The Use of Rice Husk Ash (RHA) as Stabilizer in Compressed Earth Block (CEB) for Affordable Houses

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Abstract

Shelter is a basic human need for comfort and safety; however, Nigeria has a housing deficit of 17 million units. Modern construction materials are not affordable for most earners and have a significant environmental impact.

This research investigates the suitability of substituting locally available rice husk ash (RHA) for up to 50% cement stabiliser in compressed earth blocks (CEB) over three different curing times. CEBs with up to 30% RHA substitution were produced with enough compressive strength for load-bearing use in 2 and 3 storey buildings. They also met initial hygrothermal requirements.

Data from the mechanical and hygrothermal investigation were utilised in hygrothermal simulations for normal (eg bedroom, living room) and high relative humidity spaces (eg kitchen, bathroom) to establish likely issues with condensation (interstitial or surface) or mould growth on interior wall, which could affect occupant comfort and safety, or impair structure durability. Simulation was based on the tropical Savannah climate in Nigeria for full cavity and partially insulated cavity wall structures for CEB with up to 30% RHA substitution. 20% was the highest RHA substitution CEBs achieving acceptable results. In a full cavity wall structure, it was less likely to suffer condensation or mould (than in partial insulated cavity) but would benefit from treatment with a moisture retarding material if used in a high humidity space.

Thermal simulation of a free-running building indicated that thermal comfort with 20% RHA substitution CEBs achieved similar hours at 90% satisfaction as a concrete wall, so replacement would not lead to disadvantage for occupants.

In comparison to a typical concrete mixture (1 part cement, 2 parts sand, 4 parts aggregate) which contains 14% cement (dry mix), the 20% RHA substitution CEB had 8% cement (dry mix). This is a substantial reduction in a material which has high cost and environmental impact.

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Nomenclature

A	area (m^2)
Am	Köppen-Geiger climate classification for Monsoon climate
Aw	Köppen-Geiger climate classification for Tropical Savannah climate
b_m	moisture effusivity for moisture buffering test ($kg/[m^2.Pa.s]^{1/2}$)
BSh	Köppen-Geiger climate classification for Warm Semi-Arid climate
BWh	Köppen-Geiger climate classification for Warm desert climate
CEB	Compressed Earth Block
d	mean thickness of specimen (m)
d_θ	relative humidity difference
EP	External Plaster
EPS	Expanded polystyrene
f_b	compressive strength (N/mm^2)
FHA	Federal Housing Authority (Nigeria)
g	density of water vapour flow rate ($kg/m^2.s$)
G	water vapour flow rate through specimen (kg/s)
G_t	accumulated moisture uptake
GHG	Greenhouse Gases
k	thermal conductivity (W/m.K)
L	length (mm)
L_p	plasticity index (numerical difference between liquid limit and plastic limit)
LS	longitudinal shrinkage of the soil (mm)
m	mass (g)
m_r	reference mass (g)
MBV	moisture buffer value ($kg/m^2.\%RH$)
N/A	not acceptable
NAFDAC	National Agency for Food and Drug Administration (Nigeria)

NBRRI	Nigerian Building and Road Research Institute
NP	No External Plaster
OPC	Ordinary Portland Cement
p	vapour pressure
p_s	saturation vapour pressure (Pa)
PR	point of reference
PVC	Poly Vinyl Chloride
q	quantity of heat passing through a unit area (W/m^2)
Q	quantity of heat passing through sample (W)
R_D	gas constant of water vapour = 462 N.m/kg.K (BS, EN ISO 12572:2016)
RH	Relative Humidity
RHA	Rice Husk Ash
S	suitable
SD	standard deviation
t	time (s)
t_p	period (s)
T	temperature (^oC)
u	moisture content (kg/kg)
w_l	liquid limit (water content at which soil passes from the liquid to the plastic state)
w_p	plastic limit (water content at which a specimen ceases to be plastic when dried further)
V	volume (m^3)
W	water content
WAC	water absorption coefficient ($kg/[m^2.s^{1/2}]$)
WAR	water absorption rate
WWR	window wall ratio

Z	water vapour resistance, this is the reciprocal of the water vapour permeance (m^2.s.Pa/kg)

Greek Symbols

δ	water vapour permeability (kg/[m.s.Pa])
δ_p	water vapour permeability (kg/[m.s.Pa])
ϕ	relative humidity
φ	relative humidity
μ	water vapour resistance factor
θ	temperature (ºC)
ρ	density (kg/m^3)

1. Introduction

1.1. Background

Shelter is a basic need for humans (Sekhar C & Nayak, 2018). Essentially, it provides comfort and safety for the occupants. Quality housing enhances the health and wellbeing of humans. Design and construction details and service life of the building determines the house quality. Consequently, the construction industry has undergone changes in response to changes in the environment, lifestyle of the people, increase in population, cost of construction and other factors. The construction industry has contributed to the increased greenhouse gas (GHGs) emissions which are associated with global climate change. Globally, 24% of the raw materials are used in the construction industry; while the residential and commercial buildings use 32% of total energy and account for over 30% of green gas emissions worldwide (Tettey et al, 2017). In this context, it has been reported that cement is the most widely used man-made material and is the source of about 8% of the world's CO_2 emissions (Rogers, 2018).

However, the building industry has failed to reduce the housing deficit in Nigeria. The need to provide low cost houses in Nigeria cannot be over emphasized. Indeed, it was reported that the country's housing deficit grew from 5 million units in 1991 to 17 million units in 2017. Lagos alone, the country's commercial nerve centre, has an estimated housing shortage of 5 million units. Unfortunately, about 62% of Nigerians live below the international poverty line (UNDP, 2015), which makes it difficult for them to afford contemporary housing of the types prevalent in the developed countries. Over 90% of low-income earners cannot afford decent accommodation even if they saved 100% of their income for 10 years (Emmanuel, 2012). Doing that will be contravening the recommendation that affordable house rental cost or mortgage repayment should not exceed 30% of household income (including bills). In Nigeria the rental expenditure annually in cities amount to $216 whereas the average income of 90% of Nigerians is about $113 or $31 for more than 75% Nigerians (Olanrewaju et al, 2016). Also, Government's efforts at solving the problem of housing shortage proved futile because it ended in providing unaffordable houses.

It is noticed that construction materials accounts for 60% of the total cost of building construction, hence the use of cheaper and available suitable alternative materials could contribute to housing sustainability in future. The Nigeria Building and Road Research Institute (NBRRI) and Federal Housing Authority (FHA) in a collaborative investigation noted that cost of building construction was reduced by at least 40% with the use of local materials. In this regard, use of earth material in building construction may find useful application in the context of Nigeria (Olotuah, 2002). While the use of earth material may be of considerable value in low-rise building, it may be necessary to improve the strength and durability of such construction materials if they will be used in the construction of multi dwelling unit.

Several workers have confirmed that compressed earth block (CEB), an earth material, can be stabilized to improve on its mechanical properties (Donkor & Obonyo, 2015; Taallah & Guettala, 2016). The use of several agricultural waste products including rice husk ash (Antiohos et al, 2014), waste sugarcane bagasse (Kazmi et al, 2016b), palm oil fuel ash (Karim et al, 2013) sawdust or wood ash (Chowdhury et al, 2015), etc. as stabilizing agents has been reported in other building materials.

The current study is interested in the use of rice husk ash (RHA) as a stabilizing agent in CEB because of the huge investment of the Federal Government of Nigeria in rice production in furtherance of the shift of the economy from being dependent on the crude oil to agriculture. Consequently, the waste generation from rice processing industry would increase; and it should therefore be reused to avoid environmental pollution it would cause when not properly disposed.

Cost of cement has been of concern in the provision of sustainable housing. The material is used as a binding agent in compressed earth block moulding. Sourcing an acceptable alternative low-cost binding agent will significantly reduce cost of providing housing. RHA, like other sustainable pozzolans could serve useful application here (Kumar & Gupta, 2016). (Kazmi et al, 2016b) suggested that addition of RHA in fired brick manufacturing could lead towards sustainable and economical construction. A pozzolan is a siliceous or a combination of siliceous and aluminous materials. Independently, it possesses little or no cementing property, but in a finely divided form - and in the presence of moisture – it will chemically react with calcium hydroxide to form compounds possessing cementitious properties (Mehta et al, 1996). This suggests that the stabilizing strength of RHA in earth blocks will depend on the geochemical composition of the earth material used. The geochemical composition of the soil will vary according to the nature and mineral composition originating rock.

Apart from reducing cost, RHA’s utilization in construction will displace the use of cement in the construction industry thereby reducing environmental pollution. Also, it has lower embodied energy compared to cement hence its use will save energy cost (Mithra, 2015). RHA being a product of agricultural production will raise the farmers’ income. It will be worthwhile to see the possibility of replacing cement with RHA in CEB.

It is noteworthy to add that this study is a contribution to the academic literature on CEB/RHA as opposed to the less formal work or less rigorous academic work on

CEB/RHA. Although informal work has been reviewed, the findings of such work are not included in this study. This study focuses on the determination of suitability of CEB/RHA for wall construction in tropical savannah climate of Nigeria as a means of reducing building construction cost in the poor country for low-income earners.

1.2. Aim of the Study.

To investigate the provision of low cost, sustainable wall construction material in Nigeria by focusing on CEBs stabilized using pozzolanic agricultural waste.

1.3. Research objectives

The objectives of the study are to:

1. Investigate the proportions of laterite, RHA, OPC and sharp sand needed to produce RHA CEBs for walls in the tropical Nigeria.
2. Evaluate the mechanical and hygrothermal properties of the resulting CEBs and analyse them against wall construction requirements; and
3. Simulate the hygrothermal and thermal properties to evaluate indoor air quality and thermal comfort.

1.4. Scope and focus

This work is focused on establishing the suitability of RHA to reduce the use of cement for stabilising CEBs utilising lateritic earth for low-rise affordable housing in Nigeria. There may be potential for the findings to apply to areas with similar climate and soil type with rice agriculture.

1.5. Dissertation overview

Chapter 1 (Introduction) gives the background of the study, definition of problem the research sought to address; provides the justification for the study, and the research objectives. In addition, focus and scope of the work is given in this section.

Chapter 2 (Literature Review) gives a critical evaluation of the research problem, current materials used for masonry wall construction, and sustainable and affordable design principles required for the Nigeria’s climate. It shows critical analysis of the available pozzolans in the country, and most suitable mechanical and hygrothermal property for the climate selected by studying suitable material characteristics to be used to address the research problem in the form of review of literature.

Chapter 3 (Methodology) gives the detailed description of materials, design of the research procedure (i.e. experimental design), experimental procedures of laboratory tests, and statistical treatment to which the data obtained from the research was subjected. The detailed simulation process required for the materials tested based on the characteristics of the laboratory test.

Chapter 4 (Laboratory Results) reports the results from the various laboratory tests performed on RHA, laterite and experimental CEBs. The key mechanical and hygrothermal properties of the compressed earth block masonry unit as represented by statistical analysis carried out are highlighted.

Chapter 5 (Simulation Results) reports the results from simulation using WUFI PRO 5.3, WUFI Bio and Design Builder 5.5. The simulation results were analysed to evaluate indoor air quality and thermal comfort for the occupants of the residential house.

Chapter 6 (Discussion) presents the principles and relationships indicated by the results. It points out exceptions or any lack of correlation and defines unsettled points. Finally, it shows how the results and interpretations agree (or contrast) with the existing body of knowledge. Discussion of the theoretical implication of the research results and possible practical application is given in this section, also.

Chapter 7 (Conclusion & Recommendations on future research work) states the research problem, briefly summarises work done, and the highlights of results obtained. Finally, the conclusion drawn from the results are highlighted in this section. Also, recommendations on future research work are made.

2. Introduction

The large deficit of residential houses requires that the research concentrate on affordable and sustainable building material for wall. The literature review explains a mean to achieve wall material using local material with agricultural pozzolans to partially replace Ordinary Portland cement by stabilizing earth material.

An investigation of the cause that led to the large deficit of residential house is reviewed in this chapter. This process involves studying the urban population in each urban town, the income of government worker at each level and to understand that the low-income earner reason they cannot afford a safe house. The review aims to study a sustainable and affordable wall material to reduce the cost of superstructure, as materials cost about 60% of the whole building. The chapter investigates the traditional and modern means houses to improve on the conditions of the people by studying the design strategy for the climate to ensure comfort. The common wall material used in Nigeria was then studied, it was then established to use local material to reduce cost and improve sustainability of the material. The earth material was stabilized to ensure adequate mechanical and hygrothermal property. The most frequently used stabilizing material is the ordinary Portland cement (OPC), a review of some agricultural pozzolan was then studied to partially replace OPC. The design approach to be used for masonry unit for wall was studied to ensure a means to ensure indoor air quality and thermal comfort.

2.1. Housing in Nigeria – Types, Demand Challenge and Supply Strategies

The increase in urbanisation has changed the distribution of people across the world. Since 2018, over 55% of the world population live in cities and the proportion continues to increase. together with China, India and Nigeria the urban population accounts for 35% of the world urban population and Nigeria is projected to have additional growth of 189 million by 2050 (UN, 2018). The growing urban population has led to infrastructure problems and housing shortages, with over 863 million people globally, living in slums and informal settlements (Gan et al, 2017).

Meeting housing demand in Nigeria is yet to be realized. Energy and infrastructure are inadequate to meet the nations demand, yet the cement industry dominates the construction industry. Before the monopolization of cement in construction industry, most traditional homes in Nigeria were built with earth, which requires low cost and were self-built. The old traditional types are disappearing because of increasing modernization or urbanization. Urbanization affects the social relation, economic standard, life cycle energy consumption, and climate and environmental change.

The rate of population migration from rural to urban areas in Nigeria has continued to increase for some decades. For instance, in the early 1950s, there were 56 cities in the country with 10.6% total population. By 1963 it increased to 19.1%, by 1985 increased to 24.5% of total population and in 2019 the city population increased to 48%.

The statistics shown in Table 2.1. illustrates the population densities in cities across Nigeria. The cities with highest population density may need affordable housing unit to be increased vertically (medium rise buildings) in direction rather than horizontal direction (low rise buildings).

Table 2.1. Population of the top cities of Nigeria

Cities	Population	Area (km^2)	Density (population/km^2)
	Tropical savanna climate		
Lagos	9,000,000	1425	6,316
Ibadan	3,565,108	466	7,650
Kaduna	1,582,102	153	10,341
Benin	1,125,058	228	4,934
Zaria	975,153	88	11,081
Jos	816,824	70	11,668
	Tropical monsoon climate		
Port Harcourt	1,148,065	158	7,266
Abia	897,562	91	9,863
	Warm semi-arid climate (Bsh)		
Kano	3,626,068	1965	1,845
	Warm desert climate (BWh)		
Maiduguri	1,112,449	155	7,177

©***World population review (Worldometer, 2019)***

The population of top 10 cities have been divided according to the climate in the country, from the observation 6 of the cities are located at the tropical savanna climate. The proposed affordable and sustainable design for wall material will be for the growing housing deficits.

This rise in population in cities has also led to acute shortage of dwelling units which resulted in overcrowding, high rent, poor urban living, low infrastructure services and high crime rate. Public housing provision in the country has continued to lag behind the housing demand (Ugochukwu & Chioma, 2015). The authors attributed the lag to the following reasons:

a. Absence of proper monitoring and evaluation of public housing policies;
b. Lack of access to land and other housing inputs;
c. Cost of imported material; and
d. Failure to generate tangible and sustainable housing production, particularly for low-income earners.

In a bid to find solution to housing deficit in the country, the Nigeria Building and Road Research Institute collaborated with Federal Housing Authority to compare the cost of using local materials (earth) with conventional materials (Fired earth bricks, and Sandcrete blocks) for the provision of affordable homes. The rule of thumb states that for a house to be affordable for low income earners, the cost shouldn't be more than 30% of the house income (Adabre et al, 2020). The cost of constructing a terraced single storey building with local and conventional materials was calculated to be $2717 and $14493, respectively, the US dollars have been used instead of local currency to ensure applicability internationally. In addition, the authors affirmed material constitutes about 60% of the total cost (Olotuah, 2002) and using local material can bring the total cost to approximately 50%.

The Nigeria's housing deficit was estimated at 16-17 million units as at 2015. Also, it was estimated that it would cost approximately $97,223,000,000 to fund 14 million units, an average cost of $ 6944.50 per housing unit. Meanwhile, Salary Grade Level government workers shown in Table 2.2 revealed that workers at the Director Level could comfortably afford a 25-year mortgage to buy a property costing $13194.55, whereas a more typical graduate post (Levels 8 to 9) would proportionately only be able to afford a mortgage on $2368 – significantly lower than the projected cost (Ugochukwu & Chioma, 2015).

Government workers in the Director status on Salary Grade Level 17 are in the top workers in the Public Service and are in the minority. Most of the workforce earn less, could not afford to pay mortgage and thus needing affordable housing. Consequently, the current research has focused on reducing cost building construction using cheaper and locally available materials to provide affordable housing.

Table 2.2. Income of Government Workers in Nigeria

Salary Grade	Salary per month ($)	Per year ($)	Affordable 25 yrs. mortgage ($)
Level 01	52.50	474	
Level 02		514	
Level 03		552.68	
Level 04 (School leaver)	56.25	606.37-661.01	
Level 05		693.22	
Level 06 (Officers)	73.20-112.80	860.24-1325.59	
Level 07 (Diploma certificate holder)	117.42	1409.02	1253.51
Level 08	220.34	2662.25	
Level 13-14	3261	2913.54-3194.27	
Level 15 – 17	1235.95	14831.42	13194.55

©Federal civil service commission salary structure (Chizoba, 2019; Gberevbie, 2010)

2.2. Traditional and Modern Architecture and Types of Housing in Nigeria

Traditional architecture has been an inspiration for innovation in socio-economically sustainable design and environmental planning especially in residential housing. The techniques have resolved some climatic and environmental problems caused by the modern construction. The design has harmonized nature and the built environment by providing a comfortable living environment. It can be defined as the unconscious realization and embodiment of the society with requirement for the people in nature. Traditional architecture has successfully maximized the natural terrain potentials (natural occurring materials, architecture design considering the climate conditions etc.) in its design and method of construction (Alabsi et al, 2016). The techniques used in some of the traditional architecture are currently used in present day passive designs, zero carbon energy design, low carbon design, and more.

In developing countries, it can be seen with modernization of the construction sector the traditional knowledge that previously underpinned climate responsive vernacular design is rapidly declining. Modern design pays little attention to local materials and traditional method of construction. Vernacular architecture provides strong local content both in traditions, materiality, building skills and methods. Traditional architecture buildings are built with material within 360 m of their location due to the cost and difficulty of transporting over long distance. Local materials selected are reflective on local climate and leads to significant saving of embodied energy (Alabsi et al, 2016; Kırbaş & Hızlı, 2016).

Construction with earth material is increasing due to the environmental awareness. It is estimated that two billion people are living in earth dwellings and 10% of the world heritage buildings have earth structures. Earth material has an advantage of being infinitely recyclable (without stabilizing), requiring minimum technology and no intensive energy for production, it is inexpensive and can generally be sourced around the site saving the impact and cost of transportation. It also performs well hydrothermally due to its relatively low thermal conductivity, large thermal and hydric mass and strong breathability (easy water transport). These factors ensure good comfort, remarkably small-embodied energy and light environmental impact. In addition to providing dwelling, it has the potential of solving the production of affordable housing. It is labour intensive compared to fired-clay bricks (Abd Rashid & Yusoff, 2015; Darko et al, 2017; Van Damme & Houben, 2017).

