control of moisture content in the mix before pressing. It is common practice to make too wet a mix whereas the moisture content of the proper mix is so minimal that it never really seems wet when compared with mixing concrete or adobe, the moisture contents of which are too high for CEB mixtures. One simple test is to fetch a handful of CEB mix and squeeze it into a ball as tight as possible. If the mix stays in a ball when the hand is opened, the moisture content is good. If it falls apart in the hand there is need to add more water. When the ball stays together in the hand, drop it from waist height to the ground. If the soil ball sticks together or breaks in only two or three parts on hitting the ground, it is too wet. In this case addition of some more dry soil in needed, keeping the ratio of soil to cement equal to the original mix. If the soil ball breaks into dozens of pieces, a little water should be added, (Wayne, 2011).

Minimal moisture content as (Wayne, 2011) posited, results in better strength, water resistance, durability and thermal mass in the finished block and it takes a good understanding of the structure of soil in order to understand its interaction with moisture. The presence of clay in the soil binds the sand, helping the block keep its shape. To get clay particles to stick together well, it must first be saturated with water. Mixing the wet clay makes the clay particles to align with each other because clay particles are flat, instead of round or angular like sand. Clay will stick together or adhere to sand like wet paper and thus the wet clay particles bind together and as well bind the sand particles. When brick is compressed in a machine, its volume reduces by 30%, mechanically aligning the moist clay particles, removing air pockets and sticking the clay to the sand. If there is too much water in the mix, there will be more air space between the particles when the brick dries. This reduces the strength and thermal mass of the brick and makes its surface more porous and less resistant to water and scratches (abrasion). With excess clay, more than enough to fill the spaces between the sand particles, the block becomes weaker because clay compresses more than sand, especially when wet and on drying, shrinks appreciably.

2.6.5 Innovations in Compressed Earth Brick

Over time, innovation in CEB manufacture involves changing the original shape from a solid rectangle to one incorporating holes or grooves in the blocks to accommodate steel or bamboo to resist earthquakes. Another innovation is the creation of interlocking shapes requiring no mortar bed or joint, and U-shapes or tapered bricks for use in reinforced lintels or arches. In some cases, CEBs are burnt after pressing but, once fired the bricks are no longer referred to as CEBs, (Wayne, 2011).

2.6.6 Earth Mix for Compressed Earth Brick

Several simple publications on selecting earth material and brick presses are available around the globe.Wayne (2011), sited that some of these publications are found with Brick pressing machine manufacturers and that the United Nations (UN) has simple soils testing information, while many universities provide tests for soils as well. In addition, soil engineering has been done in laboratories for road construction materials which are basically the same materials that are good for use in walls, floors and arched roofs. From experience, cuts at the roadsides or river banks show how different soil types resist erosion. The soil is said to be a good building material if it resist erosion very well. If the brick is stabilised and well cured, placing the brick in a bucket of water, stream or lake are ways of determining the water resistance of the brick.

2.6.7 Compressed Stabilised Earth Bricks

Compressed Stabilised Earth Bricks (CSEBs) are CEBs composed of Soil; water; and a binder (stabiliser) such as lime or cement to increase strength.The very low carbon footprint of CSEBs, compared to concrete materials, according to MecoConcept(2013), makes it the ultimate environmentally friendly building material. The production of good quality and durable stabilised soil bricks requires the use of soil containing fine gravel and sand for the body of the brick, then silt and clay to bind the sand particles together. Suitable stabilisingagents are added to minimize not only the linear expansion that occurs when water is added to clay fraction, but other beneficial aspects such as strength and to control erosion, (ILO-WEP, 1997).CEBs may be used for various construction works: detached houses, garages, workshops, garden sheds, and a host of other earth structures. MecoConcept(2013), posited that when CEBs are pressed at 30 tonnes, the bricks formed are very dense there-by preventing water seeping into the center of the brick. In case of rain, only a surface layer of the brick becomeswet without altering their mechanical qualities.

The addition of a binder in CEB increases stability, decreases swelling and shrinkage as a result of moisture movements and further prevents cracking due to excess or reactive clay. Some binders such as cement, also increase the density of CSEBs. The density of a CEB produced with a brick press lies between 1800 to 2000g/cm^3, (MecoConcept, 2013).

2.6.8 Stabilisers for Compressed Earth Bricks

Cement, gypsum, lime, chemical and liquids are some types of stabilisers that are used in the body or on the surfaces of bricks as evidenced by such works as (Lime, 2001); (Khalil, 2005); (Namango, 2006); (Abejide, 2007) and a host of others. When using cement for stabilising CEBs, it is very important to cure the brick by keeping it moist, watering twice a day for some weeks. Cement cures with water, so letting it to hydrate too rapidly, especially during the first week or two of curing, reduces strength. Mixing the soil with stabilisers should be thorough in order to distribute the binder evenly over the soil.

2.6.9 Advantages of CEBs/CSEBs

The advantages of CEB according Wayne(2011), include: uniform building component sizes, use of locally available materials and reduction in transportation. Uniformly sized building components result in less waste, faster construction and the possibility of using other pre-made components or modular manufactured building elements. Modular elements such as sheet metal roofing can easily be integrated into a CEB structure and often improve the overall quality of the structure as well. The use of natural, locally available materials can make good quality housing available to more people, and keeps money circulating within the local economy instead of importing the materials or buying fuel and spareparts. Building with local materials provides employment to the locals, and is more sustainable in times of civil unrest or economic difficulties. People are often able to build good shelters regardless of the political situation of the country. The reduction of transportation time, cost and attendant pollution also make CEB more environmentally friendly than other materials. Most of the time, soil for CEB is found on site or within a short distance.

Furthermore, (Auroville, 2016), has identified several advantages of CSEBs, which include the following:

i. *A locally sourced material*: the production of CSEBs is made on the site itself or in the nearby area thereby eliminating the need for transportation; fuel; time and money wastages.

ii. *Biodegradability:*With Earth as a biodegradable material, well-designed CSEB houses are able to withstand, with a minimum of maintenance, heavy rains, snowfall or frost without being damaged. The strength and durability of CSEBs have been proven hundreds of years back. Upon demolition of CSEB structures, it takes 10 to 20 years for the soil-cement mix to be decomposed by bio-chemicals present in humus soil, hence the brick returns to the natural earth again.

iii. *Limiting deforestation:*Fossil fuel is not needed to produce CSEB as compared to burnt bricks thus saving the forests, which are being depleted quickly in the world, due to short view developments and mismanagement of resources.

iv. *Conservation of Energy and the Eco-system*: Stabiliser requirement is minimal in the production of CSEB. Energy consumption in one metre cubeof wall can be from 5 to 15 times less than one metre cube of fired brick wall. The pollution emission is also about 2.4 to 7.8 times less than that of fired bricks.

v. *Cost efficiency*: As a naturally abundant resource combined withsemi-skilled labour, with little or no transport, it will be definitely cost effective.

vi. *An adaptable material:*Being produced locally it is easily adaptable to various needs; technical, social and cultural habits.

vii. *A transferable technology:*It is a simple technology requiring semi skills as such it is easily transferable to local villagers within a short time limit. Efficient training centres can transfer the technology to unskilled workers in a week time.

viii. *A job creatingactivity:*CSEB production provides unskilled and unemployed people to learn a skill, get a job and rise in their social values.

ix. *Imports Reduction:*Produced locally by semi-skilled people, there is no need for importation of materials and heavy equipment from far away.

x. *Socially acceptable:*Demonstrated, since long, CSEB is adaptable to various needs: from poor income earners to well off people or governments. Its quality, regularity and style allow a wide range of final house products. Referring to it as CSEB instead of mud brick has removed the perception of manypeople that considered earth brick as a poor building material adding to its social acceptance.

Despite these numerous advantages, CEBs have some short comings.It was observed by Gooding (1993), that the whole land surface of the Earth is virtually covered with soil, which is readily processed and moulded into blocks or bricks using simple local hand tools. Despite the fact that bricks produced from soil usually possess good compressive strength when dry, the major drawback to its application as a building material is its susceptibility to water. Although moisture plays a great role in supporting clay to bind silt and coarse materials of soil together, excess moisture tends to loosen up the grip provided by clay. Gooding(1993), asserted that on repeated wetting and drying, the outer surface of soil wall, for example, would expand and contract more quickly than the main body thus leading to cracking, spalling and subsequently, complete collapse on saturation. However, Gooding (1993), affirms that when soil is treated to reduce the effect of strength loss due to water saturation, it may be considered a permanent and durable building material termed 'Stabilised Soil'.

2.7 Soil

According to Little & Morton (2001), earth (soil) can be used in a wide variety of ways in construction of building elements such as walls (both load bearing and non-load bearing), floors, roofs and others. It has the ability to provide good thermal and acoustic insulation and has a particularly good ability to regulate internal air humidity and quality. If properly used, it is a durable and sustainable material. The most abundant and most widely used earth material for construction work is laterite or lateritic soil. Its engineering properties are responsible for making it the best as these properties could be easily altered to achieve certain requirements.

2.7.1 Laterite Soil

Selby (1971) in Khalil(2005), defined laterite as soils having oxide horizon (an altered surface horizon consisting of a mixture of hydrated oxides of iron or aluminum together with variable amounts of non-expanding lattice clays and highly insoluble accessory diluents like quartz). It was observed by Lee (1996), that unlike black cotton soils with uniform topography, laterites generally occur on gently sloping and undulating land with gradient exceeding three percent. Laterite is obtainable on the surface or deep down below with texture varying from loamy to clayey and generally well drained often gravelly due to the presence of rock or iron fragments and secondary iron nodules.

2.7.2 Properties of Lateritic Soil

Laterites, according to Lee (1996), show neutral to acidic reaction and possess low cat ion exchange capacity due to dominance of kandite clay mineralogy, low base/nutrient status, and poor organic matter but have a higher amount of iron and alumina. As per soil taxonomy, laterites are generally not saline or alkaline but mainly alfisols, altisols, inceptisols and etisols resulting from laterisation, the process by which salice is removed leaving behind surplus of oxides of iron and alumina. The oxides enriched soil becomes harder as a result of hydration and hardened mass, 'plinthite' which appears as vesicular or a honeycomb-like structure. The ratios of the percentages of silica oxide to that of the sum of alumina and iron oxide in the soil may render it as lateritic if this ratio is found to be > 2.00, (ILO-WEP, 1987). Kenyan standards according to (Namango, 2006), has suggested that the combined amount of alumina oxide, silica di-oxide and iron oxide in soil meant for the production of CEB, should be greater than 75%.

Despite the many engineering properties of laterite as a construction material, strength and durability characteristics of walling elements produced with it such as bricks, blocks and (*tubalis*) local walling units, often fall short of desired strength requirements. The soil has to be treated properly with some processes known as 'Soil Stabilisation'.

2.7.3 Soil Stabilisation

Soil stabilisation may be broadly defined as the alteration or preservation of one or more soil properties to improve the engineering characteristics and performance of a soil. The general methods of soil stabilisation include mechanicalstabilisation, chemical stabilisation using additives or a combination of both techniques including geotechnical processes, (Olaoye, 2004). The stabilisation effectiveness depends upon the uniformity obtained in blending the soil and various stabilisation materials. The method of soil stabilisation is determined by the amount of stabilising required and the conditions encountered on the project. An accurate soil description and classification is essential for the selection of the correct materials and procedures. The overall effect of stabilisation is to significantly increase the bearing capacity of the soil achievable by altering the soil properties especially cohesion and unit weight. Increase in density results to decrease in void ratio from particle parking which also increases the stress-strain modulus of the soil.

2.7.4 Stabilisation Techniques

Soil treatment could be performed in-situ to improve site soil conditions necessary for receiving foundations of structures applying such techniques as densification of soil particles by preloading, vibro-floatation, electric treatment (electro-osmosis), ground freezing and chemical grouting, (Olaoye, 2004). Another technique involves mixing the soil and additives in a stationary or travelling plant; however, other means of mixing, such as scarifies, plows, disks, graders, and rotary mixers, have been satisfactory. Soil stabilisation for the production of building elements such as bricks, blocks and tiles require the mixing of soil with the additives and moulding into the required element using the appropriate type of machine, ‘brick press’, for example. Based on these methods, soil stabilisation can be broadly classified into Mechanical and chemical techniques.

Mechanical Technique: Compaction, as opined by Olaoye(2004), is the most economical method of soil stabilisation, achievable mechanically by rearranging soil particles, adding or reducing some of the particles. This entails the increase or decrease of fine or coarse particles to improve the rate of compaction by excavating the soil to a certain depth and then carefully backfilling in controlled lifts (thicknesses) and compacting as appropriate.

Mechanical stabilisation asserted by Adam & Agib (2001),involves tamping or compacting the soil by using heavy weights to achieve a reduction in air void volume, which leads to increase in density of the soil. The major effects of compaction on soil are increase in strength and reduction in permeability the degree of which are dependent on soil type, moisture content during compaction and the compression effort applied. The best results are obtainable by mixing the correct proportions of sand and clay in a soil. Recently, developments for roads and embankment construction have led to compacting soil with vibrating rollers and tampers. Drawback of mechanically stabilised earth blocks is the lack of durability when exposed to moisture. Mechanical soil stabilisation can be achieved manually by foot treading or the use of hand tamping equipment, with compacting pressures varying between 0.05 to about $4MN/m^2$. With mechanical equipment compacting pressures of several thousand MN/m^2 are achievable, (Adam & Agib, 2001).

Chemical Grouting Technique: The National Lime Association Lime (2001), has asserted that in chemical grouting, soil stabilisation occurs when the additive combines with reactive soil elements to generate a long-term strength gain through pozzolanic reaction such as that obtained by using lime. Chemical grouting averred by the U. S Army Corps of Engineers (Engineers, 1996), is achieved by injecting the chemical grout into voids as solutions, which react after a predetermined period to form a solid; semi-solid or gel according to requirements. This differs from cement grouts which are suspensions of particles in fluid medium.

2.7.5 Soil Stabilisation Agents

Several soil treatment materials have been identified over time to improve the engineering properties of soil for various applications in construction. This has been achieved through intensified research works that have established different categories of soil stabilisers ranging from suspension materials such as cement and lime; chemical grouts such as sodium silicate systems to water proofers. The most widely used stabiliser for soil is cement especially for the production of CEB, (Matawal, 1990).

Cement Stabilisation: The hydration reaction produced when water is added to cement results in a cementitious gel that is independent of soil particles. It was adduced by Adam & Agib(2001), that the gel is composed of calcium silicate hydrates; calcium aluminate hydrates and hydrated lime. The main bulk of the gel is made up of the first two compounds, while lime is deposited as a separate crystalline solid phase. The process of cementation results in the deposition between soil particles of an insoluble binder capable of embedding soil particles in a matrix of cementitious gel. Penetration of the gel throughout the soil hydration process depends on time, temperature and cement type. The lime released during hydration of the cement reacts further with the clay fraction to form additional bonds.

Soil-cement mixes should be compacted immediately after mixing in order not to break down the newly created gel and therefore reduce the strengthening process. The basic function of cementation is to improve the compressive strength of the soil and reduce water penetration and thence its swelling potentials. These processes may vary from soil to soil. Cement is a good stabiliser for granular soils but poor for clays as such it is uneconomical because more cement is required. The range of cement content needed for good stabilisation is between 3% and 18% by weight according to soil type, (Adam and Agib 2001).

It has also been established that a relationship between linear shrinkage and cement content needed for soil stabilisation exists, in that the more the cement content, the higher the shrinkage, (Adam & Agib, 2001). For example, cement to soil ratio ranging between 5.56%

and 8.33% have measured shrinkage variation of between 15mm to 60mm respectively. More so, EARTH-BLOCK(2017), revealed that Cement and other synthetic materials, such as closed cell insulation and paint, applied to earth block walls or used in stabilising earth bricks will hinder their breathability. This is the ability of earthen walls to absorb and release water vapour molecules that are not larger than air molecules in and out of the walls without seriously transmitting water molecules. This transpiration of vapor helps to regulate and modify heat and humidity indoors, the benefit of which reduces the need for mechanical systems to maintain human indoor comfort levels. Lime or clay plasters, and environmentally friendly brick stabilisers can maintain an earth brick wall's breathability.

2.8 Cassava

The Oxford LivingDictionaries, (Oxford, 2016), defines cassava as the starchy tuberous root of a tropical tree, used as food in tropical countries. It is a member of the flowering-plants family called Emphorbiaceae which is cultivated all over the tropical and sub-tropical regions of the world. Cassava is among the most important root crops in Africa known as manioc, manihot esculenta or utilissima and yucca, a shrub with a height of about 2.7m or more. Cassava, probably a hybrid is an extremely variable species, perennial with conspicuous palmate or fan shaped leaves that resemble those of castor bean but more deeply parted into five to nine lobes. Cassava leaves are usually narrow with some varieties having yellowish-white flowers and round fruits, with the roots reminiscent of the fleshy tubers of dahlia.The cassava plant, asserted by Benesi (2005) and the Cambridge Dictionary (Cambridge, 2017), originates from South America and is particularly an important staple crop there and in Africa. As a Latin Caribbean food, Rodriguez (2017), called cassava (mandioca, casabe and tapioca), a long tuberous starchy root about two inches around and eight inches long, which has a brown fibrous skin and snow white flesh.

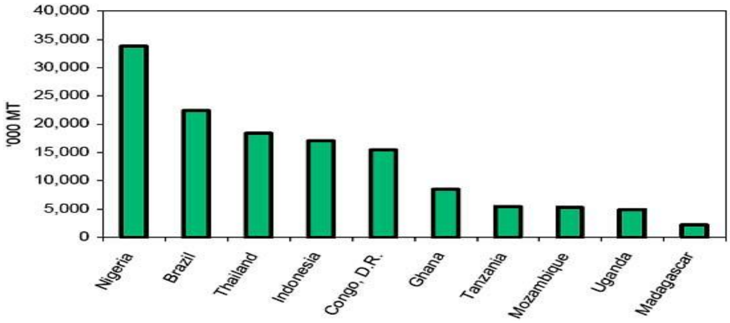
2.8.1 Cassava Types

Cassava are of two types, the 'sweet' and 'bitter' with the later varieties containing prussic acid and many other varieties contain a cyanide-producing sugar derivatives in varying amounts. Although cassava is a staple food cropOlanipekun (2012), observed that in raw form, it contains cyanogenic glucosides, which makes itpoisonous. Generally, the bitter specie contain higher levels of cyanide, but it should not be assumed that the sweet varieties are totally free of the acidor their cyanide content is low. For all cassava types, cyanide levels range from 10 to 450mg/kg of fresh root which is mostly concentrated in the skin of the root. Depending on the variety, the poisonous acid in cassava is extracted via different and complex refining processes which include cutting the tubers to smaller pieces and soaking in water for a number of days. Another process is by grating, pressing and heating the tubers. After the treatment, cassava becomes a versatile product used for food and non-food items according to theInternational Institute of Tropical Agriculture, IITA/Crops,(2005) in Olanipekun (2012).