The demand for sustainable construction at low cost is growing as a process of resolving social, economic and environmental issues.

2.2.1. Northern Nigeria traditional architecture

The Hausa-Fulani's who essentially are nomads predominantly inhabit the northern Nigeria. They are mainly Muslims and their Islamic faith accommodates the polygamous family system. The northern Nigeria architecture, therefore, has reflected the culture, climate, social/ economic status and materials in the region as indicated below.

a. **Culture:** The Islamic faith encourages segregation of female and male (Figure 2.1). They are also engaged in ornamentation and agriculture, which reflects on the façade of the buildings (Figure 2.2).

b. **Climate:** Northern Nigeria has the vegetation of the equatorial desert characterised by little rainfall and extreme temperature difference between the day and night-time; and bright sunshine, hot and dry air during the daytime and during the night-time extremely cold. The wind direction is mainly from the North–eastern (Sahara Desert) and some from South-western (Atlantic Ocean) and average speed of 2-3m/s. The average ground temperature is about 29-30^{o}C annually, relative humidity has an average of 12-29% from Oct-May and 45-59% from June-Sept (Meteonorm 7.2).

   The traditional approach to achieving an adequate comfort level in a residential house is to incorporate a shaded courtyard, open interior, opposite openings to allow cross ventilation, flat roof (lightly coloured to reflect heat), and window overhangs to provide shading and minimize glazing at the west facing facade. Enough north glazing is provided to balance day lighting and cross ventilation(Moughtin, 2013; Oluwagbemiga & Modi, 2014).

The house design has also undergone some changes because of colonialism; movement to a more urban area; and separation of the extended family within a compound. That is, making allowance for smaller unit living in the compound.

c. **Social / economic**: There has been a growing preference for a more modern style of living over the traditional styles. However, there are still several Hausa that are nomads.

d. **Materials:** The traditional materials have been abandoned for manufactured, processed or fabricated materials. Traditional materials were mainly earth, timber, reeds, grasses and stones (Oluwagbemiga & Modi, 2014)

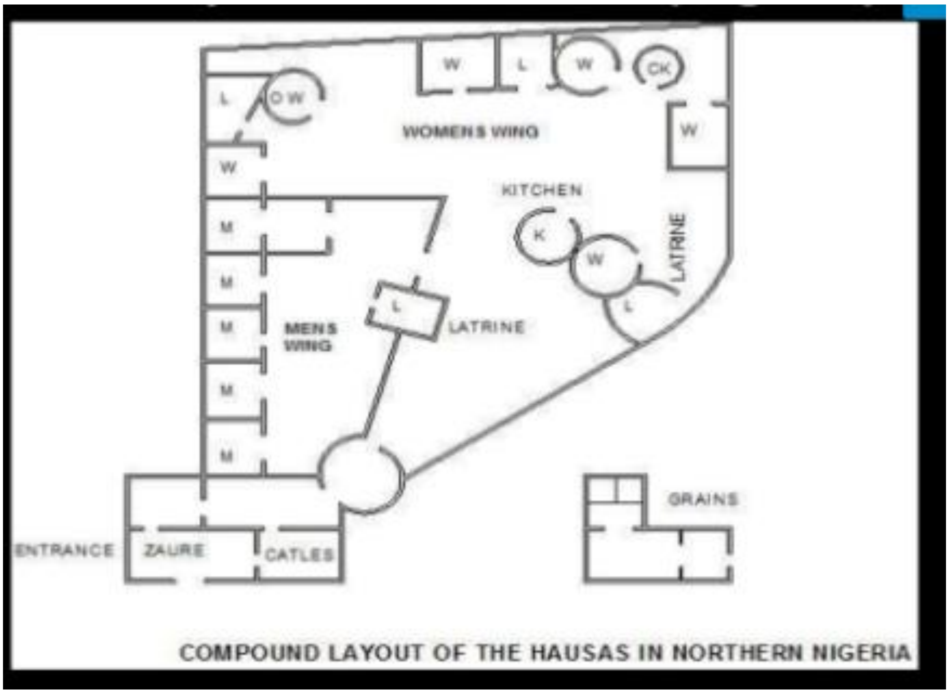


Figure 2.1. Layout of Northern Living quarters showing separation of men and women©(Moughtin, 2013)

Figure 2.2. Ornamentation of building Facade in Northern House ©Wikipedia, Hausa people.

2.2.2. Southern Nigeria traditional architecture

The Yoruba people are the predominant ethnic group inhabiting the south-western part of Nigeria. The architecture of the region is influenced as described below:

a. **Climate:** The region records average 26-28^{o}C temperature and 75-90% relative humidity annually, and predominant rainfalls. (Meteonorm and Climate consultant).

b. **Design Approach:** Architecture style of the Yoruba people is a courtyard, cuboid or rectangular form of compound. The rooms are rectangular and arranged in a linear pattern. The household leader has his room at the front of the house to provide a form of security, boys rooms are at the corner. The wall surface is made of courses of mud mixed with vegetative material such as straw and adhesives. The ceiling made of palm fronds or split bamboo. Mud is then placed on the palm fronds to use as a decking material. Construction takes place during dry season to accelerate curing. The bedrooms and storage areas have small windows to allow light and air, providing a comfortable living environment. The veranda is opened to allow light and air, while shading openings. The cooking activity is performed outside (Adedokun, 2014).

There are two house types that characterise the southern region of Nigeria as depict below:

i. **The first house type** is built around one or more courtyards. The type of family system within determines the form of the house. The compound has an open plan with a single entrance, rooms facing the courtyard.

ii. **The second house type** is a new concept that became popular in 1930s when the earning from coca, palm oil and other agricultural produce made people travel for work purposes. The house has no compound and has a central corridor with series of unconnected rooms (rooming house). The wall construction of this type of house was compressed earth blocks, some of which were used without stabilization. The design was to provide housing rental accommodation at reasonable cost for the immigrants from rural to urban area (Okeyinka, 2015).

The second house type of Yoruba architecture (rooming style) is depicted in Figure 2.3. The building has a raised ground level with a solid concrete foundation to prevent water or moisture from penetrating into the interior of the building. Furthermore, it has a veranda that the occupant uses as a sit out area. There is a long corridor with rooms along the building.

Figure 2.3. Type 2 rooming house - Southern Nigeria © (Adedamola Ojerinde,2018)

2.2.3. Integration of Modern architecture in Nigeria housing styles

The houses that integrate modern architecture in Nigeria are dependent on the income of the household. Some of the houses are privately built to architectural taste and requirements, while some developers construct houses in private gated estates. Low-income earners mainly live in government provided houses or rent from private developers. Contrary to the traditional architecture of Nigeria, these modern houses are not designed with relation to the microclimate. The difference between the houses in the northern and southern Nigeria in modern architecture is mainly the size of the building. The same type of materials and design strategies are commonly used. Figure 2.4 shows the samples of integrated modern architecture in Nigeria.

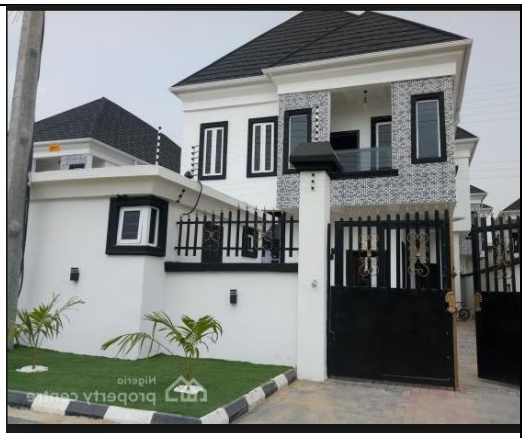
	
Bungalow	Duplex
	
Town house	Apartment house

Figure 2.4 Modern Residential Houses in Nigeria

2.2.4. Housing Demand and Supply Strategies Challenges in Nigeria

2.2.4.1. Affordable and sustainable building design

In Nigeria building materials are estimated to cost more than half of the total expenditure on housing construction. Most building developers insist on using conventional materials and technology, thus increased cost of housing provision. Nigerian buildings tend focus on the aesthetics rather than the physiological needs, the designs replicate European styles in terms of shape, windows positions and openings even with different climatic conditions, leads to dependant on mechanical devices for comfort (UN-Habitat, 2011).

African architecture has not been documented scientifically in terms of the design, constructions approach but can be deduced to have good durability property based on the long life of traditional existing buildings, which satisfies thermal comfort, aesthetic and sustainability. African architecture technology has been regarded as primitive when compared to western technology used for the construction of skyscrapers. However, there are buildings in ancient towns of Kano and Zaria in Nigeria that have lasted over 100yrs. Those buildings are affordable and comfortable with little carbon footprint. The introduction of modern technology has relegated traditional component (Akadiri, 2015; Ugochukwu & Chioma, 2015).

Affordable construction has been identified as requiring low embodied energy. Operation Energy consumption has increased in the recent years as a result of fast urbanization, continuous industrialization and improved living standards. Understanding the concept of affordable construction is predicated on understanding of the terminologies: embodied energy; life cycle energy; operating energy; affordable housing; and sustainability (environmental and social). The terms are defined as follows:

a. **Embodied energy:** It has been defined as the sum of primary energy consumed in constructing a building using construction materials, products and processes along with related transportation, administration and services. **Life cycle energy** is the sum of embodied energy, operational energy and decommission energy (Cabeza et al, 2013; Dixit, 2017).
b. **Operating energy:** It is the energy expended in maintaining the inside environment through process such as heating and cooling, lighting and operating appliances *(Cabeza et al, 2013).*
c. **Affordable housing:** usually refers to housing for people whose income is not enough to have access to appropriate houses at market value. It is important to include economical sustainability factors in order for the low-income earner to afford the house proposed. It therefore means considering the initial and future cost, transport cost and energy bill (Gan et al, 2017).
   Sustainability is generally elaborated as a development that satisfies the needs of the current generation and not at the cost of compromising future generation (Aste et al, 2017; Gan et al, 2017).
d. **Environmental sustainability** considers energy efficiency, water efficiency, effective utilization of resources, efficient water management, comfortable and healthy environment, reduction of footprint to minimize the biodiversity loss, climate change and mitigation of greenhouse gas emission. (Aste et al, 2017; Gan et al, 2017; Walsh et al, 2017). Selection of a wall material that is environmentally sustainable and doesn't compromise the economic sustainability such as local earth material is best.
e. **Social sustainability** is another important factor in sustainability. It emphasizes the equal distribution and consumption of housing resource with special attentions to horizontal equity and vertical equity. Vertical equity refers to equal treatment of people in unequal position, horizontal in equal treatment of people in equal positions (Aste et al, 2017; Gan et al, 2017; Walsh et al, 2017).

Reduction of building energy consumption will require a radical change in building design procedure. A well designed building can support the local based economy by using on site material as well as local labour forces (Aste et al, 2017). Unfortunately, too, there is infrastructure deficit in Nigeria. The infrastructure including energy is inadequate for the growing population that live in the urban areas. Almost all Nigerian home has to provide water (borehole unit), generate electricity and construct drainages around their compounds. (Ugochukwu & Chioma, 2015) identified the following challenges encountered in the delivery of affordable houses in Nigeria:

a. **Poor promotion of security tenure:** Government would have to provide incentives that encourages families to invest in their homes and communities.
b. **Inadequate supply of affordable land:** Scarcity of land has led to escalation of land prices, overcrowding of existing sites, illegal invasion of vacant land, and growth of squatter settlement.
c. **Poor infrastructure and services:** It make procurement of infrastructure by individuals difficult and unaffordable because it is very costly
d. **Utilization of local building materials and technologies**: The use of conventional materials has led to reduction of skilled artisans for traditional construction and disappearance of the buildings.

The Nigerian Government has gone through different phases since the independence of the country in 1960. Although several of the administrations have committed to providing housing for the general public, relatively small numbers of houses have been built (Olayiwola et al, 2005) and are summarized below:

a. **Colonial period (1800-1960):** The Government made no effort to provide houses to rent for the general public
b. **Post-independence period (1962-68):** The Government planned to provide 24000 housing units, however, only 500 houses were provided before the civil war in 1967
c. **The second National Development Plan (1970-1974):** The Government only provided 90 staff quarters and 4 blocks of flats for the Ministry of External Affairs
d. **The third National Development Plan (1975-1980):** The Federal Government planned to build 200,000 housing unit in 5 years. Less than one-eighth of the houses were built.
e. **The fourth plan period (1981-1985):** The Federal Government committed to building 200,000 housing units. However, a military coup occurred in 1986.
f. **Post fourth plan period (1986-1998):** The mass housing scheme was terminated until 1991. In 1994-95 121,000 housing units were to be constructed for all income groups. Unfortunately, the project was not completed due to the following reasons:
    i. Problems from site acquisition
    ii. Exorbitant contractual procedures
    iii. Inflation of labor cost

iv. Budget reduction and improper phasing of the infrastructure and housing construction
v. A slow rate of construction
vi. Lack of material choice
vii. Inadequate building and construction technology

g. **Democracy 1999 till 2005:** The Government completed 500 housing units in Abuja. In addition, partnered with private investor developers to provide 1,127 units in Abuja and Port Harcourt. Furthermore, construction resumed at previously abandoned sites in Lagos.

h. Current 2**005**-2019: the government established a mortgage payment that requires 30% of the cost as down payment for a 10-year load. The cost is not affordable for most government workers (Wallace and Adeleke 2019).

2.2.4.2. Vertical vs Horizontal buildings

Residential buildings can be categorized into high rise buildings (more than 10 storeys); medium rise buildings (3-6 storeys); and low-rise buildings (1-2 storeys). The present high-rise building evolved as a result of technology, utilities and services including stair way shaft, elevator shafts, air conditioning system, communication system, electrical power, water supply and gas system (Craighead, 2009).

Construction of high-rise building demand a huge capital, requires massive energy and mechanical services, which increase the cost of running the building. Tall buildings accommodate many people on a smaller area of land than low rise building for the same number of units. High rise buildings create open land that can be used for communal facilities such as libraries, sport areas and parks (Craighead, 2009).

There is shortfall in energy generation in Nigeria, hence the country is unable to meet the energy needs of the urban cities. Although high rise buildings, could be the fastest route to solving the housing deficit problem, they require more energy for mechanical services so will not be of use here.

Table 2.3: Number of housing unit/ net hectare provided by different types of houses.

Units of housing/net hectare	Type of housing
25-40	Single family house
50-100	Multi- storey town houses
120-250	Multi- storey Apartment blocks
1000	High- rise Apartment blocks

Table 2.3 shows the number of houses in a single hectare depending on its vertical measurement. Low rise can accommodate a smaller number of families which might not be adequate for a dense urban city. The shortage of houses in Nigeria is about 16-17 million units - providing low rise buildings will create a large urban spread, which would reduce the natural vegetation and energy efficiency of the towns that is required for vertical transportation in such buildings. Land is a scarce commodity in urban city, Arable land area is constantly threatened by urban spread. Low rise housing does not ensure adequate utilization of this resource for sustainable housing (Adabre et al, 2020).

From the foregoing, medium rise (3-6 storeys) buildings appear to solve the housing deficit in the country as they accommodate more people, reduce the urban spread, and do not require particularly high energy for vertical transport. The reason medium rise buildings up to 4 floors are suitable to provide house in a dense city and to manage the scare land available in the city.

2.3. Building element requirements and passive design strategies

2.3.1. Climate and Passive design strategies

As described, A building is to perform the function of regulating the internal thermal comfort in response to the external climate condition. High quality building construction is not only question of aesthetics, but also, it is a question of function, construction, economy, ecology and the wellbeing of the users (Hall et al, 2012). Thermal comfort is subjective but can be expressed as the condition of mind where the occupant experiences satisfaction (Taylor et al, 2008). Improving sustainable materials in order to improve its durability property in order to encourage the use in the construction industry is paramount in order to mitigate the adverse effect of other building materials. The construction industry worldwide is encouraged to use materials, designs and construction methods that improve the energy performance of buildings especially as the industry accounts for 40-50% world energy consumption (Xiao et al, 2018). Developing countries are growing and would therefore require a further increase in energy use. To avoid the energy requirement (and occupant expenditure) of heating and cooling services, passive design strategies should be employed (Ashour et al, 2015).

The temperature and relative humidity of the space affects the level of comfort for the users. To ensure the correct passive design strategy, weather data can be super imposed on a bioclimatic chart showing passive strategy options (an example is shown in Figure 2.6).

The application of passive design strategies in finding solution to housing deficit and provision of sustainable houses for the low-income mass of Nigeria population would require knowledge of the geographical location, soil and climate of the country. Nigeria, a

West African country is on Latitude 4-13ºN and Longitude 2-14ºE. It covers 923000km^2 land area. The topography is mostly flat in the south and some elevated areas and mountains in the northern part of the country (World, 2020). The lowest elevation is 0m near the Atlantic Ocean in the south and highest elevated area of 2419m at the north-eastern part of the country.

The Köppen-Geiger classification system indicates four climates across Nigeria: tropical savanna, monsoon, warm semi-arid and warm desert climate shown in Figure 2.5. The map in Figure 2.5 shows about 75% of the country has Köppen-Geiger classification tropical savannah climate (Aw).

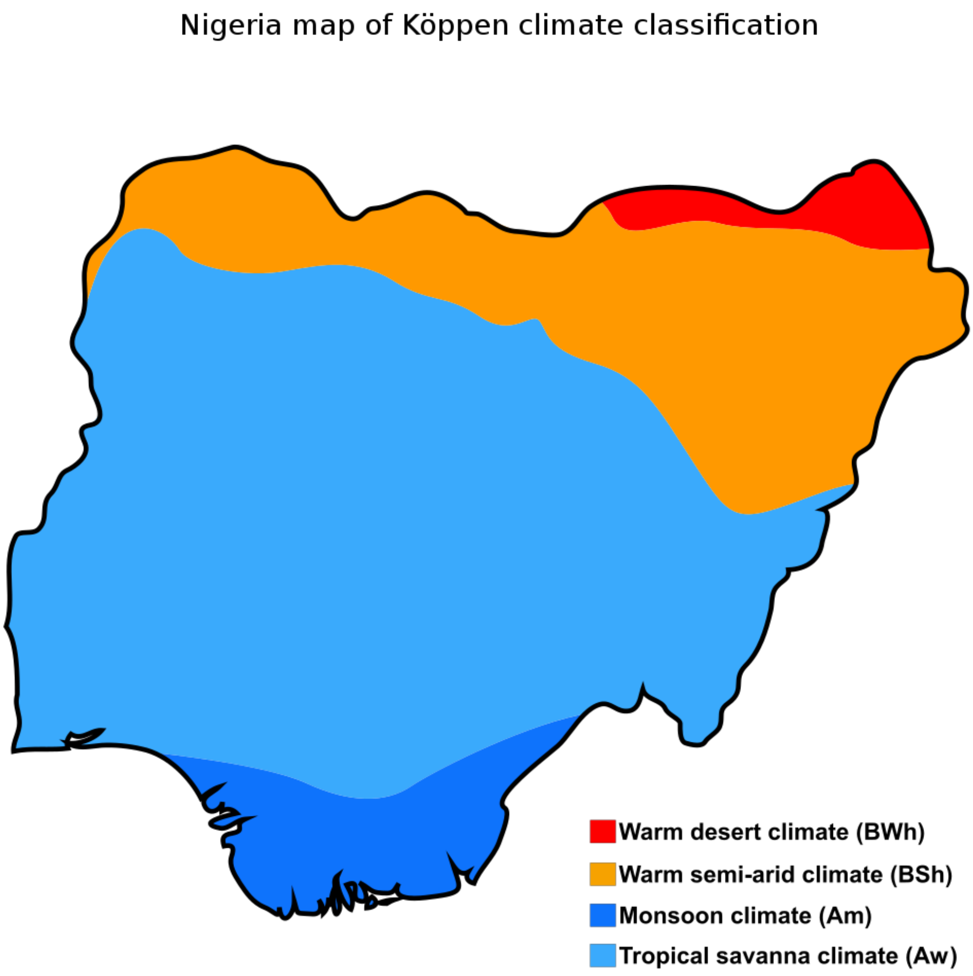


Figure 2.5: present and future Köppen- Geiger climate maps at 1 km resolution of Nigeria. Nature scientific data(Beck et al, 2018)

The main group and corresponding subgroup in the country includes the tropical (Am and Aw) and dry (BWh and BSh). The Köppen climate classification of Nigeria are explained below.

a. Tropical climate:

- Monsoon climate (Am): This region has short dry season. The driest month has less than 60mm rain, the average monthly maximum is 380mm and minimum is 20mm. The maximum temperature in this region is 28-33^{o}C, minimum temperature 18^{o}C. The relative humidity of the area is 58-80%.
- Tropical savanna climate (Aw): the driest month experiences less than 60mm rainfall, the rainy season starts around April to October. The mean temperature 28-32^{o}C with its peak in February and March (Fasona et al, 2013). The relative humidity is about 80-85%.

b. Dry climate:

- Warm desert climate (BWh): the climate experiences long hot summers, warm transitional season and short , mild chilly winters with mean temperature of equal or greater than 18^{o}C (Wang et al, 2019), The relative humidity is about 15-65%.
- Warm semi- arid climate (BSh): most of the area experiences less than 500mm rainfall annually(Engelbrecht & Engelbrecht, 2016), the maximum temperature ranges from 30-36^{o}C . The relative humidity is about 25-80% annually.

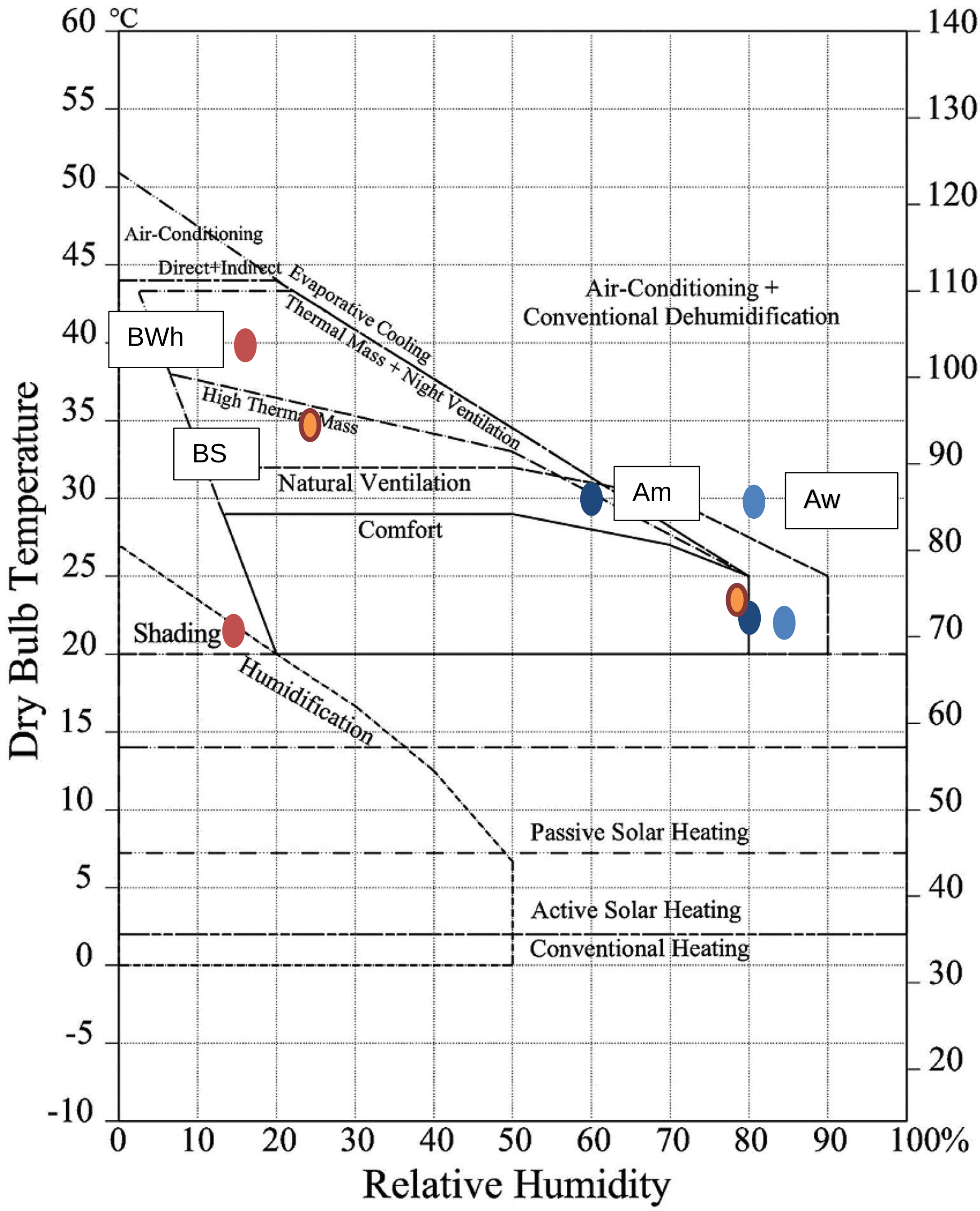


Figure 2.6. Nigeria max temperature for dry and rainy seasons climate data (Am, Aw, BWh, BSh) superimposed on bioclimatic template (Givoni, 1992; Roshan et al, 2019). NB: The comfort band is based on Givoni's work which applies to developed countries

The chart in Figure. 2.6 indicates the appropriate passive strategy for dry and rainy seasons of each climate (based on mean data):

i. Monsoon climate (Am): the position of monsoon climate on figure 2.6 shows that the passive design strategy required for this area is natural ventilation.

ii. Tropical savannah climate (Aw): the position on figure 2.6 shows that it requires natural ventilation for its user to achieve thermal comfort wet season. The use of air conditioning and conventional dehumidification is indicated for the other season, but it should be noted that the comfort band on figure 2.6 is not based on an acclimatized population. The comfort band is higher in this region.

iii. Warm desert climate (BWh): the design for thermal comfort to be achieve is shading, thermal mass with night ventilation and evaporative cooling.

iv. Warm semi- arid climate (BSh): the design for thermal comfort to be achieved is buildings with high thermal mass and evaporative cooling.

Most of the country falls in the tropical savannah climate (Aw) and monsoon climate (Am) which require shading and natural ventilation. Natural ventilation is adequate when maximum temperature is approximately 34 ^{o}C, average 32 ^{o}C, wind speed 1.5 m/s and relative humidity between 30-90% (Khambadkone & Jain, 2017). Natural ventilation can be accomplished by façade openings, solar chimney, wind catcher and atrium.

The northern part of the country warm desert climate (BWh) and warm semi-arid climate (BSh) require shading and high thermal mass (in combination with night ventilation for the warm desert climate area. Earth blocks can be used as a thermal mass material.

The comfort band based on the mean temperature for Nigeria with 80% comfort is approximately 23-30 ^{o}C and for 90% 24-29 ^{o}C (Toe et al, 2010). Adaptable comfort level of approximately 80% can be achieve at air speed 0.1-0.2 m/s. Air speed of about 1 m/s for temperature above comfort limit of 30 ^{o}C can provide adaptable comfort level. ASHRAE Standard 55-2013, comfort level can be expanded by 2-3 ^{o}C when air movement is 1-1.5 m/s for air temperature and relative humidity boundary is 90% (Khambadkone & Jain, 2017).

2.4. External wall material options and their properties

The wall, in addition to isolating the interior condition from the exterior condition, act as a structural support for the load imposed by any suspended floor and roof. Walls can function as load bearing, bracing or non-load bearing element in a building. Load bearing walls transfer force to the foundation by itself, whereas bracing walls (also known as shear walls) resist wind loads and any horizontal impact loads that are encountered. Non-load bearing wall can be classified as walls that provide enclosure, which needs to transfer its load or force to the load bearing walls, which in turn is transferred to the foundation. Load bearing walls and non-load bearing walls protects external element at the same time giving room for openings within them to provide light and ventilation depending on the requirement (Berge, 2000). Material options for the construction of external walls and their properties for low cost housing in Nigeria are reviewed in the following sections 2.4.1.-2.4.4 with a summary in 2.4.5.

2.4.1. Fired bricks

Clay is a widely available raw material, which can be used to produce bricks. Characteristically, it is suitable for brick because it could be moulded and shaped, it has enough tensile strength to keep its shape and it fuses together when exposed to adequate temperature. Clay occurs in the forms of surface clay, shales and fireclays. Surface clay are found close to the surface of the earth, shales are clays that have been subjected to high pressure and have become hard and fireclays are found at deeper levels. The most important characteristic is its ability to withstand high temperatures. Clay is a complex material but mainly composes of silica and alumina with varying quantity of metallic oxides and other ingredients. Clay can be divided into two main types. That is, calcareous clay (has 15% calcium carbonate and burns to yellowish colour), and Non-Calcareous clay (contains silicate of alumina, with feldspar and iron oxide 2-10%, with burning colour of red, buff or salmon)(Lyons, 2014).

Brick can be classified according to use:

- Common bricks have acceptable strength, water absorption durability, thermal and moisture movement. They are cheap to produce but have poor appearance.
- Facing bricks are more expensive, have better appearance and are better to use in exposed area. They have similar performance to common bricks.
- Engineering bricks are stronger than common or facing brick. They have low moisture absorption but are more expensive than common bricks. They are used where enhanced strength and low porosity is needed (Lyons, 2014).

The manufacture of clay brick can be done through three stages: excavation and preparation of the raw material; forming the shape required; and drying and firing. The process is illustrated in Figure 2.7 and explained below:

i. **Excavation of clay:** Mined material is checked for impurities before use to determine the active soluble salts content of masonry (Lyons, 2014). It quarried crushed, screened to remove stone and other debris, mixed with water and then passed through a pug mill to produce uniform clay of high plasticity (Charlett, 2013).
ii. **Forming the shape:** Shaping is made manually or by using machine. If done manually, the lump of clay is put into wooden mould that have been lined with sand or sawdust which have relatively irregular shaped and dimension. The machine or alternative clay is formed through a die and cut and shape into dimensions needed by stretched wires. Clay needed to be moderately stiff (Lyons, 2014).
iii. **Drying and firing bricks:** Firing temperature is usually around 900ºC. The bricks are dried prior firing otherwise they will crack when exposed to high temperature within the kiln. Finally, bricks are cooled by incoming air needed for combustion. (Charlett, 2013; Lyons, 2014).
iv. **Manufacture of calcium silicate:** It is manufactured with sand, flint mixed with quick lime or hydrated lime and water in protein to proportion of 10 parts sand or flint to 1-part quick lime or hydrated lime mixed with pressed steel in mould and then autoclaved

for 12h in steam oven mould at 170^{o} C temperature and 10 atmospheric pressure. It forms CO_2 when exposed to air forming calcium carbonate which provides strength and hardness. (Charlett, 2013; Lyons, 2014).

v. **Manufacture concrete brick:** It is manufactured from concrete having dense aggregate to BS EN771-3:2011. Mixture is placed in steel mould and autoclave with high pressure like calcium silicate bricks. (Charlett, 2013; Lyons, 2014).

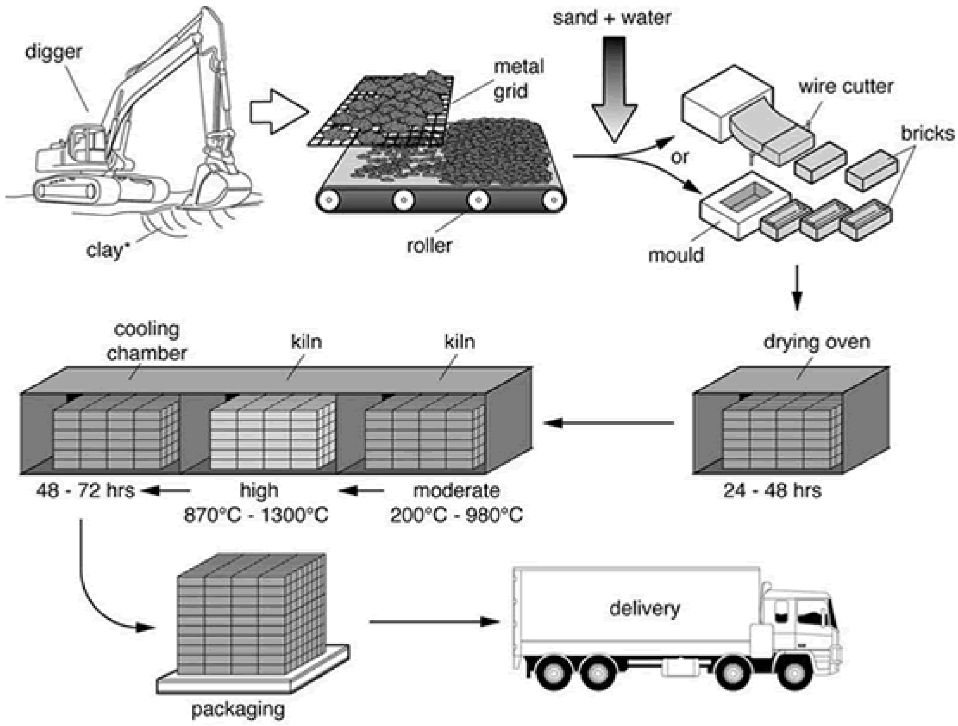


Figure 2.7: Brick production process (Suryakanta 2014)

Properties of fired clay cricks:

The properties studied includes compressive strength, water absorption, durability, thermal and moisture movement, thermal conductivity, sound insulation, fire resistance, density, appearance and sustainability. These properties are factors that ensures adequate structural safety, thermal comfort and, indoor air quality

Compressive strength.: ranges from 5-100 N/mm^2 at firing temperature of 1100 ^{o}C for fired clay bricks and calcium silicate bricks 5-75 N/^{2} (Bodian et al, 2018; Dai et al, 2019; Lyons, 2014; Phonphuak et al, 2019).

Water absorption is dependent on the type of brick and method of manufacture. Most common fired clay bricks have absorption 7-26%, calcium silicate have 8-15% depending on the size and distribution of the pore while water absorption for engineering bricks is 4.5% and class b is 7% maximum (Baden-Powell, 2011; Charlett, 2013; Dai et al, 2019).

Durability is affected by the water absorption of the brick, but clay is mainly affected by soluble salt, which could cause staining or efflorescent. Unburnt brick is less durable than fired brick. Engineering clay bricks have the best durability. Calcium silicate and concrete bricks are not affected by soluble salt like clay brick (Charlett, 2013).

Thermal and moisture movement: moisture movement is negligible in burnt bricks, but thermal movement is 0.3mm/m. It is advisable therefore to incorporate 10mm expansion joint protected by plastic sealant for every 12m wall not broken by door or window. Moisture movement is higher in calcium silicate and concrete bricks, so it is recommended to have 10 mm expansion joint at every unbroken 7m wall.

Thermal conductivity of fired clay bricks depend on the density and position, but typically ranges from 0.43 to 1.4 W/m.K and calcium silicate (0.6-1.3 W/m.K) with thickness of 100-102.5 mm (Charlett, 2013; Engineering, 2002; Lyons, 2014).

Sound insulation: Most bricks have good sound reduction values ranging from 44 to 57dB (Binici et al, 2009; Charlett, 2013; Hegger, 2006).

Fire resistance: The resistance of clay bricks has fired resistance up to 1-4 hrs. Calcium silicate provides resistance up to 3 hrs. Concrete bricks have high resistance also (Charlett, 2013).

Density: The density of bricks varies from 1600 to 2100 kg/m^3 (Ashby, 2013).

Appearance: Clay is usually faced with sand or colouring of natural pigment of clay. Calcium silicate is usually off white or pale pink in colour, smooth finish but textured can be available. Concrete has slightly rougher surface and can be available in smooth rustic or weathered finish (Charlett, 2013; Hegger, 2006).

Sustainability: The recycle fraction in current supply 15-20% (Ashby, 2013). During the production of clay bricks, the emission of carbon dioxide and other pollutant like sulphur dioxide is emitted to the environment and embodied energy for bricks is approximately 200-220 $KgCO_2$/ tonne(SFGB, 2011; Torgal & Said, 2011). Well-constructed clay bricks have long life span (50+ years) (Maia de Souza et al, 2016; Thomas & Ding, 2018; Udawattha & Halwatura, 2017) and low maintenance. The use of Portland cement requires high level of technology and skill for production.

In summary, brickwork has the advantage of being: locally sourced; able to withstand high temperature in case of fire outbreaks; amenable to different product sizes and finishes, and can be made for different uses (i.e. Engineering, decorative and regular use). However, it has drawbacks because it requires more energy, high technology would require this material high cost for production of low-cost housing with the material.

2.4.2. Blockwork

Blocks are made from either clay or concrete. Clay blocks are available in three width variation of 62.5, 75 or 150 mm wide. The 62.5mm and 75mm thick blocks are used for non-load bearing application (Charlett, 2013).

Concrete blocks are made from dense, lightweight or aerated concrete. Lightweight or aerated concrete is used for internal leaves of cavity walls or internal partitions; it has good thermal expansion, sound insulation as a result of the air voids within (Kalpana & Mohith, 2020). The size ranges from 370 to 590mm length, 140 to 290mm height and 60 to 250mm thick. Concrete blocks are made from a mixture of Portland cement and aggregates. It can be designed to be hollow, cellular, sound absorbing, insulating or solid blocks.

Blocks have unique characteristics including:

i. Light weight compares to bricks
ii. Are comparatively cheap to produce and lay, giving economical walls compared to brickwork
iii. Have better thermal resistance than brick
iv. Accept nails and screws more readily than brickwork
v. Can be supplied with a keyed or textured surface for the application of plastered rendered finish (Charlett, 2013)

Manufacture of concrete block has mixture of cement, appropriate aggregate and water. The mixture is put into a steel mould compacted by pressure or vibration, demoulded immediately and left to cure either naturally or artificially. Aerated blocks are made from sand, pulverised fuel ash, cement and aluminium powder. Like most concrete products, concrete blocks shrink as they cure.

Properties of the blocks:

Compressive strength: The minimum compressive strength for clay block is 1.4 N/mm^2 for non-load bearing and 2.8 N/mm^2 for load bearing. The compressive strength for dense concrete blocks over 75 mm thickness ranges from 2.8 to 35.0 N/mm^2 and light weight or aerated 5.5-45N/mm$^{2.}$ (Charlett, 2013; Gyurkó et al, 2019)

Water absorption: Due to the pores, blocks have higher water absorption than bricks. Dense concrete is better for below ground level since it has lower porosity than light-weight blocks. Aerated concrete is more porous, and this should be considered when designing to minimize the absorption rate (Charlett, 2013).

Durability: it has good resistance to freeze/ thaw condition beyond DPC level but compressive strength lower than 7 N/mm^2 should not beyond DPC(damp proof course) level(Lyons, 2014).

Thermal and moisture movement: They are like brick but can be bad for aerated concrete blocks if exposed to damping prior to laying which leads to cracking from drying shrinkage (Charlett, 2013).