According toIITA/Crops(2004), cassava can grow good crops in fairly poor, very dry soil which is not too stony and has the ability to thrive on marginal lands where cereals and other crops do not grow well. It can withstand drought and can grow in low-nutrient soils with the roots capable of being stored in the ground for long periods, about 2 to 3 years thereby making it possible to delay harvest until processing, market and other conditions are favourable. Cassava thrives best on well-drained loamy soil but is however, adaptable to dry alkaline soils to acid mud soils along river banks. According to varieties, cassava is cultivated from stem cuttings, planted at intervals of about 1m on ridges, mounds or even flat grounds and readily harvestable within a period starting from 6 to 36 months.

2.8.2 Cassava Statistics

The Food and Agriculture Organization (FAO) had recorded an output of about 172 million tons of cassava produced the world over in the year 2000 with Africa accounting for 54% of the output followed by Asia with 28% and Latin America and the Caribbean 19%. In the year 1999 Nigeria was able to produce 33 million tons of cassava as shown in figure 2.2,making it the world's highest producer with an average yield of 10.6 tons per hectare,(FAO, 2000).



[Source;Phillips et al 2004]

Figure 2.2: Leading World Cassava Producers

2.8.3 Cassava Applications

Cassava, according to (IITA, 2004), has approximately 150 species of genus manihot, sun-loving natives of tropical regions. These varieties have found many applications ranging from serving as food stuff; such as the gelatinous fufu of West-Africa and banmi mush of Jamaica; to industrial application in the production of the ceara rubber from M. glaziovii specie of North-East Brazil. It was also gathered by Olanipekun (2012), that cassava starch is used to improve the viscosity of drilling muds in oil wells. It can be successfully stored after grinding into granules in dry form called *gari* and flour (*alibo*) from which bread is made. Additionally, the starch from cassava is used as tapioca, a laundry starch and is further used as binding agent in paper production and textiles.Ajao & Adegun, (2009), have posited that cassava has industrial application in that approximately 16% of cassava root production was used as an industrial raw material in Nigeria as at the year 2001. Cassava as chips in animal feed took 10%, 5% was processed into syrup concentrate for soft drinks and about 1% was processed into high quality cassava floor utilised in the production of biscuits, confectionaries, pre-gelled starch for adhesives, and food seasonings. Cassava starch is one of the most naturally abundant substances, which is renewable and almost an unlimited resource.

2.9 African Locust Bean

The African locust bean tree, *Parkia biglobosa* is indigenous to the savannah regions of Africa most commonly found in the band stretching from Senegal to Uganda. Salim *et al*(2002), stated that *Parkia biglobosa* is a tree of the genus Parkia in the Fabaceae family. The fruit pulp and seed extracts according toMadan (2010), provide nutritious ingredients for traditional soups, sweetmeats and condiments across West Africa,while its fruits are fermented to a condiment called dawa-dawa or ‘iru’,(Adebayo, 2016). The yellowish powder inside the seed pods, which is sweet can be eaten directly without preparation or made into a drink. The pods are boiled and the dark brown extract is used for stabilising Earth Floors.Lawal (2012), observed that *Parkia biglobosa*occur in agro ecological zones ranging from tropical rainforests to arid zones. It is also found scattered around many countries of West Africa as a popular food plant. The tree is not normally cultivated but naturally occurring in the savannah region of Nigeria. The seed is commonly called *kalwa*and the fruit, *dorowa*or *dozim*, around the northern region of Nigeria while the Yorubas called it *Igba* or *Irugba*.Djakpo, (2005) in Lawal (2012) added that the pulp of the fruit pods is rich in sucrose and the seeds are rich in carbohydrates, proteins and lipids, thus constituting an important source of energy. Although most people may consider *ogiri* as the Igbos call *Parkia biglobosa*, an unappealing food condiment due to its offensive odour,(Onana, 2016), argued thatits health and nutritional benefits far outweighs its stench. The *Parkia biglobosa tree* is rated fifth important among thirty-one woody medicinal plants used in traditional medicine in Benin Republic. It is rated fourth from a list of eighteen priority food plants usually preserved.In association with crops, the *Parkia biglobosa* species help to enrich physico-chemical soil characteristics, which in turn, helps increase crop yields,[Eyog *et al* (2000) in Lawal (2012)].

Plate IV: Parkia biglobosa trees

Plate IV shows a typical collection of the *Parkia biglobosa* trees growing naturally without the need for cultivation. Apart from the pods, the bark of these trees is also used traditionally to stabilise rammed earth floors, (Abejide, 2007).

Figure 2.3: Geographical distribution of African Locus Bean

Figure 2.3 shows that theAfrican Locus Bean (Parkia Biglobosa) tree is densely distributed along the West African Sub-region and part of Central Africa. Nigeria can be observed to be wholly engulfed by this tree except for a small part of the coastal region where the tree may be sparsely distributed.

2.9.1 Makuba

Makuba is the husks or pods obtained from the ripe fruits of the plant of *Parkia biglobosa* after the pulp and seeds had been removed. It was established by Abejide (2007), that the African Locust bean pod contain waterproofing substances. These are stearic acids or their compounds mainly; calcium, sodium magnesium and ferric stearate found in the extract. Furthermore, Shao(2002), also established that *makuba* consist of calcium, magnesium, iron and sodium. *Makuba* when boiled in water is used to impart water resilience on floors, walls and ceramic pots. The 'sour water' produced from steeping and boiling the *makuba* is mixed with mud to produce a plaster used also as paint on walls of buildings. The plaster is also used for tamped earthen floors. The tannins present in the *makuba* act to bind the soil due to their polymeric nature, and render the surface impervious to water. The *Makuba* contains 27-44% tannin and are also used for dyeing and curing leather, (Shao, 2002).

African locust bean pod (*makuba*) was found to have the following chemical composition: the bark contains 12 - 14% of tannin while the pod contains 27- 44% of tannin. Also Campbell-Platt (1980) in Lawal (2012) reported that Locust bean pod contains 60% carbohydrates, 10-20% of which is sucrose, with 29mg of vitamin C per100g of Locust bean pod. The pulp is a beneficial food source in the middle of dry season initially white in colour, turning to bright yellow as the pod matures, [Aguwa and Okafor (2012) in Lawal (2012)].

2.9.2 African Locust Bean Application

Different parts of *Parkia biglobosa* tree are used in so many areas such as food, medicine and in soil treatment. Olugbemi (2012), asserted that the African locust bean, (JacqBenth), is a perennial leguminous tree, which grows wildly in the forest regions and savanna belts in Nigeria. Fermented Parkia seeds are locally used in traditional soup seasoning, medicinal preparations and as food additives. Additionally, boiled water obtained during fermentation process of *Parkia biglobosa* seeds is used in controlling termite infestation locally. In spite of this practice, few reports exist on the termiticidal properties of aqueous solution of *Parkia biglobosa* seeds. The seeds of *Parkia biglobosa*are fermented by the Hausa people of Northern Nigeria to make dawa-dawa, a strong smelling tasty food seasoning rich in protein.It is a basic and therapeutic food seasoning and is a source of wealth,[Sadji, (2000) in Lawal (2012)].

2.10 Applications of Cassava Starch and *Makuba* in Building Construction

Cassava Starch and *Makuba* have additional uses aside those for food and medicine. Khalil(2005), discovered the local application of cassava starch in building construction in Nasarawa state, Nigeria. In Akwanga and Wamba towns of the state, local builders used to apply the starch from cassava as additive into soil meant for house building. The technique involved mixing of soil and cassava starch powder. Water just enough to wet the mix, determined from experience is then added and the heap mixed thoroughly and covered with polythene material and left to stay overnight. The next day, more water is added to the heap, which is trampled upon by the feet to achieve a consistent sticky mix from which '*tubali*' (local walling units) are rolled out as shown in platesV and VI.

Plate V: Fresh Tubali (local walling units)

The *tubali*used to be the local walling units in Hausa land before the advent of mud blocks produced from wooden moulds. After drying out under the sun as shown in plate V, the *tubali* units would then be arranged onto stone bases, sometimes lateritic stones called *marmara*are arranged as the foundation.

Plate VI: Tubali bonded in mud mortar

The base of the wall built with *tubali* is usually wide taking up to five or six units across the wall thickness. The number of *tubali* across the thickness gradually reduces as the wall rises thus thinning out towards the roof level. These units are bonded together as shown in plate VI, with another mix of soil with different additives such as straw, horse, cow or donkey dunk, and a host of other local additives also trampled upon very well. The wet mix 'mortar' is placed on the stone base and the conically shaped *tubali* units are laid as the first course. Additional mortar is then choked around the units and on top to receive the next course. As the wall gets higher above shoulder level, work stops for the day. The next day, work continuous by raising up another section of the wall or other walls to shoulder level andafter a few days, when this short wall is considered strong enough it is then completed to roof level. In this section of the work, the master builder climbs on top of the dry short wall while the helper throws up the *tubali*and subsequently, fresh mortar for the construction of another round of course. On completing the building, both interior and exterior parts of the wall are rendered in mud stabilised with *makuba* and other additives such as dyes.

Plate VII: Makuba stabilised mud rendered wall in Zaria city

In plate VII, a typical traditional mud rendering is shown with *makuba* as the binder. Pigments of different coloursare added to produce variant designs on the wall.

2.11 Preliminary Tests Conducted on Research Materials

The research materials used in this Thesis were subjected to varying tests that would help in drawing inferences and reaching conclusions on the behaviors of the elements produced, (CSMBs). Only relevant amongst the numerous tests applied to CEBs were selected and reviewed.

2.11.1 Engineering Property Tests

i. ***Chemical Analysis:*** This test is necessary in order to determine the mineralogy, elemental and chemical compositions of the research materials, this way it is possible to determine from the onset if the materials are compatible and may not produce negative reactions that may hamper the desired results. Moreover, Standards have already been set for minimum and maximum contents of certain minerals and their combinations in a material, for example the Kenya Standard, according to Namango (2006), stipulated the percentage contents of alumina oxide, silica oxide and iron oxide to be greater than 75% of the total quantity of soil for brick production.

Size and composition are the basic fundamental attributes of sediments where optical microscopy is used to readily identify sand and coarse silt-sized crystalline materials. The United States Geological Survey, USGS(2016), opined that X-ray powder diffraction is now the commonest technique used to study the characteristics of crystalline structure and to determine the mineralogy of finer grained sediments, especially clays. X-ray diffractometry is advantageous because of its speed and ease of performance, and requires only small amounts of material. It is a nondestructive method used to perform semi-quantitative analyses of poly-mineralic mixtures.

X-ray powder diffraction (XRD) in the words of Dutrow & Clark(2016), is a rapid analytical technique used for phase identification of a crystalline material that provides information on unit cell dimensions. The analysed material is finely ground, homogenised, and the average bulk composition determined. A detector records and processes X-ray signal which is converted to a count rate and then output to a device such as a printer or computer monitor as displayed in figure 2.4.

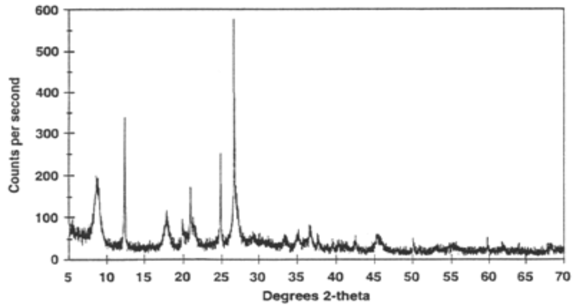


Figure 2.4: Peak Intensities of X-Ray Signals Count Rate Graph

Applications: X-ray powder diffraction is widely used for the identification of unknown crystalline materials for example, minerals and inorganic compounds the study of which, is critical to studies in geology, environmental science, material science, engineering and biology, (Dutrow & Clark, 2016). Other applications include characterisation of crystalline materials; identification of fine-grained minerals such as clays and mixed layer clays that are difficult to determine optically.

ii. Moisture Content: Water or moisture content was described byLawrence & Homberger(2007)**,**as the quantity of water contained within a material, such as soil (called soil moisture), rock, ceramics, fruit, or wood. Water content has a wide range of scientific and technical applications, and is expressed as a ratio, ranging from 0 (completely dry) to the value of the materials' porosity at saturation. This ratio is calculated on a volumetric or mass (gravimetric) basis.

The water according to (AgriInfo, 2011), is held within the soil pores, which is the major component of the soil in relation to plant growth but not all is available to plants. Part of the water remains in the soil as a thin film. Soils hold moisture due to their colloidal properties and aggregation qualities. Water is held on the surface of the colloids and other particles and in the pores. The forces responsible for water retention in the soil even after drainage has stopped, are surface tension and surface attraction called surface moisture tension. This is the energy concept in moisture retention relationships also termed as suction.

Moisture Equilibration: This is the process by which hygroscopic materials reach equilibrium with the ambient relative humidity of the air by absorbing or desorbing moisture, (Bigourdan & Reilly, 2003). There exists a constant and dynamic exchange of moisture between an object and the environment called *moisture equilibrium*, which is reached when the object neither gains nor loses moisture from or to the environment. Equilibrium Moisture Content (EMC) is the amount of moisture a material contains when it has reached equilibrium with its environment, expressed as a percentage. EMC is the percentage of the materials' mass made up by water. Only hygroscopic materials absorb or desorb water to equilibrate with the relative humidity of the environment by the process of diffusion. Non-hygroscopic materials such as metal may be affected by the environment's moisture by corrosion but do not equilibrate with the moisture content of the environment.

iii. Sieve analysis/Sedimentation (Field settling): Tawfiq(2004), explained that soil particle size distribution is determined by the process whereby coarse fractions of the soil are separated by the use of a series of sieves. Larger particles, above 0.074mm are normally analysed by sieving while materials finer than 0.074mm are analysed by means of sedimentation of the particles by gravity hydrometrically. Sedimentation test is carried out in order to determine the amount of silt in the soil according toBS812(1995), which stipulates a silt range of (8 – 13%) in soil. Excess quantity of silt and impurities adversely affect the quality of soils and may also reduce the bond between soil particles and stabilisers. Furthermore, this test is significant in order to establish the content of organic materials in the soil as well as the proportion of the different particle sizes. It was stated byWalker(1996), that clay contents of between (5 – 20%) are considered suitable for CEB production while Kenya standards in Namango(2006)recommends that the sum of silt and clay content should exceed 10%. The coarse fraction, opined by Minke(2000),should exceed 20% as this amount is required to limit shrinkage in bricks when drying out.

iv. ***Atterberg limits:*** Theseare the soil property tests that indicate the type and condition of soil as well as provide relationships to structural properties such as strength, compressibility, permeability, swelling potential, shrinkage and as Tawfiq(2004) posited, this testsare conducted on cohesive soils so as to determine their consistencies, some of which are Solid Limit (L_{sl}); Liquid Limit(LL); Plastic Limit (PL); Plasticity Index (PI); Shrinkage Limit (L_{sh}); Liquidity Index (LI).The consistency of clay in the soil relative to its moisture content varies according to its chemical constituents and mineralogy, Norton, (1997) in (Namango, 2006). This consistency which is called plasticity refers to the ability of soil to be subjected to deformation without elastic failure characterised by cracking or disintegration. The range of consistency or plasticity is determined by ‘Atterberg Limits’,(Minke, 2000). The liquid limit defines the water content on the boundary between the liquid and plastic stage. The plastic limit is the water content as a percentage at the boundary of the plastic and semi-solid state. At LL, soil starts to manifest a certain resistance to shearing; at PL, the soils stops being plastic and becomes brittle. The plasticity index ‘PI’ is the difference between LL and PL. PI determines the range of plastic behavior of the soil. The higher the Plastic Index of moistened soil, (beyond 15), the greater it’s swelling potential and shrinkage.

2.11.2 Performance Evaluation Tests

i. ***Durability Properties***

As defined byIpinge(2012)**,** durability of CEBis the ability of a brick to meet both strength and appearance parametersover its service life, under given design conditions, without undue loss of strength and aesthetic value. This durability is influenced by three factors: characteristic strength of individual brick, which determines CEBs load carrying capacity; deterioration mechanism such as the effect of moisture and erosion of particles from the surfaces of bricks due to raindrops or wear and tear; and building design, as adequatecover to CEB by a proper roof design, is a requirement.

a. ***Abrasion Resistance:*** One of the importance of soil stabilisation asserted by Heebink and Hassett (2001) is the control of dust and erosion of particles from the surfaces of especially soil construction elements. Khalil(2005), discovered that cassava starch has improved the abrasion resistance of cassava starch stabilised soil sample by about 84% at 20% starch content in laterite soil compared to an un-stabilised sample.

b. Moisture Movement

Three moisture or water movement tests were conducted in this Thesis:

Water Absorption:Water absorption as observed by Khalil(2005), is considered as ingest of water into bricks from all directions, the test of which, is a measure of the swelling potential of bricks. The higher the water absorption capacity of a brick, the higher it's swelling characteristics and consequently, the higher the measure of shrinkage level of the brick that results into the development of cracks.

Capillarity:This is the rise or depression of a liquid in a small passage such as a tube of small cross-sectional area and the openings in a porous material. Capillarity, opined by (Hauksbee, 2013)**,** is the result of surface, or interfacial forces of attraction between the molecules of water and glass walls, for example, and among the molecules of water themselves. These attractive forces balance the force of gravity of the column of water that has risen to a characteristic height. The narrower the bore of the capillary tube, the higher the water rises.

Capillarity or capillary action explained by Touchette(2013), is the amazing, gravity-defying scientific phenomenon that makes liquids to flow upwards. Capillary action depends on dissimilar, substances interacting with each other, one a liquid and the other a solid. The water molecules are attracted to the inner portion of the solid. Cohesion explains the way molecules of a single substance stick together. Water has very strong cohesion. Smaller openings, allow for more water cohesion and adhesion to the surface of the solid and is another force to reckon with.