Thermal conductivity: higher porosity leads to improved thermal resistance. Thermal conductivity for concrete block ranges from 0.7 to 1.8 W/m. K for dense block, 1.0-1.8 W/m. K for light-weight clay blocks. The low thermal values make it suitable for inner leaf cavity walls (Ashby, 2013; Charlett, 2013; Engineering Toolbox, 2002).

Fire resistance: Block is slightly less resistant to fire than clay brick. A 100mm block has 2 h resistance to its load bearing and 4h if it is non-load bearing (Charlett, 2013; Stowell, 2020).

Density: aerated blocks have density of 400-1500 kg/m^3 and dense blocks are closer to 2050-2300 kg/m^3 (Charlett, 2013; Lyons, 2014; Goodhew, 2016).

Appearance: Clay blocks have grooved surfaces to provide a surface for rendering. Dense and high strength concrete tend to be slightly rough textured which makes it good for application of finishes. Aerated blocks have smooth finish (Charlett, 2013).

Sustainability: the major environmental impacts of concrete blocks relates to the carbon emissions of cement which is attributed with 5-7% of the total CO_2 emitted worldwide and embodied energy of the material is approximately 143-375 Kg CO_2/ tonne (Alsubari et al, 2016; Liu et al, 2017; SFGB, 2011; Torgal & Said, 2011). However, the blocks often make use of recycled aggregates such a fly ash and foamed granulated blast furnace slag. The lightweight and aerated concrete blocks have reduced transportation energy in comparison with dense blocks (Charlett, 2013).

Concrete can be affected by cracking, spalling or by efflorescence (Figure 2.8). Spall is caused by a problem in the mix, water or mechanical damage, while efflorescence is caused by accumulation of salts on the surface. Unpainted block can be cleaned with low-pressure water and non-ionic detergent. Limiting the moisture movement within the wall by installing flashing, coping and using appropriated barriers can prevent the problem of efflorescence. Limiting the movement of the walls, by using concrete with limit shrinkage or reinforcement, can prevent the problem of cracking. Spall can be repaired by patching a mix like the concrete blocks (Jester & Tomlan, 2014).

The advantages of using blockwork for wall are listed below:

i. it is produced in a range of sizes,
ii. it can be used for both load bearing and non-load bearing walls in construction,
iii. production is cheaper compared to brickwork
iv. It has good thermal resistance and good sound insulation

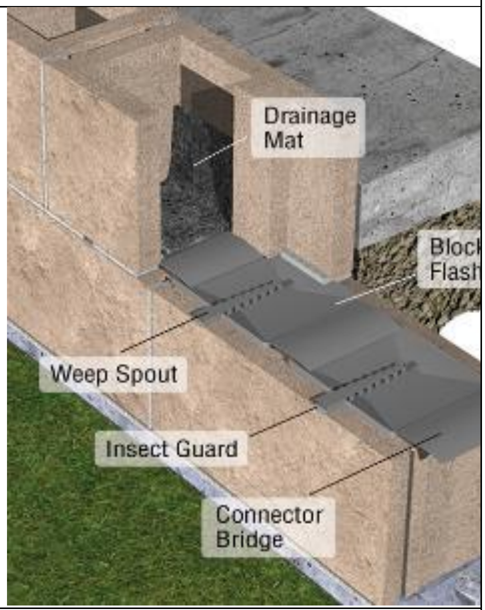
	
i.)Cracking in concrete (Holland, 2011),	ii) spalling in concrete
	
iii) effect of efflorescence in concrete(González-Jorge et al, 2013)	iv)flashing(Solutions, 2017)

Figure 2.8. Damages to concrete wall

2.4.3. Earth

Earth is a widely available material; however, its composition varies depending on location. About a third to a half of the world live in earth buildings. Most of such buildings are in developing countries, but some are in France, Germany, and United Kingdom.

Earth construction is often assumed to be best suited to dry climates. However, long lasting examples can be found in wet climates (e.g. cob houses in United Kingdom) as well as West Africa where it has been used since 1500BC (Hall et al, 2012). Stone or concrete foundations can prevent capillary rise of water, while good siting (not in a dip) and over-hanging roofs can prevent the rain from touching the wall directly.

There are several methods of utilising earth as a building material. These include:

Wattle and Daub: Straw and earth are pressed in a relatively light woven lattice of wooden strips, sometimes simple boughs, the lattice is connected to a stronger vertical or incline wooden frame (Van Damme & Houben, 2017). The image shown in Fig 2.9 (I).

Cob: uses the same straw mix as for wattle and daub but without any support for formwork, which allows a free shaped wall. The moist earth (cob) mixture is lightly tamped into place to form monolithic walls (Hall et al, 2012). The image shown in Fig 2.9(ii).

Adobe brick: can be made from earth with a clay content between 10-30% and earth containing 5-40% and no particles larger than 15mm. Straw is added to reduce shrinkage with a small amount of water to make the earth workable. The blocks are pressed in a mould, then removed and placed to dry for two weeks in a place protected from rain (McHenry, 1984). Adobe is commonly used for single and two storey houses, but it has been used for construction of 10-storey building (Pacheco-Torgal, 2015). Example in Fig 2.9 (iii).

Rammed earth: requires a formwork for the wall. Damp earth is poured into the form and tamped to compact the earth (McHenry, 1984). Rammed earth is better for lower clay levels than adobe blocks (higher clay levels increase likelihood of cracking during drying) and coarse particles can be included (Van Damme & Houben, 2017). Stabilizing agents such as Portland cement may be added to provide moisture proofing or additional strengths quality (McHenry, 1984). The formwork can be removed before the wall has fully dried (Hall et al, 2012). Rammed earth is more appropriate for humid climates than adobe (McHenry, 1984). Example in Fig 2.9 (iv).

Earth loaves: freshly hand formed earth loaves are laid like the brick construction, but only four courses are completed in a day. Stick reinforcements are introduced at every third course. After it is dried for 6 weeks the earth is strong enough to support the roof. This technique can be used for internal and external walls with load and non-loadbearing function (Berge, 2000). This technique was further developed in Germany to become the **Earth Strand** which was more suitable to the locally available earth. A brick extruding machine was used to compress and extrude a tube of 8-16cm in diameter (Berge, 2000).

Earth filled hoses are suitable for clay free earth – even for pure sand with no binding properties. The filled sacks are piled up within a light timber framework (Berge, 2000).

Compressed Earth Blocks (CEBs): The use of compacted stabilized blocks was seen after the 1940s. Paul Ramirez developed the CINVA-RAM press in 1952. Social houses were built with stabilized blocks of up to 3 storeys (Hall et al, 2012). Further details will be presented in Section 2.3.

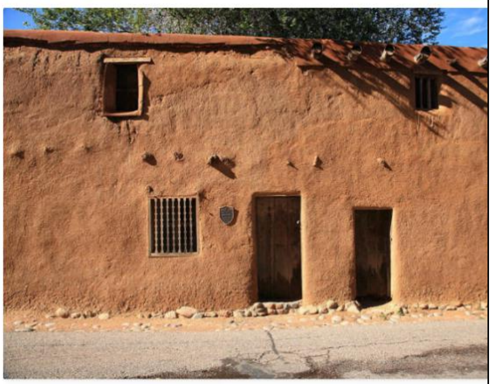
	
i) Wattle and Daub- lowimpact.org	ii) Cob- www.buildsomethingbeautiful.com
	
iii) Adobe- *Santa Fe - Adobe Building* is a photograph by Frank Romeo	iv) Rammed Earth- *Materials: Rammed Earth, Paul Downton 2013*

Figure 2.9. Traditional earth building techniques

Properties of earth construction:

Compressive strength: un-stabilized earth can have compressive strength of 0.7-5 N /mm^2, but higher once stabilized. The lower strength requires thicker walls to be built (Hall et al, 2012; Zak et al, 2016)

Water absorption: earth is an excellent regulator of humidity (Hall et al, 2012)

Thermal and moisture movement: the movement of rain on wall surface doesn't have erosive effect above 25mm/m (Torgal & Said, 2011).

Thermal conductivity: dry earth has a thermal conductivity of 1.5 W /m. K, like dense brick and dense concrete. The thermal performance of earth can be improved by adding fibres (Berge, 2000; Engineering Toolbox, 2002).

Sound insulation: the sound insulation of earth structure is 51 to 53dB (Binici et al, 2009).

Fire resistance: earth structures are considered fireproof (Hall et al, 2012)

Density: dry density ranges from 1450-2400 (Steve, 2016; Torgal & Said, 2011)

Appearance: the appearance varies from rough surface to smooth clean surface based on the images in Figure 2.9

Sustainability: earth is a low pollution material. When the building is no longer required, it can be reverted to earth (unless it has been stabilised). The replacement of concrete blocks by 5% with earth blocks will reduce the CO_2 emission by approximately 10000 tonnes. The embodied energy for this material is about 22 Kg CO_2/ tonne (Torgal & Said, 2011).

There is little documentation of methods for formal earth building construction and structural performance in construction codes is scanty. The use of earth for construction depends on constraints of mining, resource delivery and processing, access to labour force, quality control and approve building plans. However, it helps with local job creation and economic growth as well as low production and maintenance costs (Krosnowski, 2011). The material required for earth construction is locally available but the skills for construction have not been passed to the new generation as the material has been ignored for modern material as a result of social stigma attached to earth buildings as it is often used by the poorest in the community.

2.4.4. Stonework

Stone is one of the oldest building materials known to man, it was a dominant building material until the 20th century and is preferred for construction of permanent buildings.

The extraction of stone is more labour intensive, which could not compete with the growing industrialization of construction despite having a lower energy consumption compared to bricks and concrete.

The process of removing stone from earth is known as quarrying; drilling and splitting the stone can remove it. The method varies depending on the thickness of the stone. Holes can be drilled on the face at right angles, wedges are driving to the holes in order to divide the rock, the rocks are large and can be divided into pieces and shape required, the stone can be finished with planar finish, carbon finish, rubbed finish and different machine finishes. The building industry today uses stone to face building with exterior made of steel or concrete frames (Hegger, 2006; Lyons, 2014).

Rock can be classified into igneous (e.g. granite) sedimentary (e.g. limestone / travertine, sandstone) or metamorphic (e.g. marble, slate, serpentine). Stones used for construction can be classified into commercial forms, which are rubble (fieldstone), dimension (cut stone), flagstone (flat slabs), and crushed stone. Rubble stone are used the way it is found in the field, dimension stones are cut to suitable sizes, flag stones are cut to 12.7mm and up and crushed stone are cut in sizes varying from 9.5 to 152mm. Crushed stone is commonly used for aggregate in concrete or levelling for loose foundation(Richardson, 2001).

Properties of stone construction:

Compressive strength: varies depending on stone type. E.g. Sandstone and limestone 2.1 N/ mm^2, slate 3.5 N /mm^2, granite 4.8 N /mm^2 (Engineering Toolbox, 2008)

Water absorption: ranges from 1-7% (Fockenberg, 1991)

Thermal and moisture movement: the thermal expansion oranges from 0.0032-0.044% (Hackman & Kessler, 1950)

Thermal conductivity: 1.7-6.0 W /m. K (Charlett, 2013; Engineering, 2002).

Density: 2240-2650 kg m^{-3} (Baden-Powell, 2011; Charlett, 2013; Charlotte, 2011).

Appearance: colour, grain, porosity and texture are important to the appearance and vary between stone types

Sustainability: The recycling fraction in the current supply is 1-2% (Ashby, 2013). The embodied energy for stonework is 64-84 Kg CO_2 /tonne (SFGB, 2011). Stonework material is available in Nigeria but requires high energy for extraction and processing for construction use; these factors increases the cost of houses and reduces the potential for the purpose of affordable houses in the country.

2.4.5. Summary

The review on conventional material used for wall construction in Nigeria on requirement all of the materials described above can be considered (assuming earth materials are stabilized). With this basic requirement met, the decision on material choice is based on appearance, material availability and cost implications for the resulting building construction. The summary of the materials characteristics of wall material characteristics is shown in Table 2.4

The use of stonework, brickwork, blockwork require significant energy for production, the amount available in the country is inadequate. For these reasons, stabilised CEBs have been chosen as the most suitable wall material for affordable and sustainable residential building.

Table 2.4: Comparing compressed earth blocks with other masonry

Characteristics	Unit	CEBs	Fired clay bricks	Adobe	Concrete blocks
Size	Cm	29.5 x 14 x 9	22 x 10.5 x6.5	40 x 20 x 10	40 x 20 x 5
Appearance:					
Surface		Smooth	Rough - smooth	Irregular	Rough
Visual		Medium to good	Good-excellent	Poor	Average
Performance:					
Wet compressive strength	MPa	1-4	0.5-6	0-5	0.7-5
Reversible thermal dilation	%	0.02-0.2	0-0.02	-	0.02-0.05
Thermal insulation	W/m^0C	0.81-1.02	0.07- 1.3	0.4-0.8	1.0-1.7
Density	Kg/m^3	1700-2200	1400-2400	1200-1700	1700-2200
Durability	-	Low to very good	Low-excellent	Poor	Low-very good
Use in masonry		Load bearing without render	Load bearing without render	Load bearing with render	Good infill with render

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2.5. CEB (Compressed earth block)

The introduction of compressed earth blocks (CEB) is a modern method of construction that incorporates earth material by compacting the earth into a mould. The compression may be manual or mechanical using hydraulic press. CEB are denser, stronger and dimensionally more uniform than adobe bricks. Soil is compressed in dry state (about 5-15% water content). The density of CEB is about 1700-2300kg/m^3 (Van Damme & Houben, 2017).

It is common to introduce stabilization in CEB to improve strength, resistance to disintegration and erosion. In addition, it improves the strength and durability of the construction. The stabilization process involves addition of one or more of the following: earthen plaster and stuccoes, tree resins, natural bitumen, Arabic gum, agave juice, cactus juice, and cowpats. Also, synthetic compounds like polyvinyl chloride (PVC), polyvinyl acetates, acrylics, sodium silicate, hydrated lime, calcine gypsum, Portland cement or supplementary cementitious material such as silica fume, fly ash, ground granulated blast furnace slag or other pozzolans are used either alone or in association with other elements (Van Damme & Houben, 2017).

Curing is an important aspect of stabilization process. Clay soil are less reactive at elevated temperature and the kinetics of their pozzolanic reaction is slow which is the reason it is cured under a plastic cover or by sprinkling with water regularly before drying and using in construction (Van Damme & Houben, 2017). There is no restriction as to the season when CEB can be produced if measures are taken during wet and hot seasons to protect the blocks when stored.

Materials used for stabilizing CEB are used to reduce the rate of shrinkage when exposed to water or atmospheric moisture and loss of strength. Over time the development of Cement and Lime industry had caused replacement of the use of local stabilizers with cement and lime (Van Damme & Houben, 2017). However, the new method had led to other problems in the environment in terms of the cost, reuse of the material and the pollution caused by the cement industry. The challenges have led to a development of alternative materials that can combat the problems caused by the cement industry without compromising the integrity of the CEB materials. The cost of CEB is about 32% less than Sandcrete block that are commonly used in Nigeria; and that satisfactory results were obtained with CEB having 5-10% cement or lime for stabilization (Egenti et al, 2014).

The use of cheap natural pozzolans has been considered for the stabilization of building materials in order to reduce construction cost. In that regard, waste materials from the glass industry, rubber industry, and agricultural industry have been used. Also, chemicals such as geopolymer was used to develop the calcium silicate hydrate (C-S-H) to provide the binding properties that cement has over other binding agents.

Typically, CEBs requires about 5-10% dry weight- based binder added to the mix, compressive strength of 3-4 N/mm^2 (Mostafa & Uddin, 2016a). It can be used for walls up to 3 floors and higher potential to 5 floors (Hjort & Widén, 2015). Furthermore, CEB has the following advantages:

- The mechanical presses used to produce CEBs ensures it has an improved property over other earth blocks (adobe) which ensures its social acceptance.
- Its quality meets the requirement of other building products standards used in urban society
- In places where construction industry relies on small masonry (fired clay bricks, concrete blocks). CEBs is a good alternative serves as a socio-economic development of the building sector
- Policy makers find the use of CEBs acceptable in the rural and urban context

- Builders appreciate using the presses to ensure regular shape and sharp edges which ensures high density when compacted and improves the compressive strength as well as resistance to erosion
- It is flexible for use for different size of project
- It has similar property (water absorption, compressive strength, sound insulation, fire insulation and thermal insulation) with fired clay bricks
- It can be locally produced

The stages of producing CEBs are listed in Table 2.5.

Table 2.5. Stages for compressed earth blocks production

Extraction	Extraction	From the quarry pit.
Preparation	Drying Pulverizing Screening	Spreading thin layers to dry Breaking lumps of clay Eliminating undesirable element
Mixing	Measuring out dry materials Dry mixing Wet mixing Reaction time	Measuring by weight or volume the soil, stabilizers Mix all the component thoroughly To add water to the dry mix and mix again The hold back period before the mix is poured into the mould
Compression	Measuring out Compression Removing from mould	The amount poured into the mould should be adequate for the right density Compressing the mixed material Removing blocks from mould
Curing	Wet curing Drying out	The length of time varies with climate and nature of stabilizer To ensure the quality is achieved, the moisture can evaporate
Stocking	Stocking	Storing in a safe place for later use.

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It has been reported that the best results for CEB production was obtained with sandy soil. Meanwhile, the presence of iron oxides in lateritic soil allowed for efficient stabilization.

Also, soil must be free of organic matter before use for CEB production. Water with salt and in particular sulphate should be avoided to achieve the best CEB (Rigassi & CRATerre-EAG., 1985)

Table 2.6 shows the different presses that are available to produce CEB. It also highlights the average blocks that can be produced and the cost of production.

Table 2.6: Types of presses used for Compressed earth blocks (CEBs) production

	Manual	¼ Motorized	½ Motorized	¾ Motorized	Motorized	Automatic
Number of blocks daily	600-1000	1200-1500	1200-1500	1500-2000	1500-2500	5000-6000
Number of labourers	9-10	11-13	10-12	9-11	8-10	8-10
Investment on equipment	2,000	10,000	14,500	23,000	46,000	83,000
Infrastructure (excluding land)	2250	4150	4150	4500	10,000	38,000
Total blocks produced	4250	14,150	18,650	27,500	56,000	121,000

(Rigassi & CRATerre-EAG., 1985)

2.6. Stabilizers

Stabilization has been defined as the controlled modification of texture, structure and/or physio-mechanical properties of the soil. It can be in the form of physical, mechanical or chemical modification, and its main objectives are listed below:

- Improves mechanical properties: dry and wet compressive strength
- Reduce porosity and variation in volume when exposed to moisture: swelling and shrinkages with moisture content
- Improving ability to withstand weathering by wind and rain. It reduces abrasion and increases waterproofing property.
- Stabilization can increase the cost of building material by 30-50%
- Therefore, the object of a stabilizer is to: reduce the volume between the particles (i.e. porosity); block the void which cannot be eliminated (i.e. permeability); and improves binding links between particles (i.e. mechanical strength).

Stabilization can be achieved in any of the following forms:

- **Mechanical stabilization:** its inexpensive, it involves the mixture of two or more soil types to get the required grade (sand and gravel). Adding sand or gravel to the mixture can improve soil with high content of clay. Densification of soil through compaction (Hall et al, 2012; Pacheco-Torgal, 2015)
- **Stabilization by compaction:** loose soil is compacted to be denser. It imposes strength, reduces porosity, etc. - modifies physical soil texture by firing, freezing or electro-osmosis (Hall et al, 2012; Pacheco-Torgal, 2015).
- **Stabilization by additives:** Modifies soil through mixing with chemical additives such as lime, cement (4-10%) (Hall et al, 2012; Pacheco-Torgal, 2015). It helps control excessive shrinkage that causes cracks in blocks. Ordinary Portland cement is the most used stabilizer. Its content ranges from 5-10%. The formation of CSH gel in the mixture of soil, cement and water establishes insoluble bonds and binds the sand and the silt particles.