Permeability: According to the Transportation Laboratory Test 220 of California State, (PermteCT_220, 1998)**,**permeability is the rate of flow of water through the pores of soil. Permeability test is carried out primarily to determine the suitability of sands and gravels for drainage purposes made only on remolded samples. There are several test methods for permeability each for a different purpose.

ii. Elevated Temperatures

Documentation on the effect of elevated temperatures on CEBs has not been found up to the time of preparing this Thesis but, literature exists on the effect of elevated temperatures on concrete materials and structures. Naus(2005), reported that under normal conditions, structures are subjected to a range of temperatures no more severethan that imposed by ambient environmental conditions. However, there are important cases where structures may be exposed to much higher temperatures for example, jet aircraft engine blasts; building fires; chemical and metallurgical industrial applications in which the structure is in close proximity to furnaces, and some nuclear power-related postulated accident conditions. Additionally, Naus(2005) pointed outelements in designs of new-generation reactor concepts where structures may be exposed to long-term steady-state temperatures above theAmericanSociety of Mechanical Engineers Pressure Vessel and Piping Code (ASME Code)limit of 65^{0}C. The study of the effect of elevated temperatures on structures alsoinclude performance of structures associated with radioactive waste storage anddisposal facilities and postulated design-basis accident conditions involving unscheduled thermalexcursions. Under such applications the effect of elevated temperature on certain mechanical and physicalproperties may determine whether the structure will maintain its structural integrity. CEBs may not be exposed to these conditions which concrete structures are subjected to but, Earth Bricks may be applied in the walls of structures housing such facilities as bakery ovens emitting high temperatures (above boiling point) and cold houses emitting low temperatures atice point.

iii. Strength Characteristics Tests

Three strength measurements were considered for determining the effect of CSM on strength development of CSMBs:

a. Compaction Characteristics: Soil compaction as defined inBS1377(1990), is that process where solid particles of soil are packed more closely together usually achieved mechanically. Compaction has an effect on strength properties of soil especially density, the extent of which depends on the degree of compaction applied and the amount of water within the soil. Depending on the degree of compaction applied on a cohesive soil, there exists an optimum moisture content (OMC) at which the dry density of the soil reaches a maximum value. For cohesion less soils, BS1377(1990), affirmed that it might be difficult to determine OMC due to its free draining nature.

b. Compressive Strength: Compressive strength is apparently considered as the most universally accepted value for determining the quality of brick, (Riza, Abdul-Rahman, & Zaidi, 2011). It is also taken as the most important property of CSEBs upon which even durability relies. The main factors that contribute to strength of stabilised soils are: soil type; density; moisture content; stabiliser content and the compacting pressure, [Kerali(2001);Khalil(2005) and Namango(2006)].For cement stabilised CEBs, it is suggested that the stabilisation mechanism lies in the cement forming a skeleton of hydrates inside the voids, (Namango, 2006). Several codes from different countries have specified varying CSEB strength requirements. For example minimum dry compressive strength of 2MPa are acceptable according to

Namango(2006), by many codes such as Australian code, New Mexico building code and UNESCO, CRATerre. The Nigerian Building and Road Research Institute (NBRRI), has specified a minimum compressive strength of CSEBs to be 1.65N/mm^{2}at 28 days, (Ramson, 2011).

It was pointed out by Namango(2006) that investigations carried out in the area of compressed earth bricks lack consistent and comparability and even reproducibility. This is due to the non-existence of universally acceptable standards. Walker(2004) in Namango(2006), mentioned that regional, national and international standards vary considerably in approaches to testing and specifications for strength performance of CEBs. Apparently, different countries have different norms and specifications, coupled with the differences in soil compositionsfrom one region to another. In addition, Ramseyer, Reyes, & Butko(2016), opined that despite the use of earthen materials in building construction for thousands of years, many engineering properties of earthen walls or walling units are not well understood, documented, or regulated.

iv. ***Scanning Electron Microscopy:*** Scanning Electron Microscope (SEM), is a type of microscope that uses a focused beam of electrons to scan a sample and produces the images of the sample, (Conrad*et al*, 2016). The electrons interact with the atoms of the sample to produce various signals that contain information about the sample's surface topography and composition. Swapp(2016)**,** added that the signals derived from the electron-sample interactions reveal information about the sample. These include external morphology (texture), chemical composition, crystalline structure and orientation of materials that make up the sample. Data collection is achieved over a selected area on the surface of the sample and a 2-dimensional image that displays spatial variations in the properties of the material is generated. Conventional SEM techniques can scan areas ranging from approximately 1 cm to

5 microns in width with magnification factors ranging from 10 times to approximately 500,000 times and spatial resolution of 50 to 100 nm, (Hendricks, 2016).

2.12 CSEB Strength Analytical Models

Inthe quasi-static compression method of compacting stabilised soil-cement blocks,the compacting pressure is applied at a slow rate using the CINVA Ram, Brepack and a host of other brick/block presses, (Gooding, 1993). This is distinct from dynamic method of soil compaction where heavy blows are applied on the soil instantly. Therefore, Gooding(1993), developed a number of simple theoretical models that described the internal compaction mechanism of quasi-static compaction. These are the simple hydrostatic fluid model; the pipe flow model; the solid model based on Poisson's Ratio; and the elasto-plastic band compaction model.

2.12.1 The Simple Hydrostatic Fluid Model

This model, Gooding(1993) posited, assumes that soil behaves like fluid thus pressure within the soil would be the same in all lateral directions, increasing vertically downwards to lower layers only due to overburden pressure from layers above. The model predicts that on the application of a compaction pressure of say, 10MPa to the top surface of a brick mould, the surrounding mould walls and the base are also subjected to the same 10MPa transmitted. Furthermore, the model predicts the absence of any shear force between the mould walls and the soil.

2.12.2 The Pipe Flow Model

It is assumed in this model that the soil behaves like a viscous fluid flowing through a pipe, which may support shear force as it is flowing. The more viscous the fluid, (Gooding, 1993)argued, the longer it would take to flow and consequently, the larger the shear force it can maintain. The prediction by this model is that if a 10MPa pressure is applied to the top surface of the mould, the soil will flow downwards to the bottom trying to escape from the source of high pressure. The shear force from the mould walls will resist some of the applied pressure thereby reducing the pressure on the bottom of the mould. The reduced applied pressure tends to a lower lateral pressure than that predicted by the simple hydrostatic fluid model.

2.12.3 The Solid Model (Poisson's Ratio)

It was stated by (Gooding, 1993), that by applying a compressive force to the top of a solid object, a vertically oriented strain is induced in the medium that causes a lateral stress, which then develops a lateral strain. The ratio of the applied vertical force to the lateral tensile strain is given as the Poisson's Ratio of the medium, which is constant within the elastic limit.

2.12.4 The Elasto-Plastic Band Compaction Model

The elasto-plastic band compaction model according to (Gooding, 1993), is based on the assumption that the compaction effort applied continuous over a set of layers that are roughly arranged parallel to the moving compaction piston of the mould. On application of the compacting pressure, the upper layer begin to plastically compress with little elastic deformation occurring and thence, on becoming stiffer, transfers the applied pressure to the next layer. This progresses at a slower rate down the lower layers to the bottom of the mould. When the compacting load is removed, the plastic deformation remains while the little elastic compression recovers thus causing a degree of material expansion.

CHAPTER 3

METHODOLOGY

3.1 Preamble

In this section of the work full description of techniques applied in investigating the engineering properties of the research materials; methods of soil stabilisation; brick sample production and curing are made. The performance evaluation techniques of CSMBs as walling units and development of strength analytical models are also described.

3.2 The Philosophy behind this Research Work

The subject of this Thesis falls under what is now considered in many realms as 'Appropriate Technology'. The term refers to application of techniques that best fit a particular people, community or society; this in part, is pegged to economic conditions, availability of raw materials, cultural orientation and geo-climatic environmental conditions. With respect to building materials, Mathey 1983 in Namango(2006), considers appropriate technology, as the application of techniques appropriate tothe user, society and nature as well.

Appropriate construction is a reflection of theconcept of 'Ecological Building'. Other schools of thought put appropriate technology parallel with 'Alternative Technology', a term used to describe some compromise situation between the very high technologies of developed societies and the low technologies associated with poor economies, [Spence(1982) in Namango(2006)]. Principal characteristics of intermediate technologies are that they are cheap, small in scale and use relatively simple production methods from locally available raw materials. Appropriate or alternative technologies are therefore seen to be in harmony with nature, and have as a prime orientation, to provide sustainable solutions to issues related to human development.

As concerns developing nations,Minke(2000), argued that it is already recognised that the huge housing deficit cannot be met with industrially produced building materials with 25% of the world's population having no fixed abode, while 50% of the urban populations live in slums. In spite of the many effortssuch as ‘Global strategy for housing by the year 2000’ declaration by the United Nations (UN), the shelter issue remains a major problem, and hence the need to look for possible solutions, which includes scientific approach.

3.3 Materials and Methods

The raw materials used in the production of (CSMBs) in this Thesis are shown in plates XII; XIII; and XIV. These materials are readily available and obtainable within the research locality.

(a) Cassava Starch Powder (b) Laterite Soil (c) Locust Bean Pods

Plate VIII: (a), (b) and (c) Experimental Materials

Cassava starch ‘S’ was obtained in dried granular form from a market in Sabon gari Local Government Area of KadunaState, Nigeria and it was washed to remove dirt before pulverising and sieving to powder as shown in plate VIII (a).The laterite soil ‘L’ was obtained from a borough pit located at Biye in Sabon gari local Government Area of Kaduna State. It was treated and bagged as described in section 3.4.1, figure 3.4 and shown in plate VIII (b).*Makuba* ‘M’ was gotten from the bean pods of *Parkia biglobosa* trees shown in plate VIII (c), found outside one of the gates of Zaria city called Kofar Gayan in Zaria Local Government Area of Kaduna State, Nigeria.

3.3.1 Experimental Design, Procedure and Equipment/Apparatus

The experiments conducted in this Thesis were focused on the evaluation of strength characteristics, some durability properties and performance of (CSMBs) as walling units. Stabilisation techniques, which involve mixing of soils with the stabilising agents in different proportions, were adopted. Previous reference studies and information from the internet also formed the background on which this work was developed. The experiments consisted of the initial determination of engineering (chemical, physical and mechanical) properties of the research materials in the Department of Building; Multi-User Science Research Laboratory (MUSRL) and the Department of Chemical Engineering A. B. U. Zaria, Nigeria. These were followed by the controlled physical application of cassava starch and *makuba* to stabilize laterite soil.

Experimental Concept

Foursets of specimens were produced and subjected to stipulated standard tests deemed necessary for an exploratory research work. These are as shown in figure 3.1:

i. Specimens without stabilisingagents (control); batch 'L' Laterite only.

ii. Specimens stabilised with cassava starch only; batch 'SL' Starch/Laterite.

iii. Specimens stabilised with *makuba* only; batch 'ML' *Makuba*/Laterite.

iv. Specimens stabilised with CSM matrix; batch 'SML' Starch/*Makuba*/Laterite.

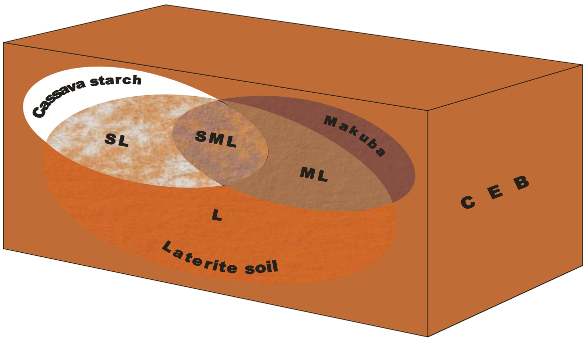


Figure 3.1: Four Specimen Sets for CSMB Production

The experiments carried out in this work were set up in three stages:

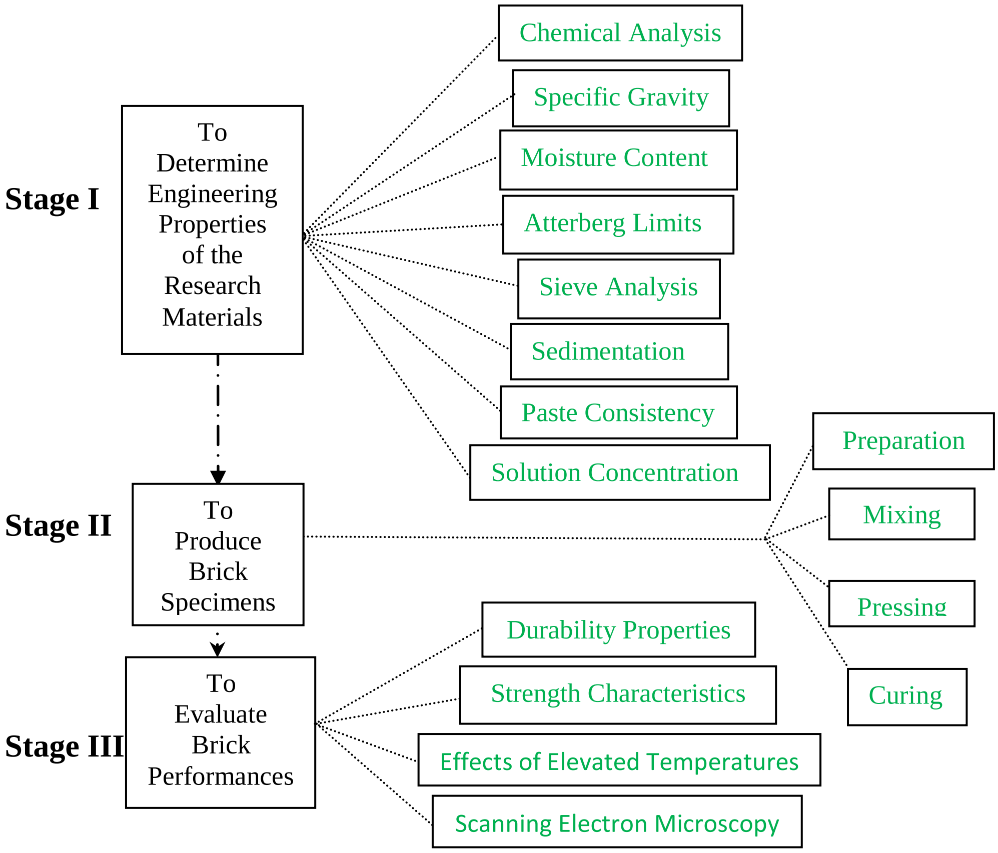


Figure 3.2: Experimental Concept

From figure 3.2, the different stages are explained thus:

Stage 1: Engineering Properties of Experimental Materials (soil, cassava starch and *makuba*) were based on objective 'i'.

Stage 2: Brick Production techniques stemmed from objective 'ii'.

Stage 3: Strength, durability and performance evaluation, were based on objectives 'iii','iv' and 'v'.

3.3.2 Engineering Properties of Experimental Materials

The basic raw material needed to produce walling units indicated by ILO-WEP(1997),is soil containing a minimum proportion of silt and clay to provide cohesion. It is evident that not all soils are suitable for building purposes due to varying soil characteristics and climatic conditions of different areas of the Earth which, must be assessed prior to usage. For example, a dry, semi-desert climate requires different soil for making bricks from those used in temperate, rainy or monsoon areas. Therefore, it is required that the soil andstabilisers be investigated to establish certain properties deemed necessary for achieving the desired objectives of soil stabilisation and brick production. The properties investigated in this work are displayed in figure 3.3.

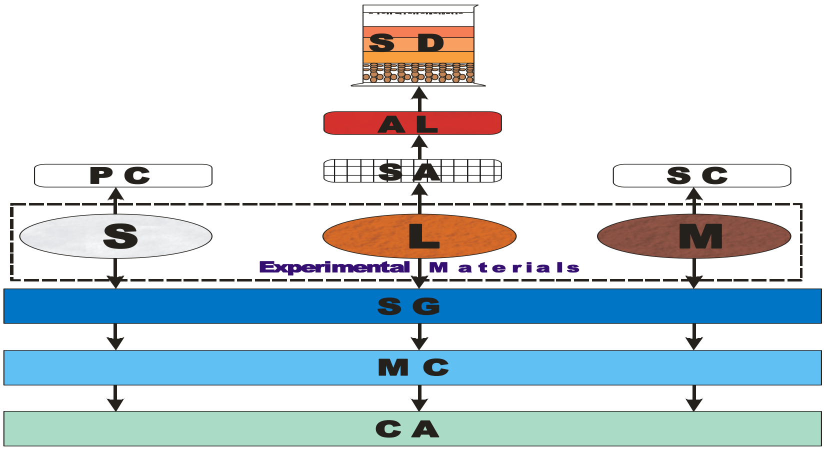


Figure 3.3: Engineering Properties of Experimental Materials

The three experimental materials (Cassava Starch/Soil/*makuba*) were subjected to three common tests, Chemical analyses (CA); Moisture Content test (MC); and Specific Gravity test (SG). Other tests conducted on each material individually include soil Sieve Analysis (SA); Atterberg Limits (AL); and Sedimentation (SD) while the starch was tested for Paste Consistency (PC) and *Makuba* for Solution Concentration (SC).

i. Chemical Analysis

The aim of conducting chemical analysis on the research materials is to determine the mineralogy, elemental and chemical compositions of the research materials using X–Ray Fluorescent (XRF) machine.BS Standards and Kenya standards have stipulated the mineral, elemental and chemical compositions of soil suitable for brick production, thus the significance of carrying out the test. This test is also important in determining the reactions between soil and stabilisers, which would assist in assessing the properties of CSMBs.Details of the procedure for this test are given in appendix 'A' and the results are given in table 4.1.

ii Moisture Content test

Moisture content has an influence on the bond between the binder and soil particles. The actual water absorption of soil has to be deducted from the total water required of the mix to obtain the effective mixing water, which controls compaction. The tests was carried out as specified in (BS1377, 1990) with results given in table 4.2.

iii Specific gravity test

Specific gravity plays an important role in densification as it is a measure of the material volume excluding pores. It is significant in this research work because it is dependent upon the gravities of the individual constituent mineral elements and on the amount of voids present. This indicates the gravity of the material without the need for crushing value test. The test was conducted in accordance with (BS1377, 1990) and specific gravity 'Sg' was calculated using the formula in equation 3.1:

$$Sg = [B – A] / [(D – A) – (C – B] \ g/m^3 \text{……………..eqn(3.1)}$$

WhereSg = Specific gravity; A = mass of Pycnometer; B = mass of Pycnometer + sample; C = mass of Pycnometer + sample + water; D = mass of Pycnometer + water. Results of this test are given in table 4.2.

The soil was further subjected to three additional tests:

i. Sedimentation (Field settling) test

This test was carried out in order to determine the amount of silt in the soils to be compared with allowable limits. Excess quantity of silt and impurities adversely affect the quality of soils and might also reduce the bond between soil particles and stabiliser.The test was carried out according to(BS812, 1995), and the results shown in table 4.3a.

ii. Sieve analysis

Sieve analysis is used to determine the grades and zones within which the soil falls. This was used to predict the size distribution and relative percentages of the particles in each sample. This test was conducted in accordance with(BS410, 1996), with theresults given in table 4.3b.

iii. *Atterberg limits*

The Atterberg limits tests are important because they refer to those properties of soils that indicate the type and condition of soil, and provide a relationship to structural properties such as strength, compressibility and swelling potential.The test was carried out according to (BS1377, 1990). Results of this test are given in table 4.3c.

3.3.3 Preparation of Binders

i. Cassava Starch Paste Consistency

Cassava starch when cooked properly provides a paste with clear appearance suitable for not only combining with colouring agents, but the paste produced do not contain uncooked powder patches that would reduce its stickiness effect, (Khalil, 2005). During trial session, three paste cooking methods were attempted.

a. Introduction of hot water unto starch Powder

Hot water at about 90^0C was added to starch powder in a glass beaker. The reaction produced soft granules about one quarter deep from the top that expanded and prevented the hot water from sinking down to the base of the beaker, thus leaving the starch powder below, dry.

b. Introduction of starch Powder into hot water

Starch powder was added into the hot water, which immediately transformed into bundles of soft balls instead of paste.

c. The production of slurry before paste

Cold water or starch powder, one was introduced into the other to produce slurry devoid of granules or balls. The slurry was stirred enough to remove air bubbles and to dissolve the powder completely. Hot water near or at boiling point was then added to the slurry, which reacted by swelling and transforming into paste.

A test to determine the amount of water for producing starch paste was necessary in order to obtain consistent paste throughout the experiment.The quantities of cold/hot water was varied while the quantity of powder was kept constant in order to achieve consistent paste by using the formulae, adopted from Khalil(2005):

$$L_S = S_p + C_w \qquad (3.2)$$

and $$U_{CP} = L_S + H_w \qquad (3.3)$$

Where L_S = light slurry, U_{CP} = uniform clear paste, S_p = starch powder, C_w = cold water and H_w = hot water. Details of this process are given in appendix 'B'.

After several efforts and calculations, the process of producing clear, thick and uniform paste with standard viscosity was achieved with a mix ratio of 1: $1^1/_5$: 4; dry starch powder to cold water to hot water at boiling point. Through this test the quantity, each of cold and hot water required to produce paste of standard consistency with paste clarity and uniform viscosity were determined.Results of this test are given in table 5.1

ii. *Makuba* Solution Concentration

The reason behind determining the solution concentration of *makuba* was based on the assertion by Abejide (2007),that the aqueous extract of the empty pods of African locust bean was used to harden the surface of lateritic rammed floors. Two processes, cold and hot,(i. e, separation of the active elements that chemically stabilise soil from the inert chaff), were involved in the production of the aqueous solutions used in stabilising brick samples directly and in the preparation of CSM matrix. In the cold process, 5, 10, 15 and 20% *makuba* contents as soil stabilisation levels were soaked in water for specified number of days. Samples were prepared from each stabilisation level daily until the third day when the colour of the solution was darkest and the chaff was observed to be pale. The second process was carried out by cooking the *makuba* to boiling point at about 100^0C. This process was observed to be faster and the solution produced was stickier than that of the cold process. The solution was used to cook cassava starch to produce dark brown paste observed to be stickier than cassava paste cooked with only water. This test was improvised as there is no standard guiding it and the procedure is fully described in appendix ‘C’.

iii. CSM Matrix Composition

To arrive at a homogenous cassava starch and *makuba*matrix, trial mixes were performed. Since the consistence of cassava starch paste has already been established in section 3.3.2 (i) with details in appendix B, the contents of the starch powder and water (cold and hot), were kept constant while the content of*makuba* was varied. In accordance with the solution extraction of *makuba*[section 3.3.2 (ii) and appendix C], 5, 10, 15 and 20% of the pods (also by volume of laterite), were heated to boiling pointusing the same volume of water required to produce cassava starch paste. Colour changes of the pastes were observed and between 15 to 20% pods content gave a colour as dark as the un-cooked pods thus, 20% pods content was adopted throughout this work.

3.4 Brick Production

There are no documented records of the methods of brick production with CSM as binders except for cement or lime stabilised bricks. However, three techniques were developed andapplied thus:

i. The procedure for compressing cement stabilised CEBs requires mixing of the soil and cement in dry form before adding mixing water and immediately pressing.

ii. In a local application of cassava starch to stabilize soil, the dry starch powder is mixed with the soil and water is sprinkled just enough to wet the mix. The mix is then covered with polythene material and left to stay overnight. The next day, more water is added to the soil/starch heap and trampled upon by the feet to achieve a consistent sticky mix from which '*tubali*' (local walling units) are rolled out.

iii. The technique applied by Khalil(2005),to stabilise soils with cassava starch, was by cooking the starch into paste.

Hence, three processes emanating from the techniques above, termed: Instant Dry Mix 'IDM';Delayed Dry Mix 'DDM'; and Cooked Paste Mix 'CPM' were applied in this Thesis. The proportions of binders in the stabilisation levels for IDM and DDM were determined by volume instead of weight due the remarkable differences between the specific gravity of the soil to those of the stabilisers. For CPM, on producing the starch paste, the mass of the mixture increased above that of the dry powder by more than 75% as such stabilisation levels were determined by weight.These processes are fully described in appendices 'D', 'E' and 'F'.

3.4.1 Materials Preparation

The production ofCSEBs of good quality and durability requires the use of soil containing fine gravel and sand to serve as the skeleton of the brick, then silt and clay as binders. Stabilisers are then added to control expansion, strength and abrasion, (ILO-WEP, 1997). The laterite soil used in this research work was dried; screened pulverised and sieved accordingly, through the No. 4 sieve (5mm aperture size) as shown in figure 3.4.

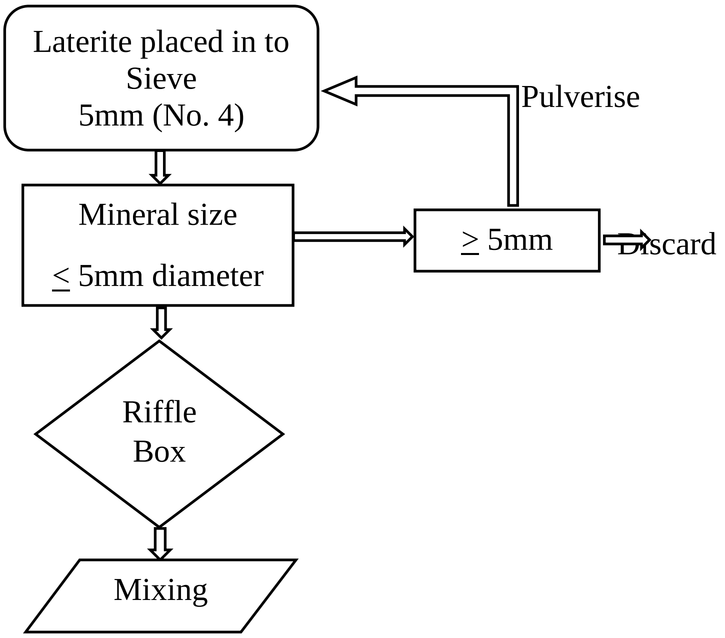


Figure 3.4: Soil Batching Flowchart

i. Batching of Soil

At the preparatory stage, soil samples for sedimentation test were fetched from various locations on the soil heap with the average percentage content of each element given as item (a) in table 4.3. After subjecting the estimated quantity of laterite through the process in figure 3.4, using a riffle box, the batched soil containing even distribution of particle sizes was stored in bags in the laboratory as shown in plate VIII, with the required quantity fetched and used as appropriate.

ii. Maximum Dry Density

Unlike the application of water/cement ratio in the determination of mixing water in concrete or Sandcrete mixes, water requirement for soil stabilisation is determined from Maximum Dry Density (MDD). MDD is the percentage of water by weight of soil, which is just enough to achieve maximum compaction and thence maximum density. The MDD for control samples (0% stabilisation level), was established and mixing water for subsequent levels of stabilisation were prepared as close as possible to the MDD. This was achieved by using the proctor mould, 25kg rammer and a digital weighing balance in accordance with(BS1377, 1990).

Table 3.1: List of Input Variables Used in the Production of CSMBs

S/N	INPUT VARIABLES	UNIT	QUANTITY	EXPERIMENTAL DESIGN	
				FIXED	VARIED
1	**Soil:**				
	Gravel	%	46.96	√	
	Sand	%	26.96	√	
	Clay	%	15.4	√	
	Silt	%	9.57	√	
2	**Starch**	%	5, 10, 15, 20		√
3	***Makuba***	%	5, 10, 15, 20		√
4	**Mixing Water:**				
	Highest	%	20%		√
	Medium	%	16%		√
	Lowest	%	14%		√
5	**Compaction Effort:**				
	High	N/mm^2	8		
	Medium	N/mm^2	4	√	
	Low	N/mm^2	2		
6	**Curing:**				
	Time	Days	7, 14, 21, 28, 56, 90, 180, 270, 360		√
	Temperature	^0C	21 - 30		√

Source: Laboratory Work Design (2012)

iii. Input Variables

The input variables are either fixed or varied as indicated in table 3.1. By subjecting the soil to batching, the elemental percentages were fixed and compaction from brick press was fixed at the medium range, ($4N/mm^2$); while cassava starch, *makuba* , mixing water, curing periods and temperature were varied. Amongst the input variables only temperature varied naturally within the given range. This range was established in the experimental period of about one year. Temperatures were taken during each session and the rangeof$21^0C$to 30^0C wererecorded.

3.4.2 Mixing of Materials for Bricks Production

Mixing of the materials for production of experimental brick samples was conducted in accordance with stipulated standards and where necessary, by improvising as explained thus:

i. Instant Dry Mix 'IDM'

In this process, the soil and binders were mixed thoroughly in dry form according to the chosen proportions of stabilisation levels (0, 5, 10, 15 and 20%) by volume of soil. Calculated mixing water was then added, mixed to consistency and immediately pressed. Details of this process are given in appendix 'D'.

ii. Delayed Dry Mix (DDM)

This process involved mixing the materials as per IDM but instead of pressing immediately, the mixed heap was covered with polythene material and kept under the sun for some days before pressing.The process is fully described in appendix 'E'.

iii. Cooked Paste Mix (CPM)

The third process, CPM was carried out by fetching the required quantity of binder and cooking with water at about 90^0C to produce clear consistent paste in the case of cassava starch; dark brown solution in the case of *makuba* ; and brown paste for CSM matrix.The details of undertaking this processes are given in appendix 'F'.

iv. Mix Proportions of materials in a specimen

The aim of the mix proportion is to produce representative sample of the mixed materials for each specimen according to the brick press mould size and to determine suitable amount of mixing water for maximum densification.The procedure for this mix proportion was carried out according to (BS1377, 1990).

Table 3.2: Specimen Mix Proportions

S/N	L (%)	S (%)	M (%)	SML(%)	TOTAL (%)	Remarks
1	100	0	0	0	100	Control specimens 'L'
2	100	5	-	-	105	Cassava Starch

1	100	10	-	-	110	Stabilised
4	100	15	-	-	115	Specimens
5	100	20	-	-	120	‘SL’
6	100	-	5	-	105	*Makuba*
7	100	-	10	-	110	Stabilised
8	100	-	15	-	115	Specimens
9	100	-	20	-	120	‘ML’
10	100	-	-	5	105	Cassava
11	100	-	-	10	110	Starch/*Makuba*
12	100	-	-	15	115	Stabilised
13	100	-	-	20	120	Specimens ‘SML’

Source: Laboratory Work Design (2012)

The proportion of binder to soil in a specimen could be achieved either by addition or partial replacement. The later requires the reduction of soil content and substituting the same amount with binder. In this work the addition method was adopted as shown in table 3.2 where the percentage levels were calculated and directly added into the same soil content (100%) at all levels of stabilisation.

3.4.3 Brick Pressing

On completion of mixing experimental materials in the appropriate proportions, brick pressing was achieved using the Nigerian Building and Road Research Institute (NBRRI) standard ram having three identical moulds capable of exerting a pressure of about 4N/mm^2, (Ramson, 2011). This pressure is considered as medium pressure range,(CRATerre-EAG, 2011). The mould capacity was calculated using the bulk density of the materials and adding 5% in excess to cater for spillages and consolidation. The moulds were filled in three layers of about 30mm by hand so as to ensure uniform distribution of the mix inside the mould. Excess material was scraped off the top of the mould and weighed before closing the lid.By manually banging the lever arm of the brick press ten (10) times, based on long term experience with the brick press, a uniform pressure and adequate compaction was applied to produce four specimen types as displayed in figure 3.5, with dimensions of the brick specimens as 140 x 140 x 80. The number of brick specimens produced for the various tests are given in tables 5.2, 5.3 and 5.4 with details in appendix ‘G’.

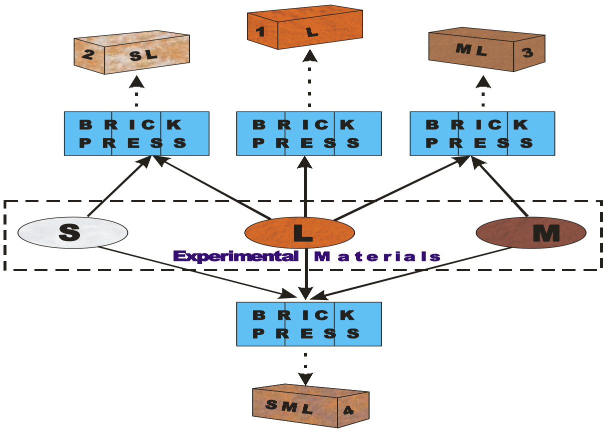


Figure 3.5: Production of Experimental Specimens

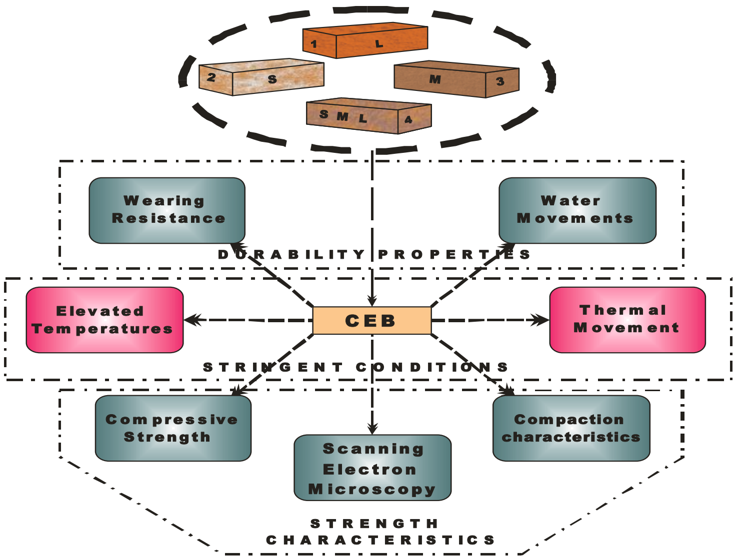
Figure 3.5,shows the combination of materials in each specimen. The control level was produced by adding only mixing water to the laterite soil and then placing into the brick press. The specimens obtained were labeled 'L'. The second specimen types wereobtained by combining cassava starch dry powder or paste (for IDM/DDM or CPM) respectively, with lateriteto produce starch/laterite bricks, labeled 'SL'. *Makuba* laterite specimens 'ML' were produced by combining*makuba* (dry powder or solution extract) with laterite and then pressing. Starch/*makuba* /laterite'SML'brick specimens were produced by combining CSM (powder or paste) with laterite before pressing. The specimens were produced according to the required percentages of binders in table 3.2.

3.4.2 Brick Curing

Curing of soil bricks is distinct from those of sandcrete bricks and concrete elements, which are sprinkled with water or completely immersed in water after 24 hours of casting. The curing method applied to Soilcrete (cement stabilised soil bricks), is by covering with polythene and sprinkling water on a daily bases. This method along with other methods such as exposure to direct sunlight were experimented during trial session for the purpose of determining the best curing method for bricks produced with CSM.

3.5 Performance Evaluation Tests

The main goal of this Thesis is that of establishing the possibility or otherwise of utilising the research materials for construction purposes. There are several methods of investigation into the properties of CEBs which are basically soil dependent. According to Namango(2006), investigations carried out in the area of CEBsso far, are inconsistent and lack comparability or reproducibility. This is due to the non-existent of universally acceptable standards. Walker,(2004) in Namango(2006)opined that regional, national and international standards vary considerably in their approaches to testing and specifications for strength performance of CEBs. Every country has its own methods and specifications, besides soil compositions differ from one region to another. For these reasons, performance indicators found adequate for assessing CSMBs considering the soil type, production method and the climatic conditions of the research area (Zaria), were carried out as shown in figure 3.6.



[Adapted from (Namango, 2006)]

Figure 3.6: CSMB Performance Indicators

In figure 3.6, the performance indicators tested in this Thesis were broken into three groups as shown. The first group consist of durability property tests, Wearing Resistance (Abrasion Resistance) and Water movements (Water Absorption; Permeability; and Capillarity). The second group represents the measurements of stringent conditions (Elevated Temperatures and Thermal Movement) tests. The third group is that of strength characteristics measurements (Compressive Strength; Compaction Characteristics and Scanning Electron Microcopy).

3.5.1 Durability Properties

i. Abrasion Resistance

Abrasion resistance 'R_a' test evaluates the resistance of stabilised soil to surface wear. One significant effect of soil stabilisation is the control of particles lose from brick surfaces, (Hassett, 2014). The results of this test are given in figure 4.3 and table 4.4

ii. Water Movements

Another measure of durability of CEBs is the movements of water or moisture that can cause deterioration of bricks. Varying water movements tests such as Water Absorption 'W_a' by total immersion in water tank; Permeability 'P_t' using the funnel method that measures rate of flow of water through pores of the bricks; and Capillarity 'C_t' by the sorption method, were conducted.

There are various procedures for determining water absorption capacity 'W_a' of bricks according to (BS3921, 1985). These are: Cold immersion in water (24 to 48 hours) after oven drying to constant mass; Boiling test method (5 hours); and Absorption under vacuum test. The cold immersion method was adopted in this research with modification to the immersion duration. During the pilot study of this work, SL specimens immersed in water dissolved after about six hours except the 15 and 20% stabilisation levels, which were only distorted but could not be removed from the water tank without failing. A technique was then improvised to allow measurements and comparison of results with the control specimen. Therefore oven dried specimens were immersed in water, starting with the control (0% stabilisation level) and the time taken for air bubbling to stop, indicating full saturation, was noted. An average of 3 minutes was adopted as this allowed the brick to be removed, strained of free water and weighed without losing particles of the soil. Two methods for carrying out this test were identified.

Method 'A': All other levels of stabilisation were immersed and the time taken for full saturation of each specimen was recorded and comparisons were made based on length of time; the longer time taken for full saturation, the higher the resistance of the specimen to water penetration.

Method 'B': All samples were immersed in water for 3 minutes and comparisons were made based on weight gain.The procedures for carrying out these tests wereaccording to (BS3921, 1985) and as described in appendix 'H'. Results of these tests are given in figures 4.2; 4.3 and table 4.5.

iii. Elevated Temperatures test

As walling units, CSMBs may be exposed to lower temperatures, (ice point), such as in cold houses or high temperatures experienced in bakeries, kilns and incinerators. CSMBs were subjected to a range of temperatures between (– 4^0C to 240^0C). Compressive strength of these specimens were then recorded. The procedure for this experiment is described in appendix 'I' and the results shown in figure 4.6.

3.5.2 Strength Characteristics

i. Compaction Characteristics

Compaction reduces voids in soils, packing closely together the particles, therefore controlling subsequent moisture changes, achieving a state of increased unit weight and hence, generally improves the strength characteristics of the stabilised soil.

The test was conducting in accordance with(BS1377, 1990) Part 4: 3.2, with results of the test given in figure 4.7

ii. Compressive Strength

Earthen walling units are often characterized in terms of compressive strength. Although CEBs can be tested for strength characteristics such as flexural and tensile, compressive strength is the most important as flexural and tensile strengths are only fractional parts of compressive strength.Namango(2006), indicated thatFlexural strength = $^1/_6$ of Compressive strength. Therefore, compressive strength ‘C_s’ test was heavily relied upon to provide the overall strength characteristic of the specimens in this research work.