However, demerits of stabilizers are listed below:

- Raw materials cost increase (particularly for cement)
- The stabilizer might not be available in some countries, so more cost is incurred from transportation
- The process of mixing and construction can be more complex
- The stabilization process might significantly affect the environment.
- The material used for stabilization might cause burns to skin, eyes (cement, lime, chemical addictive)
- Stabilization can prevent the material from being recycled at end of use.

2.6.1. Pozzolans – Definition, Functions and Mode of Action, Classification, and Characterization

A pozzolan is defined as a *'a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide to form compounds possessing cementitious properties' (Malhotra & Mehta, 1996)*. It can be explained that pozzolanic material will not react to form cementitious material alone but will react with Portland cement.

Generally amorphous silica reacts with calcium hydroxide much more rapidly than silica in crystalized form. Also, fine pozzolanic particles with higher surface areas reacts much more rapidly than larger particles.

Natural pozzolans may be classified into two principal classes. First, those derived from volcanic rocks in which the amorphous content is produced by glass fusion and second, those derived from rocks or earth from which the silica constituents contain opal, either from precipitation of silica or from the remains of organisms.

Some agricultural wastes have pozzolanic properties, i.e. they have little or no cementitious value but react with calcium hydroxide in presence of moisture to form compounds with cementitious properties. Such materials can be substituted for a proportion of Portland cement.

Pozzolans are a variety of materials or classes of materials, which may differ from one another in both their chemical and physical composition and their effect on the properties of mortars and concrete. There are three classification of pozzolans ASTM C618-19 includes class N, F and C. Class N is naturally occurring from diatomaceous earth, volcanic ashes, class F is the fly ash gotten from burning bituminous coal and class C is fly ash that is produced from burning lignite coal. The minimum percentage of $SiO2$, $AL2O3$ and $Fe2O3$ for class N. F AND C is 70,70 and 50 respectively. Agricultural pozzolan falls under the classification N.

Fineness and grain size of materials are determined using Automatic Blaine Machine and Malvern Matersizer, respectively. The amorphous or crystalize phase of material are determined with X- RAY diffraction. Chemical composition is determined by X RAY Fluorescence (XRF) test. The morphological view and shape of the particles of the material are examined using Scanning Electron Microscopy (SEM) analysis (Bahurudeen & Santhanam, 2015; Cordeiro et al, 2009a; Sore et al, 2016; Sturm et al, 2016).

The loss of ignition is also another important test used in inorganic analytical chemistry, particularly in the analysis of materials. It involves heating a material, allowing the volatile substance to escape until its mass stops to change. This is helpful because the replacement of pozzolans is specified or calculated with the volume of the material to replace Portland cement in the mix.

The fineness modulus is an empirical factor obtained by adding the cumulative percentage of aggregate retained on each of the standard sieves. It is generally used to determine how coarse or fine the aggregate is, and it affects the water- cement ratio, workability, shrinkage and creep of concrete (Aprianti et al, 2015). Creep and shrinkage occur in concrete when concrete is loaded, the structure undergoes elastic and inelastic deformation. Aggregate play an important role. The water demand and workability are affected by the particle size distribution, particle packing effect and voids present in the solid system.

Rice husk ash, Sugar Bagasse Ash, and Palm Oil Fuel Ash; like other sustainable pozzolans could serve useful application here. The binding and stabilizing strengths of the three agricultural waste materials in the production of concrete, building blocks, and mortar will depend on the geo-chemical composition of the aggregates used. The geo-chemical composition of the aggregates will vary per the nature and mineral composition of the originating rock.

Furthermore, successful replacement of cement with RHA, SBA, and POFA will provide a solution to management of agricultural waste, environmental pollution and financial sustainability (Aprianti et al, 2015; Chong et al, 2015).

The pozzolanic properties of Rice Husk Ash (RHA), Sugar Bagasse Ash (SBA), and Palm Oil Fuel Ash (POFA) are studied in detail in sections 2.6.2 – 2.6.4. The information will facilitate more understanding of the binding qualities and their use in the construction industry.

Rice husk ash, sugar bagasse ash and palm oil fuel ash have high silica content in amorphous form, which makes it useful as pozzolans. The following agricultural wastes are studied because they are common crops grown in Nigeria.

The cost and environmental hazards of cement production have been described earlier. Sourcing acceptable alternative low cost and environmentally friendly binding agent will significantly reduce cost of providing housing and the cost environmental pollution management.

2.6.2. Rice husk ash

2.6.2.1. Availability of Rice Husk Ash (RHA)

Rice Production for 2015 was 472.09 x 10^{9} kg, year and for 2016 it is 483.26 x 10^{9} kg. It is estimated million tonnes could represent an increase of 11.17 million tonnes or a 2.37% in **rice production** around the globe (Knoema, 2020). Rice husk (RH) is the by-product from rice milling industries. Rice husk ash is obtained after the combustion of rice husk. For every tonne of rice produced worldwide; about 20% mass of rice husk is obtained. and out of that 15-25 % rice husk ash. The RHA estimated to be produced in the year 2016 will be 14.5- 24.16 x 10^{9} kg globally (Heung Fai et al, 2011; Kazmi et al, 2016b; Sturm et al, 2016; Xu et al, 2012). Rice is grown in 11 out of 36 states in the country, eight of the states are in the tropical savannah climate and three are located at the monsoon climate. The states in the tropical climate are Kaduna, Jos, FCT (Abuja), Niger, Ekiti, Lagos, Ebonyi, Benue and the monsoon climate state includes Akwa-Ibom, Rivers and Bayelsa. It is estimated that Nigeria produced 4.9 million tonnes of rice in the year 2019 (Knoema, 2020)

2.6.2.2. Properties of Rice Husk Ash (RHA)

The chemical composition of RHA is largely dependent on the type of paddy, soil type and condition, geographical conditions, combustion temperature, and cooling method. RHA pozzolan is prepared by burning rice husk at a controlled temperature ranging from 600-800^{o}C, and cooled uniformly to maintain amorphous silica content of 77-95% before grinding into specified particle size (Alsubari et al, 2016; Chiang et al, 2009; Ganesan et al, 2008; Sore et al, 2016), particle size 5-10μm (Alsubari et al, 2016). The silica in RHA exist in amorphous state but becomes crystallised when burnt at a temperature higher than 600-800^oC for a few minutes or 500^oC for a longer period (Ganesan et al, 2008; Nehdi et al, 2003; Sturm et al, 2016).

The chemical activity of amorphous silica in RHA to produce the required filling effect in structures to increase compressive strength and reduce water permeability is dependent on the surface area of RHA (Givi et al, 2010). Also the fineness of the RHA influences the rate of reaction, increase in concrete strength, water-cement ratio, workability, shrinkage and creep of concrete (Aprianti et al, 2015). The RHA particle ranges from 5 to 10μm with a very high surface area of more than 250 m^2/g due to the porous nature of RHA (Aprianti et al, 2015; Van Tuan et al, 2011). RHA has 2.11 specific gravity, and a modulus of rupture ranging from 0.67-1.49 MPa (Kazmi et al, 2016a). Its colour ranges from whitish grey to black depending on the source of the raw material, method of incineration, and time and burning temperature (Aprianti et al, 2015). The amount of silicon dioxide (SiO_2), iron oxide (Fe_2O_3), aluminium oxide (Al_2O_3) in the ash should be greater than 70%, and the Loss of Ignition (LOI) should not be less than 12%, as mentioned in ASTM C618 requirement (Aprianti et al, 2015). Variations in the chemical composition of RHA in different countries are shown in Table 2.7.

Table 2.7: Chemical composition (% by weight) of RHA sample

Constituents	Malaysia	Brazil	Netherlands	Kenya
Silica (SiO_2)	93.1	92.9	86.9	75.8
Alumina (Al_2O_3)	0.21	0.18	0.86	1.15
Iron Oxide (Fe_2O_3)	0.21	0.43	0.73	0.86
Calcium Oxide (CaO)	0.41	1.03	1.4	3.25
Potassium Oxide (K_2O)	2.31	0.72	2.46	1.5
Magnesium Oxide (MgO)	1.59	0.35	0.57	0.23
Sodium Oxide (Na_2O)	-	0.02	0.11	0.35
Sulfur Oxide (SO_3	-	0.01	-	-
Loss of Ignition (LOI)	0.36	-	5.14	10.2
SiO_2+Fe_2O_3+Al_2O_3	93.52	93.51	88.47	77.81

*Abubakar et al., 2010

2.6.2.3. Rice Husk Ash as Pozzolan

Cook (1986) reported that highly reactive pozzolans such as rice husk ash can reduce the size of voids in hydrated cement paste, thus making them almost impenetrable to water and chloride ions even at early days of curing (Cook, 1986).

The silica in RHA reacts with Ca $(OH)_2$ produced from cement in the presence of water as shown below to produce Calcium-Silicate-Hydrate (C-S-H) gel

$$n\ SiO_2 + n\ Ca\ (OH)_2 + H_2O \rightarrow n\ CaSiO + nH_2O$$

The formation of secondary Calcium-Silicate-Hydrate (C-S-H) gel was obtained; the presence of this gel is what makes the possibility of the silica (SiO_2) present in RHA and calcium hydroxide (Ca $(OH)_2$) in hydrating cement to bind. RHA has been tested for its pozzolanic properties and was recommended as a supplementary cementitious material (SCM).

2.6.2.4 Effect of RHA on mechanical properties of concrete and fired clay bricks

There is a little of literature reporting the effect of RHA on OPC replacement of CEBs. The literature documenting the effect of RHA on OPC replacement in concrete and fired bricks was analysed as an indicator of potential effects.

The standard compressive strength of concrete combined with or without RHA, is within range for conventional concrete (15-45 MPa) with a density of about 2400 kg/m^3. (Aprianti et al, 2015) showed the possibility of increasing compressive strength after curing concrete for 7days and 28 days to approximately 55MPa and 72MPa, respectively.

The presence of 30%RHA in concrete mix has been noticed to improve concrete's mechanical and durability properties by producing C-S-H gel that filled the large and continuous pores within the concrete. It increased compression strength, improved the microstructure of the paste making it more homogenous and denser, and finally enhanced its resistance to water and chloride penetration to prevent the possibility of corrosion (Ganesan et al, 2008; Givi et al, 2010).

By replacing OPC by 10% with RHA, the compressive strength increased from the control, but it starts to decrease at 20% and 30% by 7.89% and 26.32%. The concrete was grade range of M25 and M35 ((Takhelmayan et al, 2014; Rama et al, 2015). Another group of researchers observed that at 15% replacement the compressive strength was maximum (Ganesan et al, 2008; Salas et al, 2009). (Tsado et al, 2014) produced concrete of grade M25-M35 by replacing OPC with RHA, the compressive strength decreased from control at 33.62MPa to 30.58, 26.51, and 17.68MPa when replaced with RHA at 10, 20 and 30%, respectively. Rao et al. (2014) achieved grade M30 by replacing OPC with RHA at 5-12.5%. (Rama et al, 2015; Ramezanianpour et al, 2009) replaced 5-20% and 7-15% OPC, respectively with RHA to make concrete grade of M45 and M40. Keertana and Gobhiga

(2016) replaced OPC with RHA at 5-10% to make concrete of grade M35-M40. Givi et al (2010) carried out similar test and noticed an increase in compressive strength. 10% replacement of volume of OPC for 95μm and 5μm particle sizes of RHA to retain and improve its properties (Givi et al, 2010). (Raut et al, 2013) produced nearly 50% higher compressive strength in bricks of about 11-15 MPa, which is 3 times greater than the normal 3MPa. In another study, replacement of OPC in mortar cubes production up to 15% with RHA resulted in optimal compressive strength. Replacement between 30 and 35% caused a sharp drop in cubes' strength (Ganesan et al, 2008). The tensile strength of concrete was optimum when 30% volume of OPC was replaced with RHA (Ganesan et al, 2008). The bulk density and compressive strength of brick is maximum at 1.68 g/cm^3 and 6.20MPa, respectively when RHA replaced 2% of the volume of OPC in brick production and when RHA replacement was 15.20% of the volume of OPC, water absorption reduction was at the maximum (Kaewkhao et al, 2012). Similarly when 0-20% volume of OPC was gradually replaced with RHA and water treatment sludge (WTS) there was a decreased in the bulk density from 2.4 to 1.6g/cm^3 with relatively high compressive strength (Chiang et al, 2009). Finally, Mehta et al (2013) replaced 7.5-22.5% volume of OPC gradually with RHA and Fly Ash in concrete mix and observed that, the maximum split tensile strength was taken at 28% was less than the control concrete, the maximum flexural strength was achieve, the workability of concrete was found to decrease with increase in RHA in concrete (Givi et al, 2010; Mehta et al, 2013).

In summary, up to 10% replacement of OPC with RHA was generally found to be acceptable for concrete, although larger replacements of OPC with RHA were found to adversely affect compressive strength.

2.6.2.5 Effect of RHA on hygrothermal properties of concrete

Water absorption percentage decreased with increasing %RHA replacement. The authors suggested that RHA particles filled the pores within the concrete mix therefore caused improvement in concrete porosity ((Aprianti et al, 2015; Givi et al, 2010; Takhelmayan et al, 2014). The porosity of the concrete improved as RHA content increased from 10 to 30% ((Dakroury & and Gasser, 2008; Givi et al, 2010), whereas permeability decreased as RHA content increased (Aprianti et al, 2015; Givi et al, 2010; Rodrigues et al, (2006); Saraswathy & and Ha-Won, 2007). Permeability of concrete increased when 7-15%RHA replaced OPC ((Ramezanianpour et al, 2009).

The presence of chloride ions in concrete results in corrosion; however, the inclusion of 7-25% RHA to replace OPC reduced the permeability of the blocks significantly ((Givi et al, 2010; Ramezanianpour et al, 2009; Saraswathy & and Ha-Won, 2007). Also, 10-15% RHA replacement reduced sulphate attack on the concrete (Rama et al, 2015; Takhelmayan et al, 2014).

Freeze and thaw resistance, water inside solid state expands by approximately 9% during this period (ASTM C67), specimen can be considered unacceptable if it cracks during freeze and thaw cycles or weight loss increases by 3%, by incorperating RHA the weight loss during the process was less than 3% which helps improves aesthetic appearance (Kazmi et al, 2016b).

RHA replacement of OPC at all levels was considered to reduce porosity and thereby permeability and water absorption.

2.6.2.6 Effect of RHA on Workability of concrete

Workability improved with increases in RHA inclusion at between 5 and 20%. The large surface of RHA reduced the water content required and increased the plastic viscosity (Coutinho, 2002; Habeeb & and Fayyadh, 2009; Laskar & and Talukdar, 2007). The replacement of OPC with 15% RHA saved cost of the material (Nagrale et al, 2012).

2.6.3. Sugar Bagasse Ash (SBA)

Sugar bagasse ash (SBA) is an agricultural waste with pozzolanic properties. It is obtained from the extraction of sugar and ethanol from sugarcane (Almeida et al, 2015; Bahurudeen et al, 2015). Sugar production for 2015/ 2016 was estimated at 1.74×10^{11} kg in the world, and that Nigeria accounted for 7×10^{7} kg (Knoema, 2020). A kilogramme of sugar cane generates 25% bagasse resulting in approximately 0.6% of bagasse ash (Kazmi et al, 2016b). The estimated amount of sugar cane plantation in Nigeria in 7.5×10^{7}kg in 2019-2020 (FAS, 2019)

When bagasse is subjected to combustion under controlled temperature of 600-800^{o}C, reactive amorphous silica is formed in the residual ashes (Bahurudeen et al, 2014). It is not clear whether the positive effect of SBA is due to physical or chemical effect; if the particle size distribution of the SBA is refined it can increase the packing density of the mixture as well as the chemical reactivity of the ash due to increase in specific surface area. There is significant availability of sugar cane farm located in the warm semi-arid climate and tropical savannah climate. There are 8 states that grow sugar cane in the country, four of which are in the tropical savannah climate and the rest in the warm semi-arid climate. The state in the tropical savannah climate include Kebbi, Kaduna, Taraba, Adamawa and the warm arid climate state includes Sokoto, Katsina, Kano and Jigawa.

2.6.3.1. Chemical and Physical Properties of SBA

Sugar Bagasse (SB) is burnt as a source of fuel during production, which lead to the manufacture of SBA. It has similarity to the RHA, as it can be used for its pozzolanic properties. It is a source of natural silicate which is cheap. Sugar cane plant ingest Orth silicic acid from ground water which later polymerised as an amorphous silica in plant cells (de Soares et al, 2016).

Table 2.6. shows the chemical and physical characteristics of SBA. The ash has two main constituents of oxides of silica and aluminium. Its specific gravity is lower compared to clay, which is 2.24 (Kazmi et al, 2016b). Increase in specific surface area is directly responsible for the kinetics of their pozzolanic reactions. The application of an ultra-finely ground SBA produced by vibratory grinding allowed the production of high-performance concrete with the same mechanical response up to 20% replacement as concrete prepared solely using Portland cement. The reaction improved the fresh state and resistance to penetration of chloride ions in concrete (Cordeiro et al, 2009b). Particle size of SBA are analysed with the Malvern Matersizer following Blaine fineness as determined according to ASTM C204 (Cordeiro et al, 2008). The compressive strength of SBA mortar is inversely proportional to the SBA particle size (Cordeiro et al, 2008).

Table 2.8: Chemical and physical properties of sugar bagasse ash (SBA)

Chemical Composition (% by mass):	
SiO_2	60.0 – 65.3
Al_2O_3	4.7 – 9.1
Fe_2O_3	3.1 – 5.5
MgO	1.1 – 2.9
CaO	4.0 – 10.5
Na_2O	0.3 – 0.9
K_2O	1.4 – 2.0
SO_3	0.1 – 0.2
Physical Properties:	
Particle size distribution (µm)	66.9 – 107.9
Specific gravity	1.9 – 2.4
Specific surface area (cm^2/g)	274.0 – 943.0
Loss of Ignition, LOI (% by mass)	15.3 – 19.6

SBA is considered as non-plastic (not clay like) and non-cohesive material. The weight per unit area when replacing clay with SBA and RHA in the manufacture of bricks is 15% and 4% lighter, respectively. These phenomena affected the weight of bricks produced with SBA and RHA such that their densities 258.6kg/m^3 and 550.54 kg/m^3, respectively and were lighter compared to clay with 1120kg /m^3. Therefore, inclusions of SBA and RHA resulted in the reduction of transportation and labour costs (transportation are priced by the weight of the material and labour is reduced by allowing the workers to move a larger volume of material faster) while at the same time reduction in structural load and flexibility to architectural design (Kazmi et al, 2016b).

2.6.3.2. SBA as a Pozzolan

The natural silicate in SBA can be used to form calcium silicate hydrate (C-S-H) gel that is usually formed in cement hydration; the gel responsible for hardening in concrete (de Soares et al, 2016; Jamil et al, 2013). The physical effects are mainly associated with the packing characteristics of the solid mixture while chemical effect is linked with capability of providing amorphous silica to react with $Ca(OH)_2$ in the presence of water during cement hydrations. The quality of ash can be improved by controlling the temperature, rate of heating, soaking time and atmosphere (Cordeiro et al, 2009a). The combustion of SBA to form amorphous or crystalline silica is determined by the time and temperature it was burnt. At a temperature of 600^{o}C the amorphous state is achieved but at or above 800^{o}C there is a peak of crystobalite using the X-ray analysis (de Soares et al, 2016; Norsuraya et al, 2016). Then, the amorphous silica changed to crystallized silica (Cordeiro et al, 2009b). SBA has the presence of silica up to 70.97- 89.04% (Norsuraya et al, 2016). The concrete or brick have been observed to show early strength as fast as 3 days curing period (Bahurudeen et al, 2015).