This test measured the strength development of stabilised soil brick specimens at different levels of stabilisation and at different curing stages (7, 14, 21, 28 and 56days; then at intervals of three (3) months up to a year to measure the pattern of strength development of CSMBs).The three month intervals was enough to allow for moisture equilibration to occur within the samples considering the climatic changes in the research area.Results of this test are given in figures 4.6 & 4.7 and tables 4.7 & 4.8.

iii. Scanning Electron Microscopy

Compaction as a means of stabilisation impacts on density only. The inclusion of stabilising materials may have an effect in the internal structure of stabilised elements and this effect can be investigated via Scanning Electron Microscopy (SEM). SEM was used to reveal the effect of CSM on the morphology of stabilised laterite and the strength properties of CSMBs.

The procedure for this experiment is described in appendix ‘J’ and the results are given in platesXVI to XXIVin chapter four.

3.5.3 Development of Strength Analytical Models

As a follow up to practically obtained results, it is important to develop equations that would help predict the strength of elements produced through some processes.To develop models for CSMB strength prediction, all strength parameters had to be considered.

i. Density: theoretical and practical densities of CSMBs were determined and compared. This way, the role played by density as a function of strength was examined and applied in developing the strength model.

ii. Compaction Pressure: the pressure from brick press determines how dense and strong a brick could be. The higher the pressure, the higher the density and strength. The standard pressure of the brick press used in this work ($4N/mm^2$), was applied in deriving the strength model.

iii. Specific gravity: the specific gravities of the three materials (laterite, starch and *makuba*), were also used in deriving a theoretical density formula.

iv. The bond between laterite and CSM: the binding effect of CSM on the particles of laterite played the most important role in the production of CSMBs. The principle behind this bond was theoretically utilised in deriving the strength model.

v. Curing: the gradual loss of moisture from pressed bricks was also a great contributor to strength development of CSMBs. The periods through which this process (curing) took place were considered in the derivation of the strength model.

Strengths of Bricks calculated from the model, heavily based on theories and some optimum strength results were then compared withpractical results and NBBRI standard requirement for the purpose of verification.The results of model testing are given infigures 4.11 & 4.12 and tables 5.5 to 5.12.

CHAPTER 4

ANALYSIS, PRESENTATION AND DISCUSSION OF RESULTS

4.1 Preamble

In this section of the Thesis, the performance of CSMBs from various tests conducted on the materials and brick samples are analysed presented and discussed in relation to conventional requirements.This is with the view of highlighting the levels of compliance and suitability of CSMBs as walling units to Building Standards.

4.2 Engineering Properties of Materials

Engineering properties of the research materials investigated in this Thesis are given and explained in accordance with stipulated standards where applicable in the following tables. Where no standards exists pertaining some methods, improvised techniques are explained as applied.

4.2.1 Chemical Analyses

Table 4.1: Chemical Composition of Experimental Materials

SN	Element	(%) Content in each Material		
		S	L	M
1	H			
2	Na_2O	-	-	-
3	MgO	-	1.874	1.498
4	Al_2O_3	9.333	21.706	12.847
5	SiO_2	71.768	62.540	51.881
6	P_2O_5	1.769	0.050	3.474
7	SO_3	3.064	0.273	2.346
8	Cl	1.183	0.030	2.100
9	K_2O	8.895	2.372	9.831
10	CaO	2.515	0.189	4.183
11	TiO_2	0.301	1.225	1.703
12	$C_{r2}O_3$	0.075	0.014	0.000
13	Mn_2O_3	0.090	0.151	0.166
14	Fe_2O_3	1.005	9.548	9.869
15	ZnO	-	0.025	0.033
16	SrO	-	0.004	0.069
17	Ni	-	-	-

Note:S = Starch; L = Laterite and M = *makuba*

Source: MUSRL Laboratory A. B. U Zaria (2012)

The elemental percentage contents of each material are displayed in table 4.1. From the chemical analyses, the soil used in this work was confirmed to be a lateritic soil since the ratio of the percentages of silica oxide to that of the sum of alumina and iron oxidewas found to be > 2.00. It alsosatisfied the requirement of Kenyan Standard because (Al_2O_3 + SiO_2 + Fe_2O_3 =93.79%), thus qualifying it fit for brick production.

Table 4.2: Moisture Content (MC) and Specific Gravity (SG)

TEST\MATERIALS	S	M	L
Moisture Content	16.90	19.60	16.16
Specific Gravity	1.40	0.94	2.06

Source: Building Laboratory A. B. U Zaria (2012)

4.2.2 Moisture Content

Water content can be calculated by volume (volumetric) or by weight (gravimetric) basis. The moisture contents of the research materials in this work were calculated gravimetrically and the results shown in table 4.2. The moisture contents of cassava starch and laterite are close, 16.90 and 16.16 respectively. The moisture content of *Makuba* 19.60turned out to be the highest which might be due to the presence of the chaff, which absorbed more moisture than the brown coating which is responsible for both bonding and water repulsion.

4.2.3 Specific Gravity

As shown in table 4.2, the specific gravity of the soil 2.06 is almost twice the specific gravity of cassava starch and more than doubles that of *makuba* with SGs of 1.40 and 0.940 respectively. This is the basis for adopting mix proportions by volume instead of weight because if proportions were prepared by weight the quantity of starch and *Makuba* would be so high as to give no reasonable representation of the percentage levels (5, 10, 15 and 20).

Table 4.3: Soil Characterization

MATERIAL	(i) SEDIMENTATION TEST			
	Composition		**% Fraction**	
	Gravel Fraction: ($\leq$ 5 mm)		46.96	
	Sand Fraction: (0.6 – 0.2 mm)		26.96	
	Clay Fraction: ($\leq$ 0.002 mm)		15.40	
	Silt Fraction: (0.02 – 0.006 mm)		9.57	
Laterite Soil	**(ii) PARTICLE SIZE DISTRIBUTION**			
	BS SIEVE NO.	**APARTURE SIZE**	**% RETAINED**	
	4	4.76mm	7.5	
	7	2.36mm	14	
	16	1.18mm	19.9	
	25	600µm	18.7	
	52	300 µm	22.1	
	100	150 µm	9.1	
	200	75 µm	0.6	
		Pan	8.1	
	(iii) ATTERBERG LIMITS			
	LL	**PL**	**PI**	**L_{sh}**
	32.38	23.61	8.77	1.86

Note: LL = Liquid Limit; PL = Plastic Limit; PI = Plasticity Index; L_{sh} = Shrinkage Limit

Source: Building Laboratory A. B. U Zaria (2012)

4.2.4 Soil Characterization

i. ***Sedimentation:***From table 4.3(i), 9.57% silt content is within the required limits; 15.4% clay content is sufficient and the combined sum of clay/silt fractions, 24.97% is greater than the minimum requirement of 10%accordingto Kenya standard. The coarse and fine sand fractions totaling 73.92% is adequate for limiting shrinkage.

ii. ***Particle Size Distribution:***British Standard,BS410(1996) requires that the grades and zones of soils for construction be determined prior to application. Table 4.3(ii) shows the percentages of soil particles retained on each sieve size and pan during sieve analysis. These values were plotted thus revealing that the lateritic soil had falling within zone II and was well graded.

iii. ***Atterberg Limits:***From table 4.3(iii), the respective values of LL; PL and PI are 32.38; 23.61 and 8.77. The shrinkage limit 'L_{sh}' recorded for this lateritic soil is 1.86.

4.3 CSMB Performance Evaluation

The bases of this research work has been the evaluation of the performances of CSMBs as walling units. Parameters deemed adequate in establishing the characteristics required of CSMBs to function as construction bricks, and to determine the applicability of CSM as soil stabilisers were selected and tested. The data from the tests were analysed appropriately and the results presented in tables, charts, figures, and plates and then discussed accordingly.

4.3.1 Results of Durability Properties

From results of the durability parameters tested, it is evident that the effect of CSM as stabilisers on lateritic soil is positive especially for CPM samples.

i. ***Abrasion Resistance***

Abrasion resistance (R_a), can be expressed as:

$$R_a = (100 - x)/100 \quad \text{..........................eqn(4.1)}$$

and $$x = 100(W_b - W_a)/ W_b$$

Where:

R_a = Resistance to abrasion

x = percentage loss in weight

W_b = weight before brushing

W_a = weight after brushing.

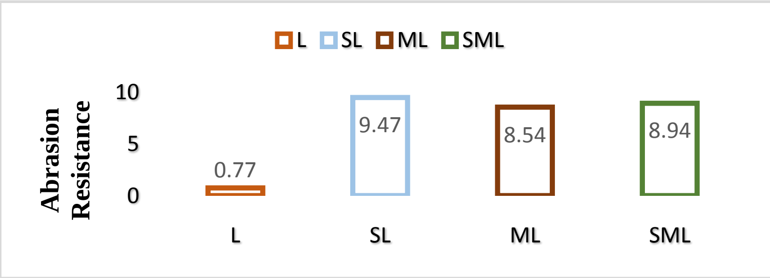


Figure 4.1: Abrasion Resistance of CSMBs for 20% level at 28days (CPM)

Abrasion resistance 'R_a', is the effect of CSM in improving resistance of CSMBs to surface wear and tear. From figure 4.1 and table 4.4, remarkable differences between the stabilised specimens and the control specimens are evident.

Table 4.4: Improvements in Ra of CSMBs (20%) against CEB (L) at 28days (CPM)

Bricks %Levels	Optimum R_a Ratio	Differences in R_a Ratio	Improvement (%)	Remarks
L (0)	0.77	-	-	Control
SL (20)	9.47	8.70	1,130	Positive
ML (20)	8.54	7.77	1,009	Positive
SML (20)	8.94	8.17	1,061	Positive

Source: Building Laboratory A. B. U Zaria Test Results (2013)

SL specimens offered the highest resistance to abrasion with 1130% improvement over the control. SML followed with 1,061% and ML has 1,009%improvement. This implies that the stickiness effect of cassava starch paste is excellent in bonding the soil particles together. From the results of abrasion resistance across the levels of stabilisation (0. 5, 10, 15 and 20%), increase in abrasion resistance as starch content was increased is also well indicated.

ii. Moisture Movements

The effect of moisture on CSMBs was measured using three different methods, (Water Absorption; Capillarity; and Permeability) as explained in chapter 3section 3.5.1(ii). Results from method 'B' made comparison easier due to the ease with which samples were removed, strained of free water and weighed. Besides, water absorption is best indicated by weight gain and the lower the weight gain by samples the greater the indication of the effect of binders in filling up voids.

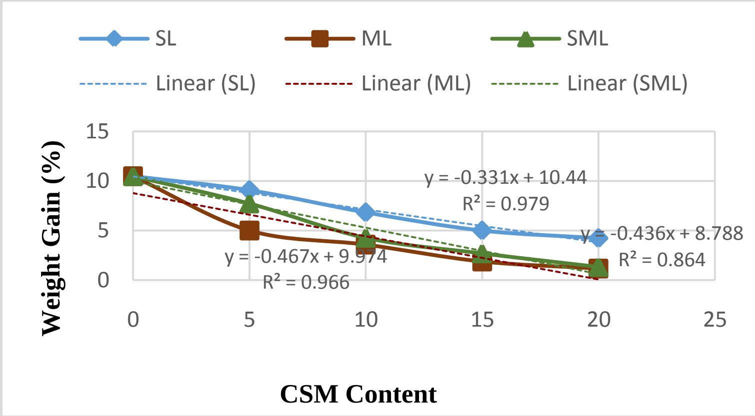


Figure 4.2: Relationship between CSM and Wa at 28 days (CPM)

Figure 4.2 shows the response of CSMBs to water absorption after 28 days of curing. As CSM was increased, $W_a$decreased. The highest water absorption of 10.49%, by method 'B' was recorded at the 0% stabilisation level 'L' even though it was not beyond 12%, which is regarded as high.According to (BS5628, 1990),Part 1, values below 7% are regarded as low, while those above 12% are high.Whenleft beyond saturation point in method 'A', the 'L' specimens began to disintegrate and gradually collapsed to a heap at the bottom of the water tank. From figure 4.2, SL specimens had higher values at allstabilisation levels when correlated with ML and SML. Going by the two methods 'A' and 'B', ingest of water into SL bricks only slowed down as cassava starch content was increased (obtained in method 'B'). In method 'A', water absorption in SL continued until the specimens become jelly and difficult to handle. This was expected because cassava starch and consequently the starch paste are water soluble.

On the other hand, the buoyancy of *makuba* (< 1), made it possible for ML specimens to withstand the devastating effect of moisture. During wet seasons, bunches of *makuba* are placed on top of mud wall fences and as the rain drops, the *makuba* substance washes off the chaff and stains the fence. The brown stains run down the wall repelling the rain water and protecting the mud from constant wetting and drying which would eventually lead to the degradation of the wall.

(a)

(b)

Plate IX: (a) and (b): Makuba on mud wall fences

Plate IX shows the placing of *Makuba* on unprotected mud wall fences.Stains are shown running down the walls and this way, durability of the fences is enhanced in service.

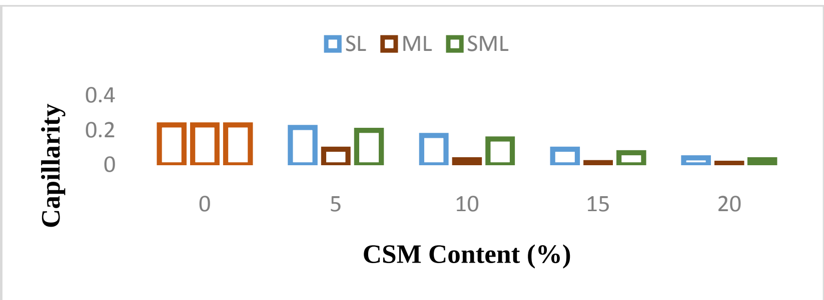


Figure 4.I: Rise of water (Capillarity) in CSMB specimens at 28 days (CPM)

Table 4.5: Improvements in $W_a/C_t/P_t$ of CSMBs (20%) against CEB (L) at 28days (CPM)

Bricks	Optimum weight gain (%)			Improvements (%)			Remarks
%Levels	W_a	C_t	P_t	W_a	C_t	P_t	
L (0)	10.49	0.230	0.019	–	–	–	Control
SL (20)	4.24	0.040	0.012	60	83	37	Positive
ML (20)	1.15	0.009	0.003	89	96	84	Positive
SML (20)	1.32	0.030	0.007	87	87	63	Positive

Source: Building Laboratory A. B. U Zaria Test Results (2013)

The permeability and capillarity testsresults of CSMBs showed similar behaviors to water absorption. From figure 4.3, increase in CSM is seen to retard capillarity and in table 4.5, resistance to permeability improved by over 35%.Among the three CPM stabilised sets, ML presented the highest resistance to water movements followed closely by SML, which could be attributed to the presence of *makuba*.

iii. Elevated Temperatures

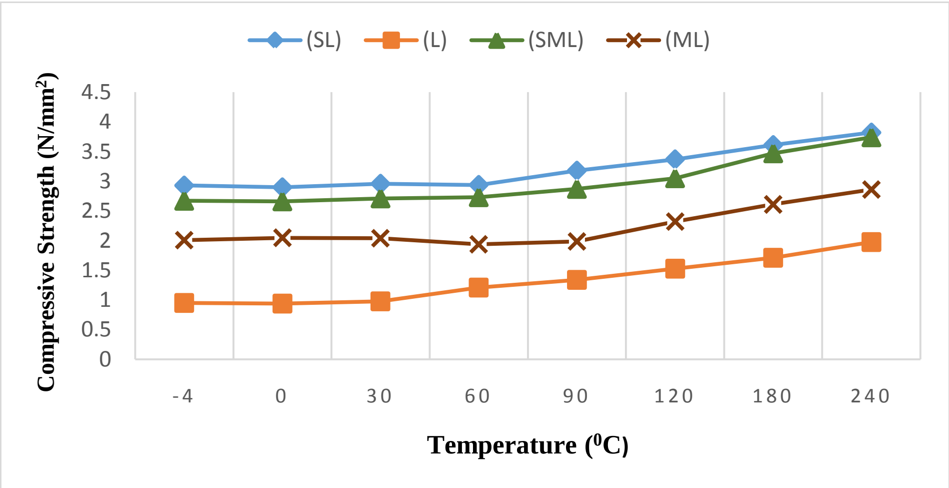


Figure 4.4: Effect of Temperature on Strength of CSMBs for 20% (CPM)

Elevated temperatures as shown in figure 4.4 and thermal movement seem to have no negative effects on laterite bricks in general. Temperatures below 30^0C, (room temperature) had no effect on the strength of CSMBs including the control specimen. As the temperature began to rise above 30^0, the strength of all samples kept rising and there were no signs of failure up to 240^0. Expectedly, the bricks have started transforming into burnt bricks with increase in temperature. Testing for temperatures above 240^0C was no longer necessary as only the properties of burnt bricks would be recorded as CSM must have burnt off.

4.3.2 Strength Properties

Laterite, cassava starch and *makuba* were expected to play different roles in the production and properties of CSMBs. From the results of engineering properties of these materials, the individual contribution of each to soil stabilisation are envisaged as shown in table 4.6.

Table 4.6: Effect of each Material on Stabilisation

ITEM	TYPE	LIKELY EFFECT	PROCESS
Laterite	Sandy, Clayey, lateritic	Compaction	Mechanical
Cassava	Starch	Bonding	Chemical
Makuba	Solution	Cementation	Chemical

[Adapted from Namango 2006]

i. Compaction Characteristics

The key feature of CEB technology is the compression of soil in a mould using a press with compaction effort ranging from low, medium to high. The medium compaction effort ranges from 2 – 4 MN/m^2 or 2 – 4 N/mm^2. The NBRRI brick press used in this work has a pressure of 4N/mm^2, (Ramson, 2011), which is the compaction effort constantly applied in producing all samples.

a. Theoretical Density

Theoretical density (specific gravity), of a material is defined as that pure density of system of particles without voids or air pores. A Pycnometer was applied in this work to determine the actual density of the samples. It was specifically designed to measure the exact volume and density of solid objects by employing Archimedes principle of fluid displacement and Boyle's law to determine the volume. The theoretical densities δ_t of the materials were determined using the formula in equation 4.2:

$$\delta_t = \frac{[B-A]}{[(D-A)-(C-B)]} kg/m^3 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.2)}$$

b. Practical Density

After de-molding, brick samples are relieved of the applied compaction effort, about (4N/mm^2) and start to transform from wet density 'δ_w' to dry density 'δ_d'. This transformation is influenced by, not only the weight and volume of the specimen, but the compaction effort; specific gravity as well as climatic changes through which the drying process was passing. The drying process is faster in dry season and slower in wet season. As long as all samples tested were kept in the same place, under the same condition, any change in moisture contents was assumed to be constant. Unlike concrete samples which must be taken to saturated oven dry conditions before determining density, it is the maximum dry density (MDD) that is commonly used for soil samplesas specified by (BS1377, 1990). The formula used for calculating 'δ_d' is given by equation 4.3:

$$\delta = \frac{m}{v} kg/m^3 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3)}$$

Where:

δ = density of sample

m = mass of sample

v = volume of sample

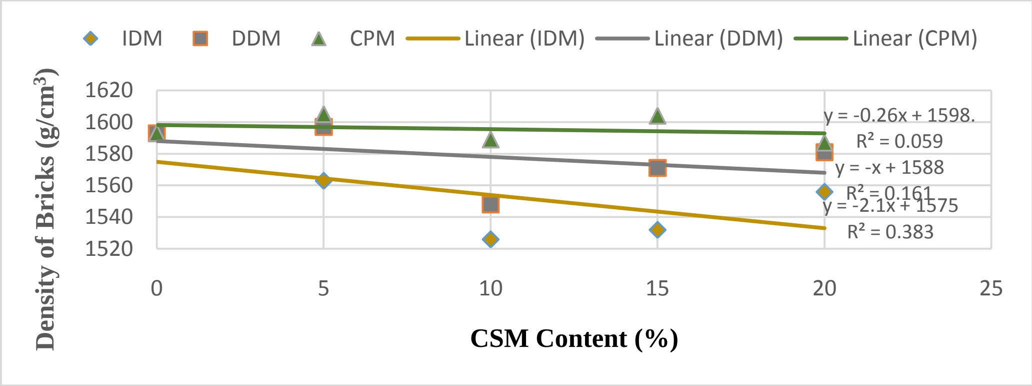


Figure 4.5: MDDs of CSMBs after 28 days

Practical density δ_p is a measure of the achieved weight and volume of samples including pores. Results of this test were used to compare the three brick production techniques as shown in figure 4.5. The relationship between density of bricks and CSM content was observed to obey the law of inverse proportionality because, as CSM content increased, densities of the samples kept decreasing. This pattern was highest in IDM with R^2 value of 0.38 (the steepest gradient) while the CPM technique displayeda gradual slope with R^2 of 0.06 indicating it as the best method for CSMB production. The simple explanation to this pattern is that firstly during mixing, required mixing water was higher in IDM whereas in CPM the moistened paste was enough to facilitate mixing especially at the 15% and 20% stabilisation levels. Secondly, the quantity of material scraped off after filling the mould for IDM was about one third greater than that of CPM. Thirdly, the soil particles must have been lubricated by the starch paste which aided densification, a phenomenon absent in the dry mix.

ii. Compressive Strength

Compressive Strength C_s is the single most important factor controlling durability which according to (Minke, 2000), depends on the quantity and type of clay, grain size distribution of silt, sand and larger aggregates as well as the method of preparation and compaction.

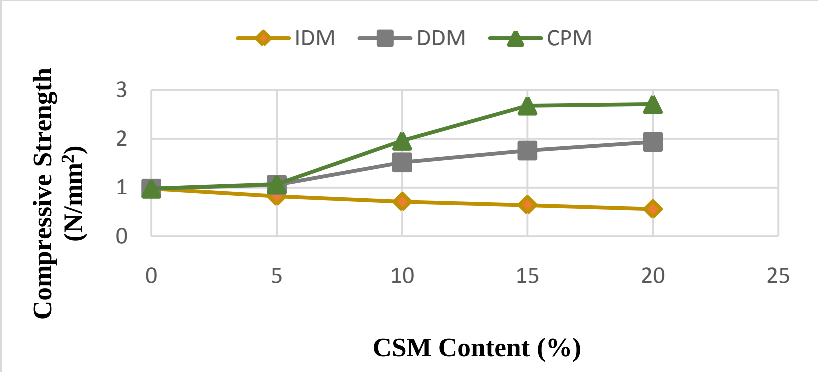


Figure 4.6: Relationship between Compressive Strength and CSM at 28days

Figure 4.6 represents the responses of test samples to increase in CSM content with respect to strength. The CPM technique of stabilisation is also seen to be the best as regards strength development because strength gain continued from 5% to 20% CSM content. DDM followed with a similar pattern but lower values. The values for IDM all fell below the control level, an indication that this technique is not appropriate. The reason behind this assertion is that no chemical reactions exist when water is added to the dry mix of laterite and cassava starch as compared to the hydration reaction of cement with water. On the other hand, *makuba* powder was observed to stain and coat the soil particles thereby providing a margin of bond but its draw back was the presence of the chaff which is inert and does not dissolve in water. It only constituted to lower densities of the ML samples, which in turn affected the compressive strength drastically. The characteristics of DDM are of special interest in that the qualities exhibited by this method are closer to those of CPM. Although the mix contents of DDM are the same as those of IDM, the explanation to the positive response to stabilisation of the former could be attributed to the delay before pressing as explained in chapter 3 section 3.4.2.

During the day time, effect of direct sunlight on the covered mixes have raised the internal temperature of the heap of soil to about 60^{0}C and the absence of air movement had also increased the humidity. As the warm moisture within the soil heap was dissolving *makuba*, cassava starch was gradually being cooked into paste.

Towards evening time when the temperature outside dropped, the covered soil heap was still humid. At night when the heat trapped during the day by the earth crust was released, this too acted as a cooking process, thus the DDM turned out to be a better stabilisation method than the IDM.

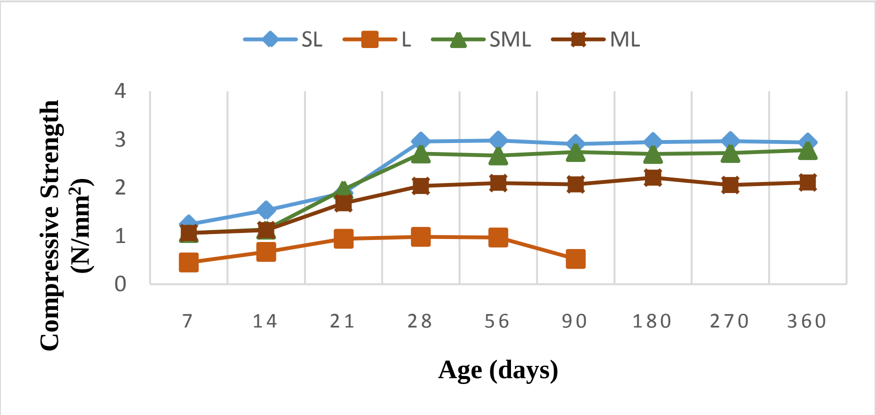


Figure 4.7: Compressive Strength Development with Age at 20% (CPM)

The efficacy of CSM matrix is clearly expressed in figure 4.7 where the behavioral pattern of the four sets of samples to strength development with age are shown. In the un-stabilised samples, the factors responsible for strength are the compaction effort and the moistened clay particles in the laterite. As moisture movement is not static due to a phenomenon called 'breathing' especially in soil bricks as coined by(Morgan, 2008), and(Oskam, 2013), the bond provided by clay starts to relax as time progresses. The only binder, clay needed to equilibrate its moisture with the environment thereby losing inexcess, the moisture required to maintain its grip on the coarse particles when the atmosphere got dry. Then, it became brittle. On the other hand, with high humidity in the atmosphere, the clay absorbed and retained moisture in excess, which weakened its grip again. This is the explanation to the behavior of the 'L' set where the maximum strength attained occurred between 28 to 56 days of compressing. After this limit the strength continued to diminish and crushing strength could no longer be obtained beyond 90 days. The other three sets SL,ML, and SML exhibited continued rise in strength up to

56 days. Beyond these points strength records became steady indicating a permanent bond provided by CSM on the laterite. This bond is neither covalent nor metallic and so, can best be described as an ionic bond, which is electrostatic in nature.

iii. Improvements in Compressive strength of CSMBs

Table 4.7: Improvements in Strength of CSMBs against CEB (L) at 28days – (CPM)

Bricks %Levels	Optimum C_s (N/mm^2)	Differences in Strength (N/mm^2)	Improvement (%)	Remarks
L (0)	0.98	-	-	Control
SL (20)	2.96	1.98	202	Positive
ML (20)	2.04	1.06	108	Positive
SML (20)	2.71	1.73	177	Positive

Source: Building Laboratory A. B. U Zaria Test Results (2013)

Table 4.7 depicts the improvements in strength characteristics of CSMBs over un-stabilised Laterite bricks. Optimum strengths occurred with 20% input of CSM in the three stabilised samples and when compared to the control sample at 28 days the percentages increase in strengths are outstanding, 108; 177; and 202% each for ML; SML; and SL in that order. This collaborates with the durability properties recorded especially abrasion resistance in figure 4.1 and this implies that CSMBs can be properly termed as 'Green Building Materials'.

Table 4.8: Improvements in Strength of CSMBs against $S_s$at 28days – (CPM)

Bricks %Levels	Optimum C_s (N/mm^2)	Differences in Strengths (N/mm^2)	Strength Increase (%)	Remarks
S_s	1.65	–	–	Standard
L (0)	0.98	– 0.67	– 102	Negative
SL (20)	2.96	1.31	79	Positive
ML (20)	2.04	0.39	24	Positive
SML (20)	2.71	1.06	64	Positive

Source: Building Laboratory A. B. U Zaria Test Results (2013)

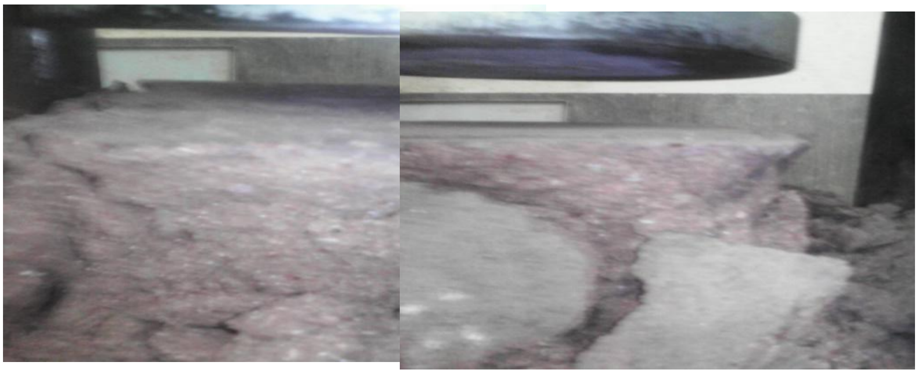
From table 4.6 comparisons were made of CSMB strengths with the NBRRI stipulated minimum required strength for CEBs, (1.65N/mm^2) at 28 days termed Standard Strength (S_s). The control sample fell short of the standard requirement by up to 102%, simply put, a retarded or negative improvement. On the contrary, CSMBs improved positively where ML recorded the least improvement of 24% beyond the standard strength while SL developed strength above it with up to 79%. This is another indication of CSMBs as green walling units.

4.3.3 Crushed Brick Failure Patterns

When thebrick specimens tested in this Thesis were subjected to crushing load under the universal crushing machine, varying failure patterns were observed as shown in the following plates. Only 20% stabilisation levels at 28 days curing period were selected and displayed for the three brick production techniques (IDM), (DDM) and (CPM):

(a) SL Brick **(b) ML Brick**
Plate X: (a) and (b): (IDM) Technique

Plate X shows the failure pattern of 20% (a) starch and (b) *makuba* stabilised brick specimens at 28 days of curing for the Instant Dry Mix technique of brick production. The bricks shattered completely similar to 5, 10, 15% stabilisation levels of the same technique (IDM) and the un-stabilised bricks ‘L’.



(a) **(b)**

Plate XI: (a) and (b): SML Bricks (DDM) Technique

The 20% Starch/*makuba* stabilised bricks in plate XI did not scatter on failure but broke into large parts with evidences of brittleness which was due to the *makuba*content. All *makuba* containing brick specimens used to shatter, snap or crack instantly at failure.

(a)

(b)

Plate XII: (a) and (b): SML Bricks (CPM) Technique

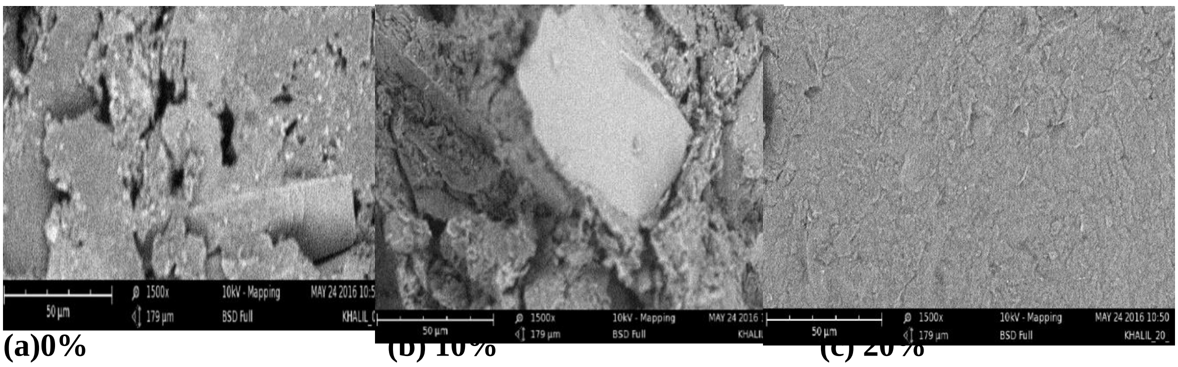
Plate XII shows a different pattern of failure for 20% SML (CPM) bricks where only big and single cracks occurred through the bricks. A stronger bond between the lateritic soil and CSM is evident in the cooked paste method of stabilisation as against the Delayed Dry Mix technique. The brittleness of *makuba* was reduced to some extent by the presence of cassava starch.

Plate XIII: SL Brick (CPM)

The 20% (CPM) purelystarch stabilised brick shown in plate XIII exhibited an elastic property because the crushing machine reached its optimum reading andstopped with no evidence of failure of any sort on the brick.

4.4 Scanning Electron Microscopy Results

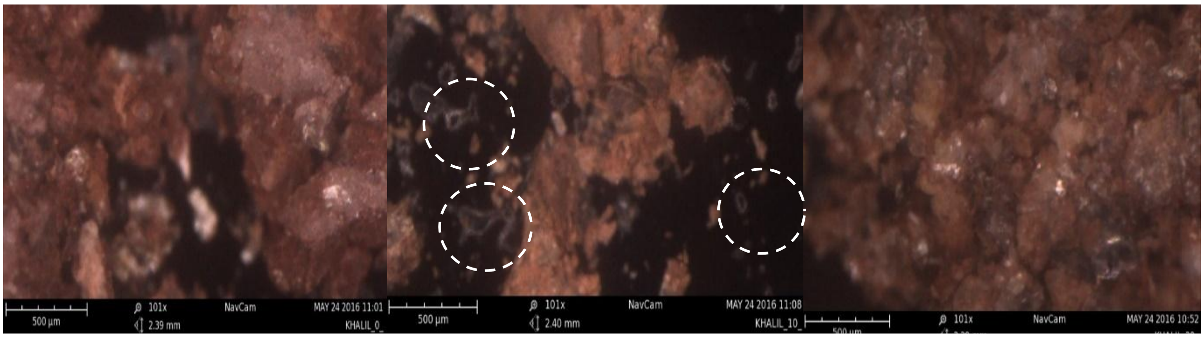
For further confirmation of strength and durability properties of CSMBs established from the various experiments conducted, Scanning Electron Microscopy (SEM) with magnification factors (mf) of 1500 was carried out on some samples of the best method of stabilisation, the cooked paste method (CPM) for Starch/*Makuba* /Laterite (SML) mix and the control sample.The effect of the morphology of stabilised bricks at 10 and 20% levels of stabilisation were compared to the control sample (0%). Three aspects of SEM, the Electron Micrographs (EMs); the Microscopic Images (MIs) and Pore Histograms (PHs) are now presented in the following plates.



(a)0% (b) 10% (c) 20%

Plate XIV(a); (b); (c): Electron Micrographs of0%, 10% and 20% stabilisation levels

PlatesXIV(a), (b) and (c)show the electron micrographs of the control level of stabilisation (0%), then the 10% and 20% stabilisation levels,at 1500 magnification factor. It is very clear from these graphs that the homogeneity of the 20% level as a result of compaction is highest followed by the 10% stabilisation level indicating an ascending progress of the microstructure of CSMBs as CSM was increased.



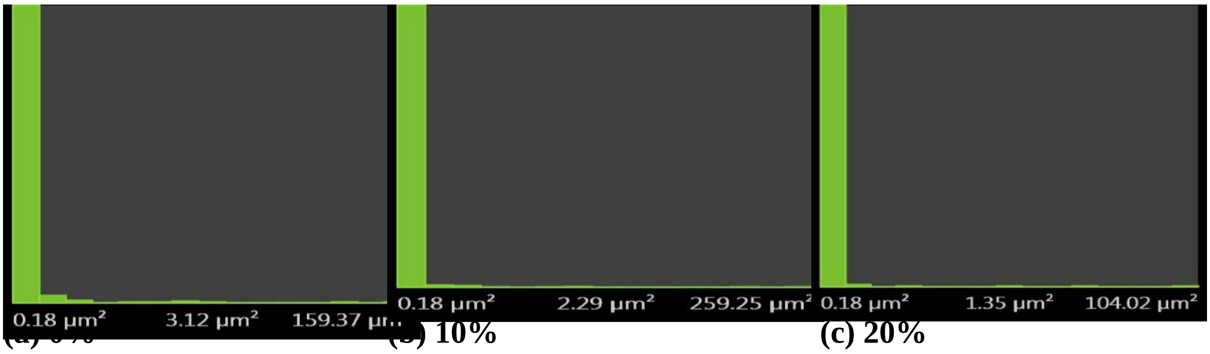
(a)0% **(b) 10%** **(c) 20%**

Plate XV: Microscopic Images of 0%, 10% and 20% stabilisation levels

From plate XV (a), (b) and (c), the absence of binder is evident in theimage of the control sample 0% stabilisation level except for the gold plating shiny substance.

A close look at the 10% stabilisation level,would reveal molecules of cassava starch tinted with the brownish colour of *makuba*, (white circles) insert. In the 20% stabilisation level, the stabilisers are well fused into the soil devoid of the dark parches (pores or voids) present in the 0 and 10% levels of stabilisation.

The pore histograms in plate XVI (a), (b) and (c), reveal three pore sizes, minor; medium; and major. It is normal for the scanning system tosynchronise one of the pore sizes, as such the minor pore sizes of the three samples was given as(0.18µm^2) so as to give room for comparingthe medium and major pore sizes.



(a) 0% **(b) 10%** **(c) 20%**

Plate XVI: Pore Histograms of 0%, 10% and 20% stabilisation levels

The medium pore sizes indicated filling up of voids as CSM was introduced from larger area of 3.12 µm^2 for the 0% stabilisation level to 2.29 µm^2 for 10% stabilisation level and 1.35 µm^2 for 20%. The major pore sizes were still in favour of the 20% level, which had the least pore area of 104.02 µm^2 but the 10% level had larger pore area of 259.25 µm^2, than that of the 0%, which has an area of 159.37 µm^2. This was expected because 5 and 10% levels of stabilisation required additional mixing water, which on evaporation, left behind larger pore areas whereas, the 15 and 20% levels of stabilisation, required no additional mixing water as the matrix paste mixed very well with the soil.

4.5 Strength Analytical Models

As a pioneer work in the area of combining alternative local building materials in soil stabilisation, predictive models cannot be easily carried out using standard methods. Methods such as Design of Experiments (DOE) that have been developed based on long periods of experiments on conventional building materials especially concrete. Besides, models would not be necessary if the results obtained from the whole work had proved otherwise. Also, some of the basic parameters tested yielded negative results such that other bases for strength development of CSMBs had to be envisaged. Thus the reason for starting the models from first principles.