The temperature needed for calcination of cement is up to 1450^{o}C, a temperature relatively higher than the temperature used to form amorphous silicate or crystalize silicate. It implies lower energy requirement for the latter (Fairbairn et al, 2010; Tian & Zhang, 2016).

Initial rate of absorption can be defined as the absorbed water over the brick bed area of 19354.8 30 sq.mm for one minute. It has been noted that the initial rate of absorption for bricks with RHA and SBA are higher compared to that of controlled bricks (bricks with no substitution with pozzolan). The rate of absorption was 0.78g/cm^2/min when 15% SBA was incorporated while clay absorbed at the rate of 0.46g/cm^2 /min. The limit should lie between 0.025 and 0.15g/cm^2/min; which means bricks should be wetted before laying to ensure efficient bond between bricks and mortar (Bahurudeen et al, 2014).

The compressive strength of brick dropped from 8.38 to 5.10 MPa with the incorporation of SBA and RHA. Although there was increase in porosity, strength (5MPa) met the minimum standard. Modulus of rupture is the maximum bending strength before failure of a structural element. The modulus of rupture reduced from 1.49 to 0.72 but still within the minimum standard (0.65 MPa) stipulated in the ASTM C67 guidelines. The water absorption of bricks with SBA was 21% which is according to ASTM C62 for bricks in moderate weather (Kazmi et al, 2016a).

The reduction in particle size with increase in grinding time is accompanied by an increase in pozzolanic activity index with lime and is also responsible for microdefects and electrostatic charges on the particles increasing their surface energy. Increase in compressive strength can also be as a result of the packing density with is linked to the filler effects of the ultrafine particles of SBA (Cordeiro et al, 2008).

SBA was successfully used as SCM in the production of concrete and bricks by (Bahurudeen et al, 2014). Concrete with SBA replacement show equal or marginally better strength performance even as early as 3 days and the replacement up to 25% replacement can be used (Bahurudeen et al, 2015).

2.6.3.3 Effect of SBA on mechanical properties of concrete and fired clay bricks

As with RHA, there is a lack of literature reporting the effect of SBA on OPC replacement of CEBs. The literature documenting the effect of SBA on OPC replacement in concrete and fired bricks was analysed as an indicator of potential effects. The compressive strength of concrete increased with the partial replacement of OPC with 10-30%SBA where 20% replacement produced concrete of grade M25-M30. Also, some researchers (Malhotra & Mehta, 1996)produced grade M25-M30 concrete and noticed higher compressive strength with 5-15% but observed a decline with further increase in replacement of OPC. They recorded the lowest strength at 30% replacement. In making M40 concrete, (Amin, 2011) observed that replacement of OPC with 5-20%SBA resulted in compressive strength higher than the control but the highest strength was attained at 10% and the least at 30%. The compressive strength of concrete with 5% each of SBA and RHA replacement showed 7.18 and 6.62 MPa, respectively. The concrete still attained the minimum strength for building brick of 3.5 MPa. 5% replacement of clay by SBA led to approximately 14% decrease in compressive strength. The reduction of compressive strength is approximately 50% in 10% and 15% replacement of aggregate (clay) (Kazmi et al, 2016a).

The split tensile strength was higher than the control concrete when partially replaced with 10-30% SBA, while the highest strength was at 20%, (Subramaniyan & and Sivaraja, 2016). Similarly, (Ganesan et al, 2007) noted that 15% produced the highest strength while the split strength at 5-15% was approximately 4.5-5 MPa. The splitting tensile strength values at 28 days containing SBA up to 20% increased to 4.81 MPa and at 25-30% of SBA the value decreased to 3MPa (Aprianti et al, 2015).

According to ASTM C67, the minimum permissible limit of rupture is 0.67 MPa, brick with SBA inclusion had a modulus of rupture ranging from 0.67 to 1.49 MPa. It therefore implied that the usage would help produce efficiently mass scale production, leading to economical gain and sustainable construction.

2.6.3.4 Effect of SBA on hygrothermal properties of concrete and fired clay bricks

SBA inclusion remarkably affected water absorption coefficient where 5-20% caused reduction while it was the reverse at 30% replacement (Ganesan et al, 2007). Permeability of chloride ion reduced as OPC was replaced with 10-40%SBA, it was lowest at 20%-25% after curing for 28 days (Amin, 2011; Ganesan et al, 2007; Subramaniyan & and Sivaraja, 2016). The sorptivity of concrete was tested when OPC was partially replace with SBA at 10-40%, it was lower than that of control and lowest at 10% and 15% (Ganesan et al, 2007; Subramaniyan & and Sivaraja, 2016).

(Almeida et al, 2015) suggested that the substitution of natural sand with SBA up to 30% could lead to improvement of maintenance properties, micropore clogging and durability of the mortar in comparison with control mix. The workers added the increased chloride penetration resistance could be as a result of the physical and chemical effects of SBA. The durability and porosity of bricks, which can affect the mechanical property, was improved with inclusion of SBA (Almeida et al, 2015; Fairbairn et al, 2010). It can therefore be best utilized in places where insulation and heat transfer resistance are required.

Water absorption also affects the durability of bricks, in corperating SBA showed that the rate of absorption was less than 21%, according to ASTM C62, water absorption should not be more than 17% for severe weather resistance and 22% for moderate weather resistance which means it can be used in places with moderate weather condition i.e. Nigeria. (Kazmi et al, 2016b). It was also observed by increasing temperature of firing of fired clay bricks from 900 to 1000 ^{o} C, absorption reduces from 40% to 2%.

Efflorescence is considered as an aesthetic problem. Inclusion of SBA can lead to improved aesthetic behaviour of masonry construction.

Sulphate attacks reduces the compressive strength, incorperating SBA improves resistance against sulphate attack by 5% (Kazmi et al, 2016b).

2.6.3.5 The effect of SBA on workability of concrete

The workability of concrete increased as OPC was replaced with 10-40%SBA (Subramaniyan & and Sivaraja, 2016). Workability increased from 5 to 10% and then declined thereafter as SBA content increased further.

2.6.4. Palm Oil Fuel Ash (POFA)

The high productivity of oil palm is concentrated at the tropical zone, located 10^{o} to the north or south of the equator, which Nigeria falls within. Global palm oil production in 2015 was 5.3379 x10^{10}Kg. The estimate for 2016 was 5.8513 x 10^{10}Kg, which represented an increase of 5.125 x10^{9}Kg or 9.6% (Knoema, 2020). It was estimated that Nigeria would produce 8.799 x10^{8}Kg, palm residue amounting to 15% shell and 85% fibre. Furthermore, the residue would lead to 5% ash by weight of solid waste. The availability of palm oil fuel ash is located 6 states that are in tropical savannah climate, and monsoon climate. There are three state that have palm oil in the tropical savannah climate which includes Enugu, Ogun and Oyo. The monsoon climate state includes Imo, Cross-river and Rivers state.

Tangchrapat et al. (2009) defined palm oil fuel ash (POFA) as an agricultural waste formed when palm oil residue is burnt at 800-1000ºC to produce steam for electricity in biomass thermal power (Alsubari et al, 2016; Tangchirapat et al, 2009).

2.6.4.1. Manufacture and properties of POFA

POFA is dried initially in oven at 105 ± 5ºC for 24h; the combustion process is at a temperature of 700-1000ºC and sieved (1.18mm opening) to remove impurities. The different sizes of POFA are based on the specific gravity original size (OP), medium size (MP) and small size (SP) was 1.89, 2.36 and 2.43, respectively. It shows that the grinding process does not just improve the fineness but also the specific gravity. The ash has different colours ranging from greyish in colour and becomes darker as there is increase in unburned carbon. POFA has content of silica amounting to 59.6-66.9%, the loss of ignition (LOI) detected is 8.25% which is higher than the maximum value of 6% stipulated in ASTM C618 which will affect the correct proportion of volume replacement of OPC in the mix (Alsubari et al, 2016; Aprianti et al, 2015).

The specific gravity of ordinary POFA ranges from 1.89 -2.43 and that of ground POFA ranges from 2.05 to 2.78 (Antiohos et al, 2014). Sata et al 2004 and Tangchirapat et al 2009 found that by grinding process, the pozzolanic reactivity of POFA increased in response to the increased fineness of POFA. Based on ASTM C618 the strength activity index which is an indirect method of measuring pozzolanic activity specifies the minimum strength index for fly ash as 75% (Khankhaje et al, 2016). Unground POFA have shown to have larger size, which makes its highly porous compared to ground POFA. Fly ash concrete requires less water compared to POFA concrete to achieve the required slump because of its spherical shaped particles and the solid texture of fly ash. Increasing water in the mix lowers the pH value of concrete and increases the distance between cement hydration products resulting in delay or decrease in the hydration activities of the cement particle. It also decreases the setting time as the fineness increased (Khankhaje et al, 2016).

Fire resistance is an important issue in buildings; in concrete, it must preserve its structural actions for prescribed timespan. The mass loss of concrete containing 20% POFA was lower than control concrete under fire test conditions (Khankhaje et al, 2016).

2.6.4.2. Pozzolanic Reaction of POFA

The increase of pozzolan replacement and fineness will cause a reduction in the $Ca(OH)_2$ content, while improving the sulphate resistance in concrete. The pozzolanic reaction shows that POFA is slow at the early stage and increased at a later stage. The reaction also confirmed that faster reaction of finer particles. The median size particles (10μm) utilized in high strength concrete had compressive strength ranging 60-66 MPa with 20% replacement of OPC at 28 days with total binder 550-560 kg/m^3. The increase in fineness will reduce the expansion and loss in the compressive strength of concrete(Jaturapitakkul et al, 2011).

POFA chemical and physical properties are similar to fly ash, which attracted its use as cement substitute in concrete (Khankhaje et al, 2016).

2.6.4.3 Effect of POFA on mechanical properties of concrete and mortar

By grinding treated POFA (TPOFA) and subjecting it to heat treatment, the compressive strength of concrete will increase because of the finer particles. Tay (1990) discovered that the drying shrinkage of POFA concrete containing 10% POFA was the same as the OPC control mix (Tay, 1990).

Particles containing 10μm POFA showed a reduced expansion compared to control mix and mortar containing 45μm POFA, this is because 10μm hasten the pozzolanic reactivity forms secondary C-S-H gel in a short time. It can also serve as a favourable pozzolan replacing part of Portland cement in producing mortar that exhibits a low carbonation depth and a high strength (Khankhaje et al, 2016).

Replacing up to 30% of OPC with POFA performed adequately but higher proportions caused significant reduction of compressive strength (Aprianti et al, 2015).

(Khankhaje et al, 2016) observed that compressive strength of concrete that contains 20% ground POFA was like OPC concrete. However, increasing the ground POFA content lowered compressive strength because of high water demand. Sumadi and Hussin (1995) reported that inclusion of 20% ground POFA produced durable concrete that was like OPC concrete.

Abdullah et al (2006) suggested that replacing 10-35% of cement with POFA is likely producing aerated concrete. Hussin and Abdullah (2009) demonstrated that 30% of OPC replacement with POFA was able to produce an aerated concrete panel exhibiting strength equivalent to that of an aerated concrete with 100% cement (Khankhaje et al, 2016).

(Jaturapitakkul et al, 2011) investigated the use of POFA to replace 10-40% cement and noted the compressive strength of mortar varied from 0.1MPa to 4.5 MPa at 7 days and 2.5 MPa to 22.5 MPa at 90 days. Also, concrete samples with 20% and 30% POFA showed compressive strength of 59 and 60 MPa, respectively. (Jaturapitakkul et al, 2011).

2.6.3.4 Effect of POFA on hygrothermal properties of concrete and fired clay bricks

The incorporation of POFA improves mortar's resistance to chloride penetration. This is because of pozzolanic reactivity, the reduced $Ca(OH)_2$ and the improved permeability of the mortar. These researches (Khalid et al, 2016) observed that the higher the fineness levels of POFA, the faster the pozzolanic reaction for formation of extra C-S-H gel thus creating denser concrete and enabling it to exhibit better resistance to chloride attack and the longer the curing days (Khankhaje et al, 2016).

2.6.3.5 The effect of POFA on workability of concrete

Literature revealed that replacing up to 30% of OPC with POFA performed adequately but higher proportions caused significant reduction of workability. While for self-compacting concrete, studies showed improvement on workability, enhanced concrete characteristics, decrease cost and saved energy due to POFA inclusion. This is beneficiary to sustainable construction method (Aprianti et al, 2015).

2.6.5. Geo-polymer Concrete

Replacing cement with geo-polymer as a stabilizing agent in concrete could prove economical. In addition, it alleviates environmental pollution caused by cement and aggregate production. Indeed, Gartner (2004) reported that geo-polymer could reduce CO_2 emissions in the atmosphere cause by cement and aggregate industries by approximately 80%. It is a friendlier alternative to stabilizing bricks during raining periods. It involves using amorphous silica (SiO_2), alumina (Al_2O_3), and alkali hydrate. The mixture of alkaline hydrate (NaOH) with water and amorphous silicate produces the same gel (C-S-H) made when cement mixes with water.

It could also be another way to make use of RHA, SBA and POFA because the alkali silicate geo-polymer manufacture could be made from the agricultural wastes (Ariffin et al. 2011). The mixture of pulverised fuel ash (PFA) and POFA completely replaced the combination of sodium silicate and sodium hydroxide solution in the manufacture of geo-polymer concrete. A ratio of 70:30 PFA: POFA achieved the highest compressive strength of 25MPa. The compressive strength also increased with the longer the curing time (Khankhaje et al, 2016)

Karim et al (2013) made a non-cement composite binder (NCB) using slag from cement manufacture, POFA, and RHA with NAOH as the activator. The combination of 42% slag, 28% POFA and 30% RHA with 5% NaOH at 28days achieved the highest compressive strength of 40.68 MPa and flexural strength of 6.57 MPa. (Khankhaje et al, 2016)

Geo-polymer concrete showed better structural stability than OPC concrete after exposure to 800^{o}C. Surface cracks appeared at temperature between 600 and 800^{o}C for geo-polymer concrete whereas it was noticed in OPC concrete at a temperature of 200°C (Khankhaje et al, 2016).

2.6.6. Comparison of agricultural pozzolans

A comparison of the agricultural pozzolans is presented in Table 2.9.

Table 2.3: Comparison of the properties of agricultural waste ash pozzolan material and ordinary Portland cement

Property	Rice husk ash (RHA)	Sugar bagasse ash (SBA)	Palm oil fuel ash (POFA)	Ordinary Portland cement (OPC)
Reactive amorphous silica content	77 – 95%	70 – 89.04%	59.6 – 66.94%	-
density of bricks (kg/m^3)	550.54	258.6	550-560	1120
Compressive strength of bricks (MPa)	5.1	8.38		
Compressive strength of Concrete (MPa)	11-15	8.38	60-66	
Optimum replacement value for OPC (%)	15-30	15-30	15-30	
Modulus of rupture (MPa)	6.62	7.18		
Tensile strength				

The selected pozzolan is RHA as it’s the most widely available in the location the material is required and has good properties based on the pozzolans available in the country.

2.7. Mechanical and Hygrothermal Properties

2.7.1. Mechanical Properties of building materials

Since CEBs are masonry units that act in compression when laid, it is necessary to ensure that they have enough compressive strength. Compressive strength adequate for medium rise building is defined in Table 6.1., Section 6.2.1.2

2.7.2. Hygrothermal properties of building materials

Moisture affects the building energy efficiency, the service life, the indoor climate and the air quality. Durability properties affect the life span of the material and the building (Mukhopadhyaya et al 2002). Lowering permeability of materials can cause improvement in the durability of the materials through reduction of moisture, sulphate ions, chloride ions, carbon dioxide and other harmful substances. The absence of moisture in the building materials will prevent crystallization and recrystallization of ions in building materials as it would not be transported from the atmosphere or ground to the materials (Al-Naddaf 2018). Natural pozzolans have lowered permeability in building materials. The replacement of 10% cement with fine pozzolan caused reduction in sorptivity (Sicakova et al. 2017).

In the tropical climate, building materials used for external purpose are subjected to extremely high temperature, high relative humidity and heavy rainfall. Materials used under such conditions will change in mass if they allow moisture into their membranes. The phenomenon had been the reason for testing the water absorption coefficient of compressed earth blocks. Additionally, it helps to understand how the blocks will perform.

2.7.2.1. Water absorption coefficient and Moisture absorption

Moisture has long been a cause of problem in building structure. This phenomenon results in decay, deterioration, unhealthy environment, inadequate comfort level in the interior of the building, structural and durability problems in building. Water enters the building material through direct rainwater contact on the wall surface, ground water rising, moisture in the atmosphere, etc. (Sicakova et al. 2017; Al-Naddaf 2018; Feng and Janssen 2018). The rise of ground water is known as capillary rise through permeable wall structure causing the material to be damp. Building materials can retain a little water or moisture in the structure and still perform adequately. However, the presence of water becomes a problem when it becomes more than the material can accommodate to maintain comfort and structural purpose. The knowledge of water or moisture movement in materials is important for durability, design use of the material. Capillarity water absorption is related to water sorptivity defined as the tendency of material to absorb or desorb water by capillarity (Karagiannis et al. 2016; Sicakova et al. 2017). Water absorption coefficient is the mass of water absorbed by a test specimen per face area and per square root of time, it can be determined by weighing the samples at different times (Janetti and Wagner 2017; Al-Naddaf 2018). It can occur when capillary movement is caused by the difference between fluids surface capillary pressure and its gravity pressure which causes fluid movement until balance is reached (Sicakova et al. 2017). Water absorption coefficient governs liquid movement into a material (Mukhopadhyaya et al 2002).

Water absorption coefficient required for CEBs unit is discussed in section 6.2.2.1 and moisture absorption is discussed in section 6.2.2.3

2.7.2.2. Water vapour transmission

The process of vapor transportation is the movement of water vapor in the opposite direction from higher vapor in the atmosphere through the material surface to a lower vapor atmosphere. Water vapor transport in porous building material have negative effect on the service life of a building (Kočí et al, 2011). Water vapor resistant factor indicates the degree to which moisture transfers from the external surface to the internal surface, it can be expressed as the capacity of a material to let vapor pass or to block vapor from passing through (Ducoulombier & Lafhaj, 2017; Zhao & Plagge, 2015). The rate of water vapor flow is measured by using the wet/dry cup method. This method is called a CUP method as it utilizes a cup with desiccant (dry) or distilled water/saturated salt (wet) sealed with one side of the material and the cup is placed in a climatic chamber (Maillard & Aubert, 2014; Zhao & Plagge, 2015). It measures the vapor diffusion through a unit area of the material at a unit time under controlled temperature and relative humidity. The change in mass of the sample against the time is then used to determine the water vapor flow rate (G) (Zhao & Plagge, 2015). The ability of a porous material to retard vapor diffusion can be described as vapor diffusion resistance factor (μ) which indicates how much vapors can diffuse through the material (Maillard & Aubert, 2014; Zhao & Plagge, 2015).