Dry density, asserted by (Kerali, 2001) is a valuable indicator of the quality of CEBs. Density however, also depends on the degree of compaction, specific gravities of the constituent materials, soil grain size gradation and on the form of brick (solid; hollow; *etc.*). Theoretically, density is said to be a function of strength with respect to cement stabilised elements. This holds true because cement has higher density than laterite, so increase in cement content of brick would naturally result to higher density and strength of the brick. The converse is the case with CSMBs where the MDDs of bricks kept dropping as CSM was increasedas shown in figure 4.7. The specific gravity results obtained for the laterite, cassava starch and *makuba* differ from one another (2.057; 1.395; 0.940)kg/m^{3}respectively, and as such the resultant theoretical density for each mix proportion had to be computed at each level of stabilisation using a derived formula.

4.4.1 Theoretical Density Model

The resultant density of a mixture of two or more materials of different densities would not just be the average of the sum of the individual densities, (Dohrman, 2013). This is because density is the ratio of mass and volume of substances. Whereas an increase in volume is direct and linear, increase in mass is the average of the combined masses of the individual constituent materials. As a result, the numerator (mass) and the denominator (volume), must be treated separately to arrive at the actual density of a mixture.

A formula had to be derived to calculate the theoretical density of the mixture of CSM and laterite at the various levels of stabilisation. Hence, by assuming the mass and volume of laterite to be 100%;

$$\delta_{ta} = \frac{L_m\% + a\% \text{ of } (S_m + M_m)/2}{(L_v + a)\%} \text{ of } \delta_L \text{ kg/m}^3 \qquad \text{eqn(4.4)}$$

Where δ_{ta} = theoretical density of a mix containing a% CSM matrix; L_m = laterite mass;L_v = laterite volume; a = 0, 5, 10, 15 and 20% (stabilisation levels); S_m = starch mass; M_m = *makuba*mass and δ_L = density of laterite.

Thus: $$\delta_{t0} = \frac{100\% + 0\% \text{ of } (0 + 0)/2}{(100 + 0)\%} \text{ of } 2.057 = \underline{2.057\text{kg/m}^3}$$

$$\delta_{t5} = \frac{100\% + 5\% \text{ of } (1.395 + 0.940)/2}{(100 + 5)\%} \text{ of } 2.057 = \underline{1.9602 \text{ kg/m}^3}$$

$$\delta_{t10} = \frac{100\% + 10\% \text{ of } (1.395 + 0.940)/2}{(100 + 10)\%} \text{ of } 2.057 = \underline{1.8722 \text{ kg/m}^3}$$

$$\delta_{t15} = \frac{100\% + 15\% \text{ of } (1.395 + 0.940),2}{(100 + 15)\%} \text{ of } 2.057 = \underline{1.7918 \text{ kg/m}^3}$$

$$\delta_{t20} = \frac{100\% + 20\% \text{ of } (1.395 + 0.940)/2}{(100 + 20)\%} \text{ of } 2.057 = \underline{1.7182 \text{ kg/m}^3}$$

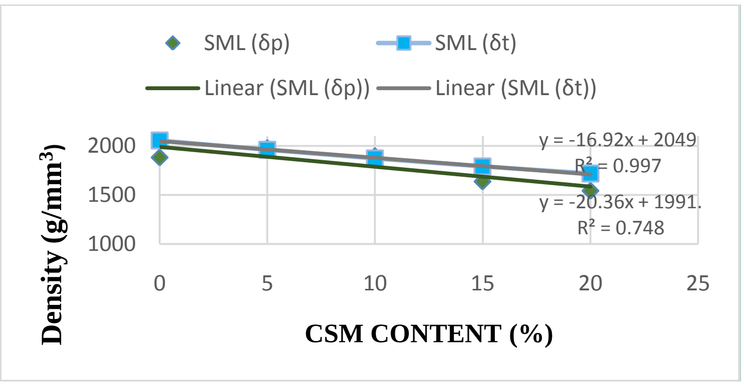
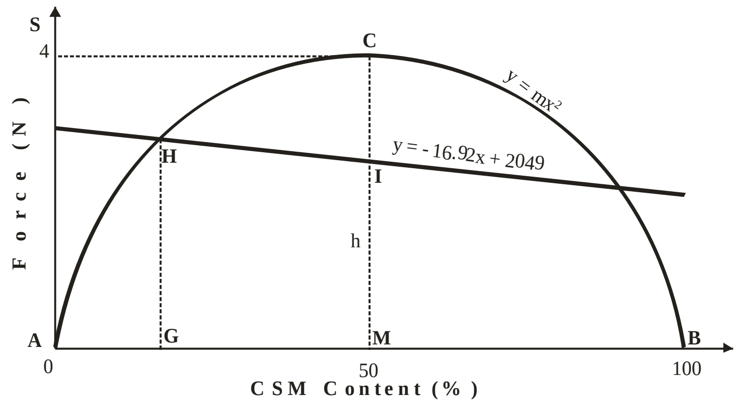


Figure 4.8: Theoretical Vs Practical Densities of CSMBs

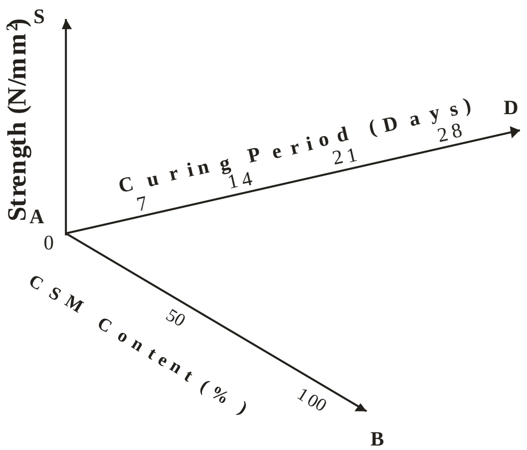
Both the theoretical density (δ_t) and practical density (δ_p) decreased when CSM content was increased as depicted by the closely related negative gradients of the graphs in figure 4.8.Contrary to this behavior, strength was observed to increase as CSM increased; indicating the presence of other variables responsible for strength development in CSMBs. Compaction effort (force), exerted by the brick press; the bond between laterite and CSM matrix; and curing period have played major roles in strengthdevelopment of the bricks. From the results of chemical analyses carried out on the research materials, the active elements in laterite, cassava starch and *makuba* are Hydrogen (H), Carbon (C), Oxygen (O) and Nitrogen (N), (Infrared Spectra 2012). Atoms of these functional groups are said to collide to form Electrostatic-Hydrogen bond with each other, (Ramson, 2011). Hydrogen bonding is a special type of intermolecular attraction between the hydrogen atom in a polar bond (particularly an H – F, H – O, H – N bond) and an unshared electron pair on a nearby small electronegative ion or atom (usually an F, O or N atom in another molecule), [Brown et al 2006 in (Ramson, 2011)]. The hydrogen bonds account for the strength and durability characteristics of cassava starch stabilised bricks and this could be said of *makuba* too since their functional groups are similar from the results of chemical analysis.

4.4.2 Strength Model

To derive a formula for predicting the strength of CSMBs, the bond between laterite and CSM matrix can best be described by a parabolic mathematical relationship because this bond (ionic bond), involves the transfer of electrons (in pairs). As CSM content increases in the mix, the network of bonds also rises up to a maximum point where electron donation is assumed to be in equilibrium. From this point on, with any addition of CSM excess free ions would begin to build up thereby unwinding the networks of bond resulting in the fall of strength. The general equation of a curve ($y = mx^2$) can serve well to represent this phenomenon. Furthermore, the negative impact of density on strength must be considered along with other strength parameters.



(a)



(b)

Figure 4.9 (a) and (b): CSMB Strength Parameters

Presented in figure 4.9 (a) and (b) are the envisaged relationships within the parameters that bear direct effect on strength of CSMBs. The curve AHCB in (a) is the likely plot for strength due to the bonding effect of CSM on laterite. The line AB is the increase in CSM content (0 to 100%); line AS is the theoretical line of forces (strength); MC equals the maximum applied force from brick press; GH is the optimum resistance to applied force offered by the brick due to the restraint presented by the negative density represented by line HI.With regards to density, as it reduces, strength is assumed to drop in the same manner and thus a plot for strength would be parallel to the plot for density,thus line HI is a line of force with the same equation as that for the theoretical density. Figure 4.9b shows the relationship between Compressive strength and increases in both CSM and curing days. Lines AS and AB are the same as in figure 4.9a and line AD is for the curing period in days. Lines AS and AD are perpendicular because these parameters (increase in CSM content and curing periods), are independent of each other. Without CSM, the strength of the control samples grew with increased in days of curing and vice-versa.

Considering the point of intersection H of curve AHCB and line HI as the optimum force of resistance by CSMB, the curve can be isolated and placed on the Cartesian axes for a geometrical analysis of the force ‘γ’. By establishing an equation for strength at point H in figure 4.10, the strength of CSMBs between A and H can be predicted given any value of ‘a%’, (CSM content).

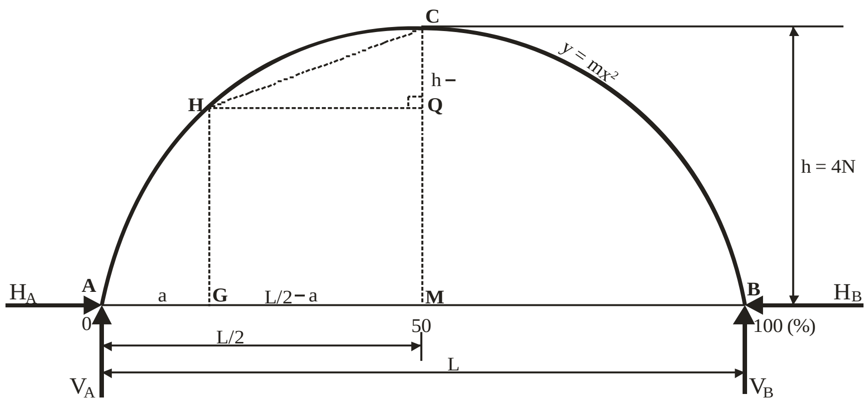


Figure 4.10: Geometrical analysis of Force of resistance 'γ'

V_A and V_B are the vertical resistance exerted by the bottom plate of the brick mould opposing 'h', the applied force; H_A and H_B are the horizontal thrust exerted by the mould sides

From figure 4.10, given the general equation of a curve $y = mx^2$, changes in y and x can be denoted from triangle CHQ as:

$h – \gamma = m(L/2 – a)^2$…………………eqn(4.5)

When 'a' tends to 0, $\gamma = 0$, therefore; $h = m(L/2)^2$

and; $m = 4h/L^2$………………………..eqn(4.6)

Substituting for m in eqn(4.5); $h – \gamma = 4h/L^2(L/2 – a)^2$

Hence; $\gamma = 4ha/L^2(L – a)$……..…………eqn (4.7)

Where γ = optimum resistance of brick (force of resistance); h = maximum applied force by brick press (4N); a = any percentage of CSM; L = CSM (100%); m = slope.

Compressive strength $C_s = F/A$;

Where F = failure Load and A = area over which the force is applied. Theoretical strength (T_s) can now be expressed thus: $T_s = \gamma/A$

$T_s = 4ha/AL^2(L – a)$

This formula had to be multiplied by a factor such that predicted values of strength from this model would fall close to the minimum required twenty-eighth day strength of ($1.65N/mm^2$) for CEB according to NBRRI.So, the formula reduced to:

T_s = 8ha/A(100 – a)……………….eqn (4.8)

For the model to accommodate the curing period as a strength parameter, the relationship between practical compressive strength and CSM/Curing days expressed in figure 4.9b must be taken into account. Practical strength P_s is partly constant and partly changing with increases in CSM content and curing days. Therefore;

P_s = pa + qd………………………..eqn (4.9)

Where P_s = Practical strength;a = CSM content (%); d = curing days while p and q are constants of proportionality.

When a = 10% at 28 days, P_s = 1.70N/mm^2; and when a = 20% at 28 days, P_s = 2.10N/mm^2; Each of 1.70N/mm^2 and2.10 N/mm^2 arethe average practical compressive strengths of DDM and CPM at 10% and 20% stabilisation levels respectively. This was done to carry both techniques along in the model.

Therefore; P_s = 0.04a + 0.05d …………..……………….eqn (4.10)

In order to avoid 'd', appearing in the unit of strength as(Nd/mm^2), the curing periodsare simplified to 7/7; 14/7; …. n/7 (i.e 1; 2; 3; 4…), as ratios. Where n is any number of days.

For all parameters highlighted earlier as CSMB strength contributors to be captured in the model, theoretical strength T_s and practical strength P_s must be equal thus, the two equations are combined to give:

M_s = 4ha/A(100 – a) + (4a +5d) x 10^{-2})N/mm^2……….. eqn (4.11)

Where: M_s = strength model; h = Applied pressure; a = CSM content; A = area over which pressure is applied; and d = curing period.

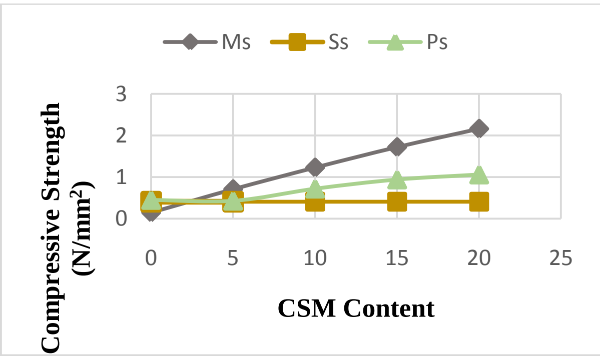
4.4.3 Testing of Strength Model

The idea of this model is to serve as a mathematical tool for predicting the likely strength of CSMBs given the values of parameters responsible for strength development as captured in equation 4.9. The model utilises the input variables, production process and curing periods therefore, testing of the model involves substituting the values of some variables (CSM content and curing periods) while keepingconstant, the applied pressure and area over which the pressure is applied. The plots (M_s) from this procedure are then compared with the NBRRI standard (S_s) and practical strengths (P_s).Positive result were obtained by the DDM and CPM methods of stabilisation, hence only these two methods were chosen for testing of the strength model.

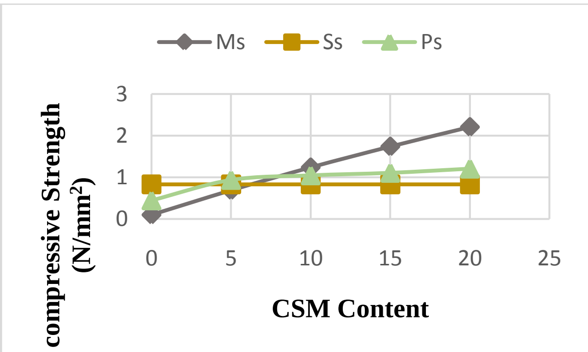
The NBRRI standard stipulated a minimum strength of 1.65N/mm^2 at 28 days for CSEBs. CSMBs are assumed to attain a quarter of this value at 7 days, half at 14 days and three quarters at 21 days.

$$\mathbf{M_s = 4ha/A(100 - a) + (4a + 5d) \times 10^{-2}\ N/mm^2}$$

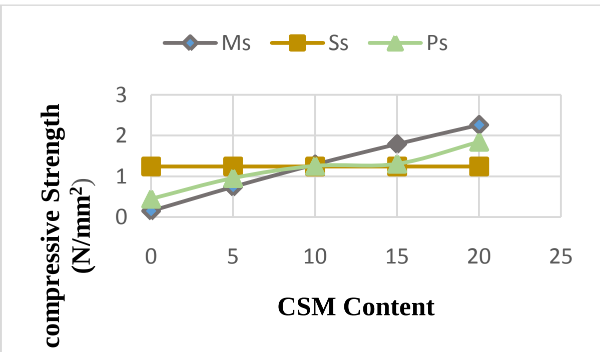
Given that: h = 4N; a = 0, 5, 10, 15 and 20; A = 19600mm^2; and d = 1, 2, 3 and 4; the predicted strengths, (M_s) of CSMBs in figures 4.11 and 4.12 were plotted and compared with CEB standard strength requirement, (S_s) and the practical strengths, (P_s) obtained.



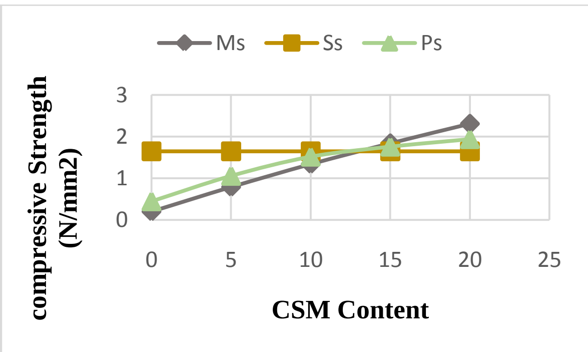
(a) 7days



(b)14days



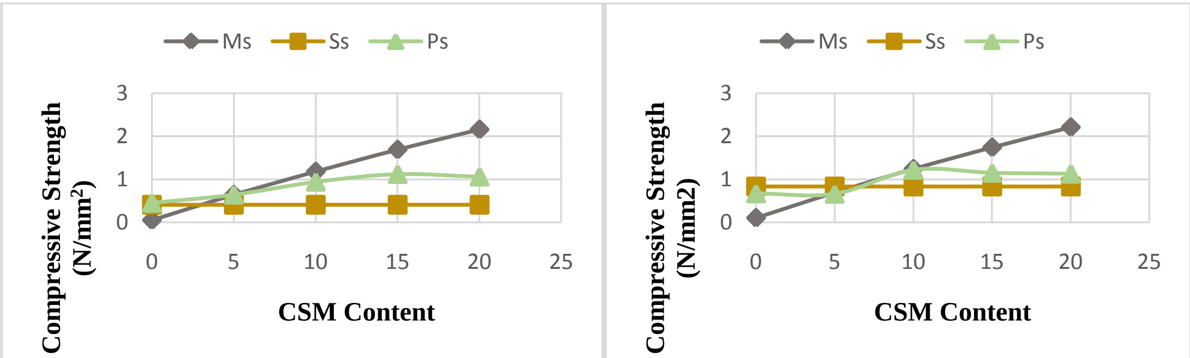
(c) 21days



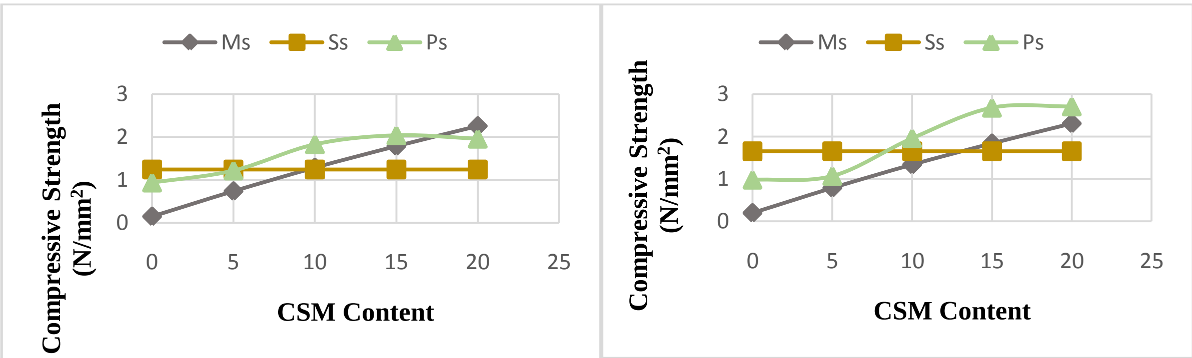
(d) 28days

Figure 4.11 (a); (b); (c); (d): Comparison within M_s; S_s and P_s for SML – (DDM)

Although the practical strengths of (DDM) for SML bricks fell below the predicted values with a few exceptions as shown in figures 4.11, higher contents of CSM (15 and 20%) are seen to fall above the standard strengths, figure 4.11 a – d. From 21 days upwards, the practical strengths levels improved showing close agreement with the model.



(a) 7days (b) 14days



(c) 21days (d) 28days

Figure 4.12 (a); (b); (c); (d): Comparison within M_s; S_s and $P_s$for SML – (CPM)

CPM samples of SML bricks show closer agreement with the model where some values of higher levels (10, 15 and 20%) went slightly above predicted strengths, as shown in figure 4.12 c – d.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

This Thesis aimed at investigating the performance of Cassava Starch and *Makuba*matrix in stabilising laterite soil. From the experiments conducted, it had been established that cassava starch and *makuba* have the potential of being applied in construction work especially in the production of Compressed Stabilised Earth Bricks. Major performance indicators of the bricks produced, are now highlighted.

i. After studying the engineering properties of the research materials, three techniques for CSMB production were developed in this Thesis based on material mixing methods.Theseare: Instant Dry mix, Delayed Dry Mix and Cooked Paste Mix with optimum content of the matrix as 20% in each mix.

ii. Reduction in practical densities of CSMBs as CSM was increased occurred partly due to lower specific gravities of CSM, (as indicated by the engineering properties of the materials) and partly due to the scraped off excess materials during the filling of brick press moulds which ranged from 2 to 6% for 5 to 20% levels of stabilisation respectively.

iii. CSMBs recorded an optimal compressive strength of $2.71N/mm^2$ and improvements in some durability properties such as resistance to abrasion where CSMBs recorded over 1000% improvement above the control samples and water absorption resistance was enhanced by about 96%.

iv. Properties of CSMBs were not tempered with when subjected to elevated temperatures ranging from – 4^0C to 240^0C instead, the bricks started transforming into burnt bricks when temperatures were raised above ambient limit with increase in strength of up to $3.82N/mm^2$.

v. Scanning Electron Microscopy SEM through electron micrographs; microscopic images and pore histograms were supportive of the physical characteristics of CSMBs' by revealing the internal structure of the bricks at a magnification factor of 1500.

5.2 Conclusions

Cassava starch and *makuba* (African Locust Bean Pod), were used in stabilising Laterite soil in this Thesis, out of which Compressed Stabilised Earth Bricks were produced. The performance of these bricks tagged CSMBs were measured and the following conclusions made, thus:

i. For any construction material to be appropriate for usage, it has to be abundant and affordable. Nigeria happened to be the leading World producer of Cassava,and the geographical distribution of *Parkia biglobosa* in Africa covers almost the whole of Nigeria.It is concluded therefore that CSM could be appropriate building materials.

ii. The best technique for the production of CSMBs is the cooked paste method 'CPM' because out of all the parameters tested, CPM samples offered the best results. The technique requires the generation of heat only to about 100^0C, which is considered as very low compared to the heat needed for the production of cement and burnt bricks, (about 1500^0C), for example.

iii. Before subjecting CSMBs to performance tests and examinations, different curing methods were applied. By exposing brick samples to direct sunlight, as a means of curing, cracks developed as a result of fast evaporation of mixing water. Samples covered with polythene material developed fungi because the moisture collected at the surface of the bricks was restrained from escaping thereby attracting microbes. Therefore, the best method for curing CSMBs is open air drying under shed.

iv. The optimum level of the matrix in soil stabilisation for the purpose of bricks production is 20% CSM matrix.

v. CSMB has been discovered to achieve compressive strength and durability properties above the minimum requirement of NBRRI (2.71N/mm^{2}to 1.65N/mm^2;CSMB to NIBBRI respectively),hence it is concluded that it can possibly be used for the construction of storey buildings above two floors.

vi. It has been discovered that CSMBs can withstand temperatures ranging from ice point to above boiling point without failure thus, these bricks can be used in walls exposed to extreme temperatures as in cold houses and bakeries.

vii. In the whole process of CSMB production, little heat is required ($\leq$ 100^{0}C). No heavy machineries or expertise are needed. CSM are renewable so from ethical point of view these materials can be used for medicinal purposes, food and construction with their demand rising and in return increasing job opportunities. It is therefore concluded that CSMBs can be termed as appropriate (green) walling units.

viii. Cassava starch was discovered to have a higher binding effect on the laterite when compared to *makuba*, (2.96N/mm^2 to 2.04N/mm^2; SL to ML respectively) while the role of *makuba* is in improving water absorption; Capillarity; and Permeability resistance of CSMBs, (84% to 37%; ML to SL respectively).

5.3 Recommendations

i. Cassava starch stabilised bricks (SL) have been discovered to possess elastic properties in that at the optimum level (20%) the samples did not fail or got shattered on crushing even after 360 days of curing. Therefore these bricks can withstand seismic movements and are recommended for application in load bearing walls and regions prone to landslides provided they are well protected from moisture.

ii. *Makuba* stabilised bricks (ML) are recommended for use as fencing walls due to the strong ability of *makuba* at resisting moisture movements and the brownish colour of *makuba* would add aesthetic value to the wall.

iii. Cassava starch/*makuba* stabilised laterite soil (SML) could be utilised for wide application in building construction ranging from load bearing walls, partition walls, cast walls, composite walls; rammed earth floors; parapets and for esthetic designs as the surfaces of the bricks may not require finishing in the form of plastering, cladding or painting.

5.3.1 Recommendations for Further Studies

i. Even though CSM are abundant, it is required that the economic viability, (affordability) of using CSMBs be established compared to the use of other available soil binders such as cement, lime and chemical grouts.

ii. It is also recommended that varying sizes of brick units stabilised with CSM should be tested to ascertain the effect of size of bricks on strength and durability properties of CSMBs.

iii. CSMBs should be exposed to the external weather for a long period, say three (3) years to determine deterioration of the bricks due to inclement weather conditions and biological effects.

iv. CSMBs should be subjected to other tests such as Unconfined Compressive Strength, California Bearing Ratio, Tensile stress, flexural strength, thermal movement and other tests necessary for assessing strength and durability properties.

5.3.2 Contributions to Knowledge

i. This research work has developed a strength prediction model for CSMBs

$$M_s = 4ha/A(100 – a) + (4a +5d) \times 10^{-2} \text{ N/mm}^2$$

Where M_s = Strength model; h = Applied pressure; a = CSM content; A = area over which pressure is applied; and d = curing period in weeks.

ii. The research established a 20% CSM matrix content by volume of laterite for Delayed Dry Mix and 20% CSM paste by weight of laterite for Cooked Paste Mix as the optimum matrix level for the production of durable laterite bricks.

iii. The research discovered that bricks produced with CSM can withstand temperatures ranging from ice point, (– 4^0C) to above boiling point (240^0C) without failure. CSMBs can be used for construction of walls exposed to extreme temperatures as in cold houses and bakeries.

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APPENDICES

APPENDIX A: Chemical Analysis

TEST: Chemical Analysis test.

PROCEDURE: Finely grounded powder samples of cassava starch, *makuba* and laterite were each placed into a sample holder, which was then inserted into the X – Ray diffractometer.

X-rays were generated in a cathode ray tube by heating a filament to produce electrons. The electrons were accelerated toward the target by applying a voltage, and bombarding the target material. When electrons have sufficient energy to dislodge inner shell electrons of the target material, characteristic X-ray spectra were produced. When the geometry of the incident X-rays impinging the sample satisfies the Bragg Equation, constructive interference and a peak in intensity occurred. A detector recorded and processed this X-ray signals and converted the signals to a count rate which was then output to a computer monitor. The ratio of the peak intensity to that of the most intense peak (*relative intensity* $= I/I_1 \times 100$) is termed 'chemical analysis' of the material. The results obtained for chemical analysis of the research materials in this work are presented in table 4.1 and plates 5.1 a, b and c.

APPENDIX B: Paste Consistency

TEST: Mix design for starch paste production

PROCEDURE: Paste production required mixing the starch powder first with an amount of cold water (at room temperature). Hot water near or at boiling point is then added to the cold slurry to form paste the consistency of which depends on the quantities of both cold and hot water determined thus:

Table 5.1: Paste Consistency Results

i. a) 200g (S) + 100g (C_w) = T_s

b) 600g (H_w) + T_s = non-uniform, whitish paste

ii. a) a) 200g (S) + 200g (C_w) = L_s.

b) 600g (H_w) + L_s = uniform, whitish paste

iii. a) 200g (S) + 240g (C_w) = L_s

b) 800g (H_w) + L_s = Uniform, clear, viscous paste

iv. a) 200g (S) + 240g (C_w) = L_s

b) 1000g (H_w) + L_s = Uniform, clear, watery paste

Source: Building Laboratory A. B. U Zaria (2011)

The thirdmethod, which gave 200g of starch powder to 240g of cold water to 800g of hot water; 1: $1^1/_5$: 4; was adopted as the best.

APPENDIX C: Solution Concentration

TEST: Extraction of *makuba*solution

PROCEDURE: The two extraction methods employed in this work are:

i. The Cold Process

The pods of the African Locust Bean are weighed to the required percentages and placed in a transparent plastic bucket. Calculated amount of water was added plus about 5% to make up for water absorbed by the chaff. The change in colour of the water was observed on daily basis until the colour was as dark as that of an un-soaked pod and the colour of the chaff was pale, whitish. The chaff was then sieved out and the solution applied appropriately for soil stabilisation.

ii. The Hot Process

In this process, the weighed pods and the required water content, this time plus about 10% to make up for vapour loss during cooking are placed in a pot. As soon as the chaff was observed to be pale and the solution dark enough, cooking stopped.

APPENDIX D: Instant Dry Mix 'IDM'

The required percentages of stabilisers are weighed in dry powder form and directly introduced into the soil. After mixing thoroughly, required mixing water was then added, mixed again and bricks are pressed instantly.

APPENDIX E: Delayed Dry Mix 'DDM'

In this process, cassava starch dry powder (in the case of 'SL'), was mixed with the soil thoroughly. Required mixing water was then added and the heap covered with polythene material and kept under the sun for some days. In the case of 'ML', the solution extracted from the pods was used to mix the soil, covered with polythene material and also kept under the sun for some days before brick pressing. For 'SML', the dry starch powder was first mixed with the soil. Extracted *makuba* solution was then applied in place of mixing water, also covered with polythene and kept under the sun and delayed for some days before brick pressing.

APPENDIX F: Cooked Paste Mix 'CPM'

i. 'SL' mix was achieved by weighing the required quantity of cassava starch cooked paste (after cooling) and adding unto the soil, mixing thoroughly and immediately pressing bricks.

ii. 'ML' mix was obtained by fetching the required *makuba* solution from the cooking pot (after cooling), and applying in place of mixing water in the soil, mixing thoroughly and immediately pressing the bricks.

iii. 'SML' was produced by first preparing starch slurry using cooked and cooled *makuba* solution in place of ordinary water. The *makuba* solution was then re-heated to boiling point and poured into the slurry to produce the paste.

APPENDIX G: Brick Specimen Output

Table 5.2: Compressive Strength/Compaction Characteristics Tests

	IDM				DDM				CPM									
Days	**7**	**14**	**21**	**28**	**7**	**14**	**21**	**28**	**7**	**14**	**21**	**28**	**56**	**90**	**180**	**270**	**360**	
Levels%								Number of Cubes										**Totals**
L 0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**51**
5	3	3	3	3	3	3	3	3	3	3	3	3						**36**
SL 10	3	3	3	3	3	3	3	3	3	3	3	3						**36**
15	3	3	3	3	3	3	3	3	3	3	3	3						**36**
20	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**51**
5	3	3	3	3	3	3	3	3	3	3	3	3						**36**
ML 10	3	3	3	3	3	3	3	3	3	3	3	3						**36**
15	3	3	3	3	3	3	3	3	3	3	3	3						**36**
20	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**51**
5	3	3	3	3	3	3	3	3	3	3	3	3						**36**
SML10	3	3	3	3	3	3	3	3	3	3	3	3						**36**
15	3	3	3	3	3	3	3	3	3	3	3	3						**36**
20	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**51**
								GRAND TOTAL										**528**

Source: Research Design (2011)

Table 5.3: Abrasion, Water Absorption, Capillarity & Permeability Test

	IDM				DDM				CPM				
LEVELS	A_r 28	W_a 28	C_t 28	P_t 28	A_r 7	W_a 14	C_t 21	P_t 28	A_r 7	W_a 14	C_t 21	P_t 28	**TOTALS**
						Number of Cubes							
L 0%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
5%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
SL 10%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
15%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
20%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
5%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
ML 10%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
15%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
20%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
5%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
SML10%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
15%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
20%	3	3	3	3	3	3	3	3	3	3	3	3	**36**
						GRAND TOTAL							**468**

Source: Research Design (2011)

Table 5.4: Performance of CSMBs under elevated temperatures Test

	CPM								
^{0}C	**– 4**	**0**	**30**	**60**	**90**	**120**	**180**	**240**	**TOTALS**
Level				**Number of Cubes**					
L 0%	3	3	3	3	3	3	3	3	**24**
SL 20%	3	3	3	3	3	3	3	3	**24**
ML 20%	3	3	3	3	3	3	3	3	**24**
SML20%	3	3	3	3	3	3	3	3	**24**
			GRAND TOTAL						**96**

OVERALL TOTAL	**1092**

Source: Research Design (2011)

APPENDIX H: Water Movements

i. ***Water Absorption:*** Specimens were weighed before immersion in water. After the stipulated time for this test, the specimens were removed from the water, strained of surface water and re-weighed. Increase in weight expressed as percentages of the dry weight is termed the swelling characteristics or water absorption of the bricks.

ii. ***Capillarity:***the sorption method was adopted in this test. An adhesive was placed around the upright sides of the specimen to prevent ingest of water through the sides but only from underneath, (upwards rise of water 'capillarity'). After the adhesive had dried up, the specimen was weighed and placed on specially arranged supports that allowed only the underside of the specimen to come in contact with water in a tray. After a constant predetermined period, the specimen was removed, strained of surface water and re-weighed. Increase in weights expressed as percentages of the dry weights is termed 'capillarity'.

iii. ***Permeability:*** Measurement of the rate of flow of water through pores of the bricks was conducted using the funnel method. Funnels with the same outlet diameters and capacity were glued on top of each specimen by applying super glue and ash and then weighed. The same quantity of water was poured into each funnel after the glue had dried. At the end of a stipulated period, the remaining water in the funnel was thrown off and the assembly, (specimen and funnel), re-weighed. Weight gain over the time taken expressed in g/s is termed 'capillarity'.

APPENDIX I: Elevated Temperatures

TEST: Measurement of the effect of extreme temperatures on the strength of bricks.

PROCEDURE: Specimens were weighed before placing into refrigerator and oven. The refrigerator was regulated at ice point (– 4^0C) while before placing the specimens into the refrigerator they were wrapped in air tight polythene materials to prevent them getting direct contact with moisture. The oven on the other hand was regulated at intervals of 30^0C starting from 60^0C to 240^0C. Each set of specimens were removed from the refrigerator and oven after 24 hours, weighed again and crushed to obtain compressive strengths. The strengths obtained were then plotted against the different temperatures.

APPENDIX J: Scanning Electron Microscopy

TEST: Determination of the internal structure of brick specimens.

PROCEDURE: A representative portion of the specimen was glued to a stand. All the specimens were then placed into a gold plating machine. The specimens were fully gold plated because soil cassava starch and *makuba* are non-metals. Each specimen was in turn placed into the wormed up scanner which was set to varying levels of magnification. After the images were captured and special regions were covered in the monitor of the scanner, the results of each specimen was saved.

APPENDIX K: Strength Model Testing

$$M_s = 4ha/A(100 – a) + (4a +5d) \times 10^{-2} N/mm^2$$

Table 5.5: Strength Prediction at 7 days for SML - DDM

Levels	M_s	S_s	P_s	Remarks
0%	0.15	0.41	0.45	–
5%	0.71	0.41	0.43	–
10%	1.23	0.41	0.72	+
15%	1.72	0.41	0.94	+
20%	2.16	0.41	1.06	+

Table 5.6: Strength Prediction at 14 days for SML - DDM

Levels	M_s	S_s	P_s	Remarks
0%	0.30	0.83	0.45	–
5%	0.86	0.83	0.94	–
10%	1.38	0.83	1.05	+
15%	1.87	0.83	1.11	+
20%	2.31	0.83	1.21	+

Table 5.7: Strength Prediction at 21 days for SML - DDM

Levels	M_s	S_s	P_s	Remarks
0%	0.56	1.24	0.45	–
5%	1.01	1.24	0.96	–
10%	1.53	1.24	1.26	+
15%	2.02	1.24	1.31	+
20%	2.46	1.24	1.85	+

Table 5.8: Strength Prediction at 28 days for SML - DDM

Levels	M_s	S_s	P_s	Remarks
0%	0.60	1.65	0.45	–
5%	1.16	1.65	1.06	–
10%	1.68	1.65	1.52	+
15%	2.17	1.65	1.76	+
20%	2.61	1.65	1.94	+

Table 5.9: Strength Prediction at 7 days for SML - CPM

Levels	M_s	S_s	P_s	Remarks
0%	0.15	0.41	0.45	–
5%	0.71	0.41	0.64	–
10%	1.23	0.41	0.94	+
15%	1.72	0.41	1.12	+
20%	2.16	0.41	1.06	+

Table 5.10: Strength Prediction at 14 days for SML - CPM

Levels	M_s	S_s	P_s	Remarks
0%	0.30	0.83	0.67	–
5%	0.86	0.83	0.66	–
10%	1.38	0.83	1.22	+
15%	1.87	0.83	1.15	+
20%	2.31	0.83	1.13	+

Table 5.11: Strength Prediction at 21 days for SML - CPM

Levels	M_s	S_s	P_s	Remarks
0%	0.56	1.24	0.94	–
5%	1.01	1.24	1.22	–
10%	1.53	1.24	1.83	+
15%	2.02	1.24	2.04	+
20%	2.46	1.24	1.96	+

Table 5.1 12: Strength Prediction at 28 days for SML - CPM

Levels	M_s	S_s	P_s	Remarks
0%	0.60	1.65	0.98	–
5%	1.16	1.65	1.07	–
10%	1.68	1.65	1.96	+
15%	2.17	1.65	2.68	+
20%	2.61	1.65	2.71	+

Note: M_s = Model Strength

S_s = Standard Strength

P_s = Practical Strength