Water vapor transmission required masonry unit such as CEBs in section 6.2.2.2

2.7.2.3. Moisture buffering

Earth is a reusable and environmentally friendly material that can exchange moisture effectively with the environment. The hydrothermal properties of building materials as be observed to influence indoor comfort level of building users. Materials with good moisture storage abilities on the other hand can absorb water vapour from the environment when the Relative Humidity (R.H) increases and released water vapour when the R.H decreases in order to maintain a more stable indoor comfort level (Zhang et al., 2018). Earth materials have a large moisture capacity compared to fired clay bricks and concrete (Zhang et al., 2018). The ability of a material to properly absorb or release moisture from its body plays a significant role in the risk of biological growth on the surface of the material (i.e. mould growth on wall surface).

Moisture buffering performance is the ability of the space to regulate relative humidity level daily or seasonally. The moisture buffering value is the amount of water that is transported in and out of a material per open space during a certain period when it's subjected to variation in R.H of the surrounding air. The effect of moisture buffering on the compressed earth blocks stabilized with ordinary Portland cement and rice husk ash was explored by subjecting the samples in a cyclic variation of low (33%) and high (75%) relative humidity variation (Adam & Jones, 1995). The objective was to determine the moisture buffering value of both fully and partially stabilized with ordinary Portland cement compressed earth blocks according to NORDTEST method (BYG DTU R-126, 2005). Before the test was initiated the samples were conditioned at 23±5ºC and R.H pf 50±5% for a period of 2 weeks till constant mass was reached. Samples were exposed to R.H of 75% and 33% for a period pf 8hr/16hr interval. Temperature was controlled at 23±5ºC throughout the cycle. Five humidity cycles were then performed which was enough to attain steady state conditions. Steady state is reached when mass change of three consecutive cycle at moisture uptake at 75% and moisture released at 33% R.H must not vary more than 5% (BYG DTU R-126, 2005). Moisture buffering value for construction material can be classified as negligible, limited, moderate, good or excellent as indicated in Figure 2.11. Moisture buffering requirement based on literature review in discussed in section 6.2.2.4

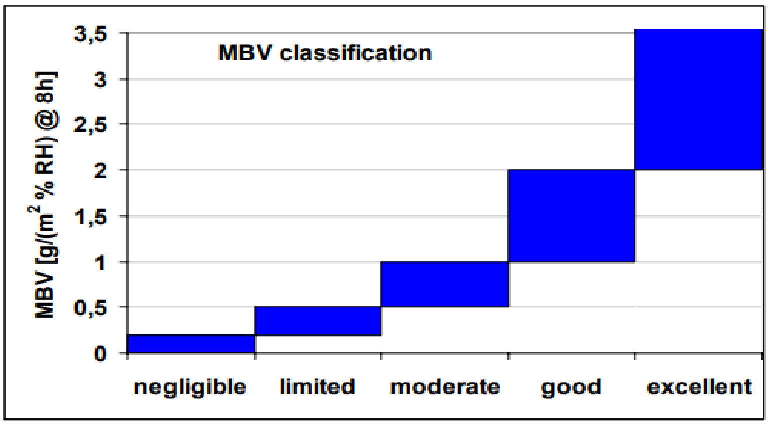


Figure 2.10: Classification moisture buffering values (McGregor et al, 2014)

2.7.2.4. Thermal property of the material

Climate change has led researchers to focus on a means to reduce energy consumption, improve hydrothermal comfort during the construction phase and the service life of the building (El Fgaier et al. 2015). Earth is considered a good material to achieve these factors. Earth material is considered a suitable material as its widely available, low cost, low energy required to use, transportation, recyclability as there is lack of affordable houses for low-income earners experienced in Nigeria and other developing countries. These have led to this research concentrate on using compressed earth blocks to help reduce the high energy and greenhouse gases caused by the construction industry. A building is to perform the function of regulating the internal thermal comfort in response to the external climate condition. Thermal comfort is subjective but can be expressed as the condition of mind where the occupant experience satisfaction (Taylor et al. 2008). The temperature and relative humidity of the space affect the level of comfort for the users. To ensure the sustainable thermal comfort building the thermal performance criteria has increased from the norm where high heating and cooling services are required to achieve comfort for users (Ashour et al. 2015).

Thermal conductivity required for masonry unit such as CEBs is discussed in section 6.2.2.5.

2.7.3. Indoor Air Quality

Indoor air quality is one of the most serious elements for the health of the building's occupants (Nguyen et al. 2017). For example, high moisture in the building can cause, hydration of absorbed inorganic salt, dampness of material, presence of organic growth on the wall surface (mold, algae, fungi etc.) and loss of insulation properties within the internal spaces (Kočí et al. 2011; Ducoulombier and Lafhaj 2017; Nguyen et al. 2017). Moisture transfer in a building occurs mainly through water vapor and liquid transport under actions of capillary forces (Ducoulombier and Lafhaj 2017). When the indoor air temperature is higher than the outdoor temperature, water vapor diffusion occurs (Ducoulombier and Lafhaj 2017). When relative humidity increases, the moisture in the atmosphere increases and more adsorption occurs, as a result, the pores are covered with a film of water, the adhesive holding the water particle from moving into the internal space decreases, some become mobile and initial surface diffusion occurs (Ducoulombier and Lafhaj 2017).
Moisture causes dampness, deterioration to the fabric, corrosion to metals in building and mould, rot, and decay within the building structure. Moistures can cause an adverse reduction in thermal resistance of the materials within the structure and increases the risk of mould and interstitial condensation. Initial moisture in building can be from construction, moisture can also be introduced to building fabric as a result of occupants and their activities i.e., bathing, cooking, indoor swimming pool, industries, food factories generate large moisture (Zemitis et al. 2016; BS 5250:2011+A1:2016). The different activities in a residential house generates different moisture in the space. It can be shown in the table below.

There is a high risk of mould growth on the external fabric of a building when the relative humidity is above 70% for a long period of time, the risk can be reduced by increasing temperature, or decreasing vapour pressure or a combination of the two factors. Moisture can also be introduced into the building structure from sources such as follows.

a. Water used in construction: masonry structure, concrete, plastering of the walls etc.
b. Ground water seeping in from walls and floors in contact with the ground.
c. Flooding:
d. Precipitation: Rain fall been a major factor in the southern part of Nigeria.
e. Spillage or leaks

f. Airborne moisture, continuous high relative humidity
g. Building use: areas such as kitchen and bathrooms has more moisture in the internal spaces than areas used for living rooms or sleeping areas (WHO 2009). Data related to this is presented in Tables 2.10 and 2.11.

The two parameters considered most relevant to the interior moisture level of the building's life are building use and external climate. The moisture attributed to these parameters is now discussed in more detail.

A. **Building use**

Table 2.4: Moisture generated by different household activities in residential buildings.

Household Activities	Moisture generation rage	Moisture rate typical person in a day
People: Sleep Active	 40g/h per person 55g/h per person	 320g/day per person (Bedroom in 8hrs sleep) 440g/day per person (living room, dining, bedroom 8hrs)
Cooking: Electricity Gas	 2000g/day 3000g/day	 2000g/day 3000g/day
Dish washing	400g/day	400g/day
Bathing/washing	200g/person per day	200g/per person day
Washing clothes	500g/ day	500g/day
Drying clothes indoor	1500g/person per day	1500g/ per person day

(BS 5250:2011+A1:2016)

Internal Moisture content in buildings

In a typical house in Nigeria with 4 people living in the space, cooking is primary done using gas as a source of fuel in the house. The calculation of moisture that can be done by the people using the space on a washing day.

From the table 2.11, its observed that some part of the house generate more moisture in the spaces depending on the type of activities that is carried out in the space. The moisture content in a typical Nigerian house generate in living room, bedroom and dining room combine is less or about the same as a place like kitchen alone in one day.

Table 2.5: Typical moisture generated in areas with normal and high relative humidity in a typical house generated from table 2.10

Interior spaces	**Moisture content rate**
Normal relative humidity areas	
Bedroom	1280g/day
Living room, dining room	1760g/ day
Total moisture content normal relative humidity	3040g/gay
High relative humidity areas	
Kitchen:	
Cooking	3000g/day
Dish washing	400g/day
Total kitchen moisture content	3400g/day
Bathroom:	
Bathing	800g/day
Washing cloth	500g/day
Drying cloth	1500g/day
Total bathroom moisture content	2800g/day
Total moisture content high relative humidity	6200g/day

2. external climate- (Rainfall or precipitation rate of building location)

Rain fall is natural climatic factor that occurs in the Southern part of Nigeria regular with high driving force. The driving rain direction intensity on the building structure can be influenced by factors such as mentioned below:

1. Location of the building

   Köppen-Geiger climate location: Nigeria contains four climate types – monsoon climate (Am) in part of the coast, tropical savannah climate (Aw) across most of the country, warm semi-arid arid (BSh) and warm desert climate (BWh) in the northernmost part.

   Nigeria has a mix of urban and rural areas. Urban areas are characterised with a high population density supported by high-rise buildings and proximity of surrounding buildings to one another. Rural areas have less population density, more open areas which could have green areas for farming, grazing for animals or just open green areas for wild animals to live. This work focuses on building in city that are sheltered by surrounding buildings. Building located in urban areas are more likely to be sheltered by other buildings, thereby reducing driving rain intensity compared to buildings in rural areas.

2. Orientation of the wall: the wall facing the predominant rain direction is likely to be more exposed to rain or moisture on its surface than other walls in other direction. So, walls in that direction should be treated to ensure the rainwater or moisture does not remain on it for a long period of time.
3. Degree of the shelter: walls can be subjected to low slope roof, high slow roof or subjected to high rain runoff. In the southern rain areas of Nigeria that experiences high rainfall, the use of walls that area subjected to high rain runoff is to be avoided as much as possible but if it cannot be avoided should ensure the material of the wall is not easily damage by presence of moisture or treated adequately. The use of high slope roof is the most adequate to remove rain load from the building easily, especially when considering the use of earth material that has high affinity to water absorption when exposed.

2.7.3.1. Mould growth in buildings

Dampness on the surface of the wall can lead to biological growth or material degradation when not adequately removed. Dampness can cause mould growth and interstitial condensation. Dampness may occur in new and old building. In existing building when poorly, insulated spaces lead to low internal surface temperature and in new building airtight envelope with bad ventilation management may lead to high internal relative humidity (Fantucci et al. 2017). Mould is likely to occur in spaces with high relative humidity, poor or no ventilation and cold surfaces. Structural damage, water damage, rising damp, leaks can also promote mould growth in a building surface (Hurraß et al. 2017). Mould is used to describe fungi which is visible or invisible to the human eye. Mould spreads and reproduces spores. It grows on different surfaces such as paper, cardboard, masonry, plastics etc. Indoor mould is a major health issue such as allergy respiratory diseases, asthma, allergic rhinitis, hypersensitivity pneumonitis (HP), exogenous allergic alveolitis (EAA). Promoting respiratory infections (e.g. bronchitis) have been proven to be caused by exposure to mould (Hurraß et al. 2017). It is also suspected to cause rheumatism, arthritis, sarcoidosis, cancer, neurotoxic effects, atopic eczema, chronic obstructive pulmonary disease (Hurraß et al. 2017).

Mould can reduce the quality of a building fabric. Mould in building also causes negative effect on the physiological, visual hazard and health risk to the users of the space (Marincioni and Altamirano-Medina 2017). Mould may release volatile organic compounds (VOCs) which can lead to sick building syndrome (Sadovský and Koronthályová 2017).

People often spend 90% of their time indoor so it is important to ensure that mould growth is eliminated. The tropics (latitudes from 23.4367^o North to 23.4367^o South) is the worst climate condition for building materials as its exposed high amount of rainfall, high sun radiation, high humid wind etc (Udawattha et al. 2018).

Large mould spores are present in the atmosphere at relative humidity of 80% which also provides oxygen and moisture resulting in easy germination. Mould spores can germinate at relative humidity lower than 80% and survive in dry environment although it would not germinate during such conditions. Mould growth can occur in the winter because of greater duration of relative humidity remaining at 70% or more during this season. Problem of indoor air quality is an important risk factor for health of both the developing and developed countries. A rule of thumb states that relative humidity higher than 80% presents a risk of mould growth, the risk is dependent on the surface temperature and the number of days of exposure.

These findings are supported by the work of Gradeci et al (2017) carried out an investigation which found that relative humidity was the most important parameter in relation to mould growth. Mould growth would likely occur at relative humidity of 75-95% and temperature of -20^{o}C to 60^{o}C (Gradeci et al. 2017). Germination of mould will occur in interior spaces when high relative humidity for longer than a day and if the dry period or low humidity is experienced long the germination possibility is low or negligible. Mould growth is likely to occur during desorption period than during the absorption period as growth is not just the function of water activity but also moisture ration. It is affected by how fast the building material is likely dry or lose its moisture (Gradeci et al. 2017). An increase in relative humidity by 1% is more likely to cause a change in the germination process than an increase in temperature by 8^{o}C for relative humidity higher than 85% (Gradeci et al. 2017).An investigation of mould growth analysed the following materials: engineering bricks, cement blocks, cabook, cement stabilized earth blocks, mud concrete block, fly ash stabilized earth blocks Engineering brick was found to be the most susceptible to mould growth and cement stabilized earth block was the least susceptible to mould growth(Udawattha et al. 2018).

Mould risk can be predetermined or assessed using one of the following principles mentioned when simulations are run on the building materials.

1. Mould can be assumed to occur when the conditions for “mould risk” in Figure 2.12 are met in the internal space. When the relative humidity is greater than the critical relative humidity at certain temperature mould is likely to germinate (Sadovský and Koronthályová 2017)(Fedorik & Illikainen, 2013).

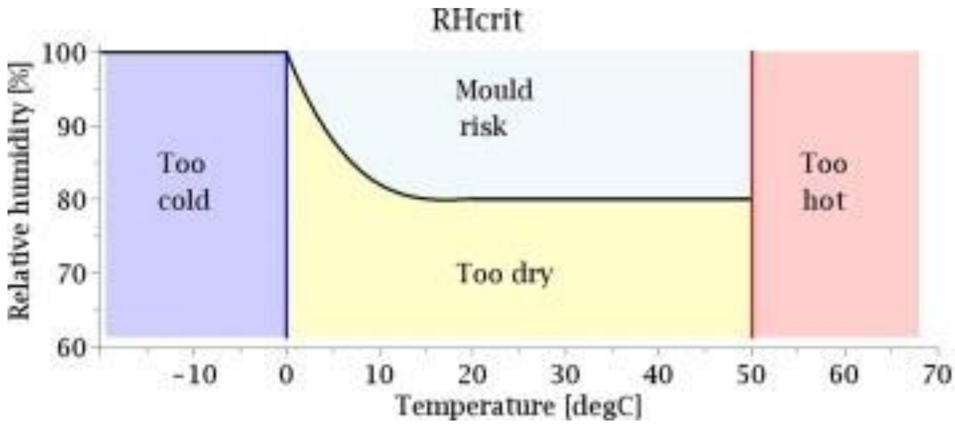


Figure 2.11: Range of temperature and relative humidity for mould germination.(Fedorik & Illikainen, 2013)

- The critical relative humidity varies for temperature from ≥ $0^{o}C$ < $20^{o}C$. the relative humidity at each point needs to be mathematically calculated using the formula below

  $RHcrit=-0.00267T3+0.161T3+3.13T+100$

- The critical relative humidity for temperature ≥ $20^{o}C$ ≤ $50^{o}C$ is 80%.

2. buildings require that 30 day moving average of relative humidity to be below 80% for the surface and temperature should be between 5-$40^{o}C$, this is more severe than the ISO standard (BS EN ISO 13788:2012) used for interior surface that states.
   - For 7 days duration moving average relative humidity should be below 98%
   - For 24 hours (1 day) moving average relative humidity should be below 100%,
   - If the relative humidity on the surface passes 100%, condensation has occurred, (Fantucci et al. 2017)
3. Mould prediction can be done some using simulation software (e.g., WUFI Pro). Inputs for the simulation software include the internal temperature, moisture, substrate of the material and exposure time. The substrate class of different building are be described in Table 2.12.

Table 2.6: Substrate class for mould growth

Sensitivity class	Examples of building materials	Min relative humidity	Substrate	Description of materials
Very sensitive	Pine sapwood	80%	0	Optimum culture medium
Sensitive	Glued wooden board, paper surface	80%	1	Biodegradable building materials
Medium resistance	Concrete, aerated and cellular concrete, wool, polyester wool	85%	2	Building materials with some biodegradable compounds
Resistant	Polished surface	85%	3	Non-biodegradable building materials without nutrient

(Gradeci et al. 2018)

The mould growth simulation is based on data representing total water content, temperature and the relative humidity the wall is exposed to. After the simulation has been complete the mould growth on the surface of the material can then be classed using the index described in Table 2.13.

Table 2.7: Mould index

Mould Index	**Mould growth(mm)**	**Mould coverage**	**Description**
0	0	0%	No growth
1	50-130	1-20%	Small mould growth seen with microscope
2	131-199	21-40%	Several growths seen with microscope
3	200-238	41-60%	Visually seen with 10% coverage or less than 50% seen with microscope
4	238-335	61-80%	Visually seen of about 10-50% or less than 50% seen with microscope
5	336-450	81-100%	Plenty growth with less than 50% seen visually
6	575	100%	Heavy tight growth with about 100% coverage

(Chen et al. 2016; Gradeci et al. 2018)

Mould growth prediction would be checked using the WUFI Pro checking the relative humidity and temperature within the building structure and in the building for a year and WUFI bio mould index would also be analysed to accurately predict the indoor air quality of the building using the selected material.

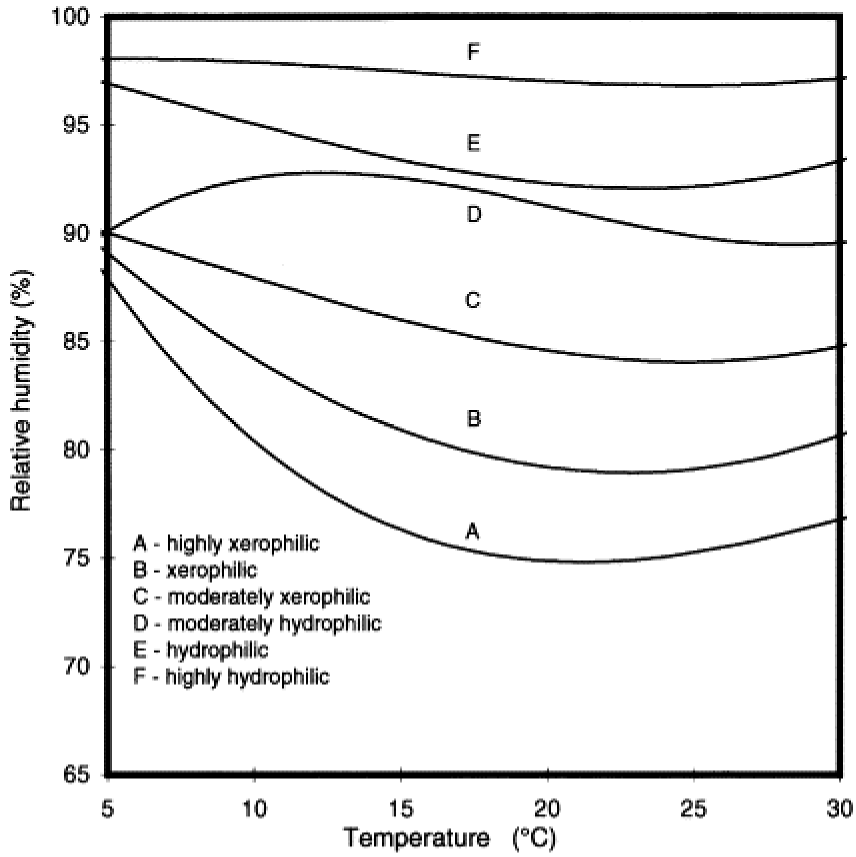


Figure 2.12: Limiting growth curves for mould growth categories (Clarke et al, 1999)

Xerophilic organism can grow with low moisture content and hydrophilic organisms needs high moisture content to germinate. The figure shows that the increase in relative humidity which means increase in moisture content agrees with the hydrophilic and xerophilic characteristics of mould organism.

2.7.3.2. Condensation

Condensation can occur in building in two forms – condensation on the surface of the building material and interstitial condensation. Both are described below.

1. Condensation on the surface of the building material

Surface condensation occurs when humid air cooled to its dewpoint meets cold non-absorbent surface such as glass (Fantucci et al. 2017). The surface condensation is affected by two factors that includes the temperature and vapour pressure of the air.

Temperature of the surface of building material can be affected by; time rate of heating in the building, ventilation rate, thermal property of the surface finish of the building fabric, external temperature. The building material in Nigeria climate is to be exposed to external climatic factors which cannot be change, thermal property of building material is gotten from the thermal conductivity rate. The ventilation rate is the factor that can be adjusted to meet the need of the people and the building. It can be through natural or HVAC system. To achieve affordable and sustainable building, the natural means of ventilation is the most adequate.

Vapour pressure of the building can be influence by, water vapour production within the building space, ventilation rates, moisture content of the outdoor air, ability of building to absorb or desorb water content (moisture buffering effect) (BS, 5250:2011+A1:2016). The different spaces in the building have different vapour pressure. The moisture production in the building spaces differ based on the use of the space which is discussed in Table 2.10 and 2.11.

2. Interstitial condensation

Interstitial condensation occurs within the building material when water vapour moving through it meets material that is at a temperature and relative humidity below the dew point of the vapour. In the winter, interior of building is warmer, and air contains more moisture than the external side of the building. In spring, autumn as well as summer, surface temperature might be lower in the external side, the external surface of south facing walls may be wet by driving rain and can be heated by sun causing when the moisture can dry. Interstitial condensation can lead to staining, odours, deterioration of fabric and loss of thermal performance.

Relative humidity of interior air, air tightness of the vapour barrier and the temperature are all import factors to study in order to prevent interstitial condensation in building structure. The indoor environment can be improved by controlling the external climate that is allowed into the space. It can be controlled by altering the building form and adjusting the orientation of the building in relation to the topography, prevailing winds, sun light, and shadows caused from surrounding buildings or obstructions (BS 5250:2011+A1:2016).

The interior space can be improved by improving the air tightness in wall cavities to reduce hygrothermal risk. Relative humidity of interior air can also be reduced by providing adequate source of ventilation. Increasing the ventilation alone cannot reduce hygrothermal risk but in tandem with an increase in temperature and or increasing air tightness can also improve the risk in buildings.

Interstitial condensation can occur easily in areas of the house such as;

- Corners of the rooms, mostly external walls
- Lintels and windowsills
- Behind the furniture placed against external walls

- Internal part of the building facing the driving the driving rain direction (BS 5250:2011+A1:2016).

To prevent interstitial condensation on building structure the following should be followed according to BS EN ISO 13788: 2012

a. Coldest month should not have internal relative humidity above 80%
b. Any interstitial condensation that occurs during the winter should be evaporated during the summer period.
c. The risk of degradation of material should be assessed in terms of the level of condensation which might occur.

It is necessary to consider the conditions which facilitate interstitial condensation in the context of the human comfort level which lies between 45-70% relative humidity at 18-24ºC. There is little gap between human comfort level and conditions which encourage mould growth. Therefore, when relative humidity exceeds 70%, it important to remove excess moisture from the space by providing ventilation or dehumidification source (BS 5250:2011+A1:2016). Natural Ventilation allows air pressure to move across the building envelop as a result of the internal and external temperature difference together with wind forces. Dehumidification is a mechanical process of removing moisture from the building.

The external climate allows the building structure such as wall component to be exposed to solar gain, night sky radiation and exposed position.

- Exposure to solar gain: the building structure increases temperature which promotes rapid drying of any condensation that nay have occurred.
- Night sky radiation: the external surface of the building cools easily at night which means interstitial condensation can occur on the internal surface easily and can then be easily evaporated during the daytime to reduce condensation on the building fabric. (BS 5250:2011+A1:2016).
- Exposed position: (BS 5250:2011+A1:2016). In an urban city, some areas of the building are exposed to external climate and the other part of the building can be sheltered. The exposed area has high wind speed and driving wind that cools the external surface of the building and cools the internal areas closest. (BS 5250:2011+A1:2016).

2.8. Design principles for buildings in Nigeria

Nigeria is in the tropics where heating of interior spaces is not needed to achieve comfort for the users, however there are several approaches that are appropriate for the region. The interior climate in Nigeria can also be controlled by using one of the following approaches:

1. Ventilation: constant flow of air allows internal relative humidity (moisture in the air) to remain between 40-70% to ensure comfort and reduce mould risk. Ventilation is also used to remove unwanted smells and pollutants from a space (BS 5250:2011+A1:2016). This is usually achieved by natural ventilation. The rate of ventilation depends on the size of the openings/vents, driving force of air which can create wind pressure and buoyancy from temperature difference can also cause stack effects. Wind pressure is dependent on the wind speed and direction. Natural ventilation in a house can be achieved through different means such as single sided ventilation, cross ventilation, wind tower, stack system, atrium ventilation. The southern climate of Nigeria commonly uses cross ventilation and places that can't be cross ventilated use single sided ventilation. The northern climate of Nigeria commonly uses the wind tower system
2. Insulation: building insulation can raise the surface temperature of the building (BS 5250:2011+A1:2016).
3. Places with high relative humidity such as kitchen and bathroom can control the moisture content by doing one or a combination of the following:

   a. keeps the internal doors for kitchen closed and leave the windows opened while cooking.

   b. keeps the doors closed while bathing and open the windows after bathing or showering.

   c. uses an electric fan till the mist in the air clears in the space.

   d. if condensation has occurred on the surface it can be mopped dry.

The current research concentrates on using compressed earth blocks for the construction of affordable and sustainable walls. The different wall system is to be studied to under the most suitable for Nigerian climate. Solid walls include stonework, brickwork, blockwork, earthwork or concrete. The thermal mass property allows change in temperature to respond to change in air temperature slowly and of moisture change to some degree.

2.8.1. Possible walls system used for construction with compressed earth blocks.

There are different wall types that be used in construction earth walls in Nigeria. Each is described below in relation to their risk of interstitial condensation and mould risk. The wall design is studied to understand the best principle that should be applied in a place with tropical savanna climate, with high relative humidity and high temperature to prevent moisture build up in the building structure.

1. Solid masonry wall- external insulation with low pressure resistance finish is illustrated in Figure 2.13 (internal finish on right). Insulation can be applied to new and old

buildings. External insulation when applied reduces the risk of thermal bridges and risk of water penetration. There is no calculation needed for mould growth and interstitial condensation (BS, 5250:2011+A1:2016).

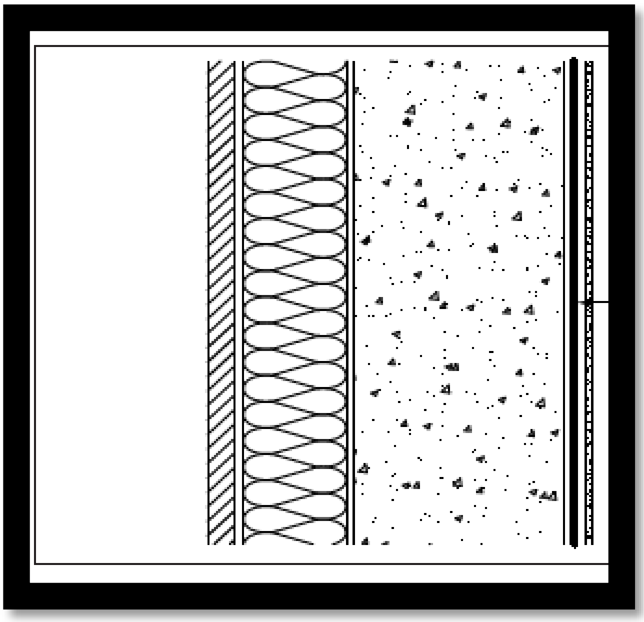


Figure 2.13: Solid wall with external insulation with low resistance finish, (BS, 5250:2011+A1:2016)

2. Solid masonry wall- external insulation with high vapour resistance finish is illustrated in Figure 2.14 (internal finish on right) A ventilated cavity is present between the insulation and the finish. The risk of mould growth should be calculated following the principles of BS EN ISO 13788(BS, 5250:2011+A1:2016).

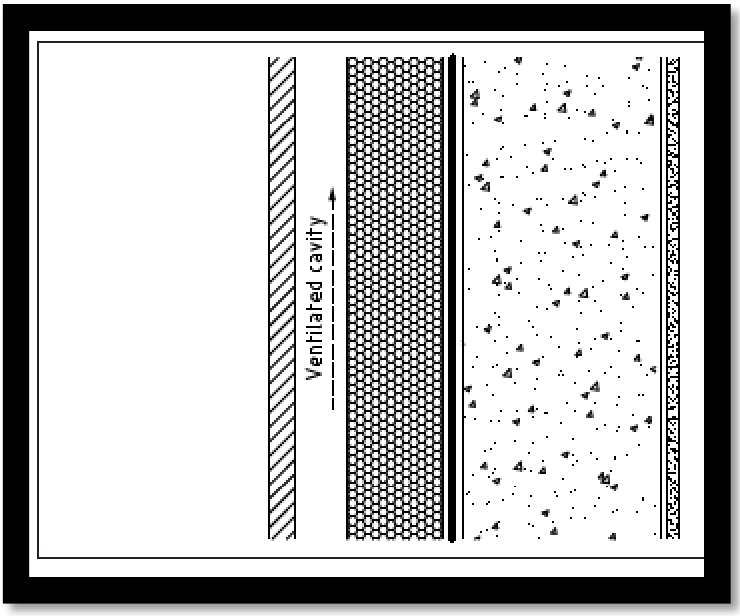


Figure 2.8: Solid wall with external insulation with high vapour resistance finish, (BS, 5250:2011+A1:2016)

3. Solid wall- internal insulation is illustrated in Figure 2.15 (internal finish on right). the risk of moisture risk on the wall is calculated using BS EN 15026: 2007(BS, 5250:2011+A1:2016; BS EN, 15026:2007)

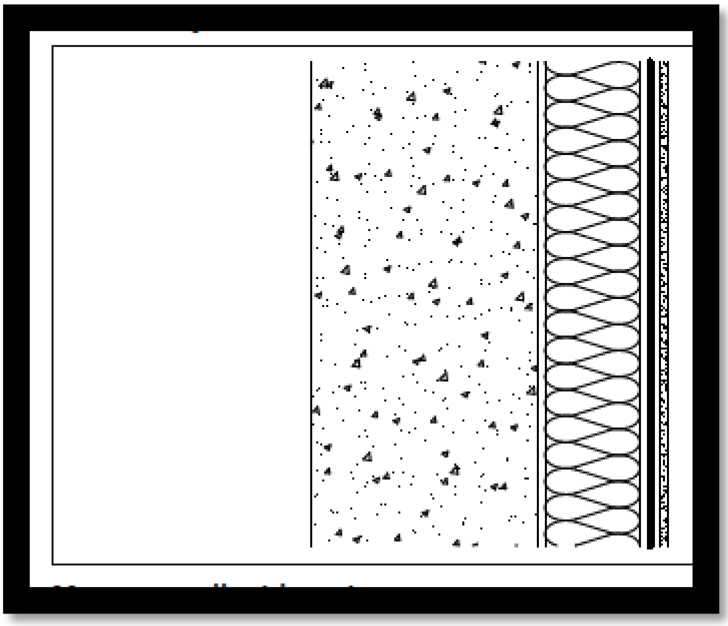


Figure 2.9: Solid wall with internal insulation, (BS, 5250:2011+A1:2016)

4. Masonry wall with cavity- External insulation is illustrated in Figure 2.16 (internal finish on right). The use of external insulation might be necessary for improving thermal performance. There is a risk of interstitial condensation when the building is heated; however, a Nigerian building does not get heated as it has warm climate all through the year, therefore no calculation is needed for mould growth and interstitial condensation. (BS, 5250:2011+A1:2016)

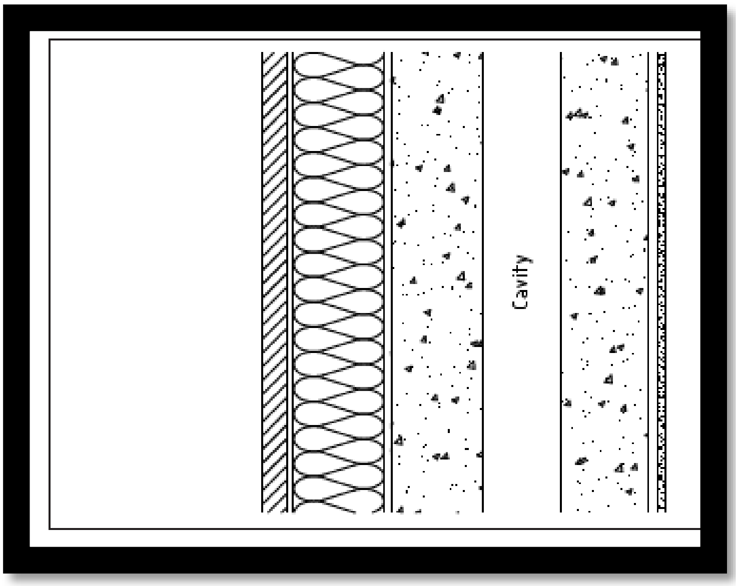


Figure 2.10: Masonry wall with cavity, external insulation (BS, 5250:2011+A1:2016)

Cavity is to prevent rainwater to the interior of the house. Rainwater may penetrate the external skin of the structure if it's not adequately constructed but the cavity will reduce the chances of it going through the inner skin and entering the interior space. The use of these wall system seems to be a very good for the climate in Nigeria that is considered. (BS, 5250:2011+A1:2016)

5. Masonry wall with cavity- internal insulation: The insulation could fully or partially fill the cavity. The introduction of insulation in the cavity might reduce the primary purpose of the cavity of reducing rainwater. The risk of interstitial condensation depends on the heating regime of the interior space and the type of thermal mass material used in the inner leaf. There is a higher risk of interstitial condensation when a higher density is combined with a heating regime. Nigeria house doesn't have any heating regime throughout the year. The use of fully insulated cavity will not be advisable to use in the country as the external wall is required to keep the large driving rain fall from coming into the internal space (BS, 5250:2011+A1:2016). The risk of moisture is calculated using BS EN 13788, (BS EN, 13788:2012)

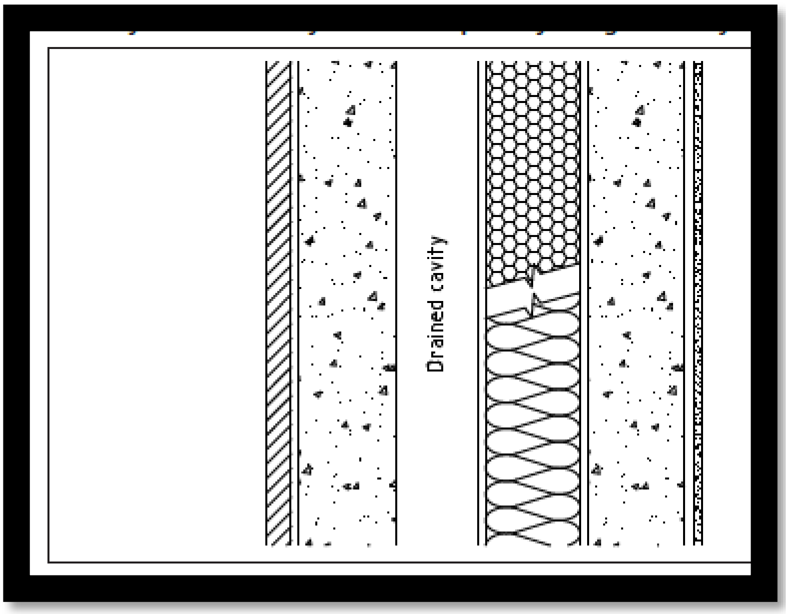


Figure 2.11:Masonry wall with cavity- insulation partial filling the cavity(BS, 5250:2011+A1:2016)

2.9. Summary of literature findings

There is significant housing deficit caused by several factors mentioned by (Ugochukwu & Chioma, 2015). Key factors are lack of land and cost of materials.

Medium rise housing appear to be the optimum compromise between low rise housing (significant land use) and high rise housing (significant energy use particularly for vertical transport) (Craighead, 2009). Medium multi-story (3-5 storeys) houses were found to have the best compromise between minimising land use and minimising energy consumption –

particularly for vertical transport. The quality of the building design strategy for passive environment is to be analysed used simulation too design builder to ensure maximum adaptable comfortable interior environment.

(Olotuah, 2002) found that using local materials could reduce the overall cost by 50%.

Traditional architecture responds to local culture, climate, and materials (Alabsi et al, 2016; Kırbaş & Hızlı, 2016). The traditional architecture tends to use local material and passive design strategies that are important to the climate such as shading ventilations and thermal mass in the north and in the south roof with wide slope, raised building and cross ventilations. Whereas the modern residential building uses materials that focuses on the aesthetic and international designs strategies not suitable for the climate. This modern design raises the building materials and increases the energy required for the operation and construction of the building. The need to provide affordable houses should be reconciled consideration to the environment - this research aims to solve the problem of accommodation while minimising problems to the environment.

The building material was the focus to reduce the cost of building material and energy use of building. The requirement of the building material required needs to be affordable, minimise environmental impact, structurally appropriate, conducive to thermal comfort and good indoor air quality and avoid social stigmatisation.

The present research concentrates on materials used for wall construction for residential building. The materials most used are blockworks, fired clay bricks, stonework and earth blocks. Blocks and fired bricks– not affordable and have significant environmental impact. Stone has fewer environmental impacts than bricks and blocks, but there is not a sufficient local resource, which requires importing and expense. (Ashby, 2013) (Charlett, 2013).

Earth is labour intensive and has many environmental benefits in construction and in use (Abd Rashid & Yusoff, 2015; Darko et al, 2017; Van Damme & Houben, 2017). However, in some forms (particularly adobe blocks) it is associated with poor quality construction and social stigmatisation. This can be addressed using CEBs which have a different appearance, but more importantly have appropriate strength and durability if incorporated in a sympathetic design which protects the blocks from driving rains common in Nigeria. However, using the lateritic earth available in Nigeria it requires stabilisation. Cement is currently used, but this has associated costs and environmental impacts. Ashes from agricultural waste (rice husk, sugar bagasse and palm oil fuel) have been researched as cement substitutes in blocks, bricks and mortar applications. These sources have particularly been chosen for their availability in Nigeria. The impact on mechanical properties of a range of cement substitute proportions have been analysed for these three materials (Almeida et al, 2015; Ganesan et al, 2008; Givi et al, 2010) (Khankhaje et al, 2016). The waste product considered were rice husk ash, sugar bagasse ash, and palm oil fuel ash. Rice husk ash is deemed to be the most suitable agricultural waste as it's widely available in the country, particularly in the Tropical savannah climate which dominates Nigeria.

The reason for abandonment includes factors such as strength, durability, social stigmatization. The current research would aim to improve factors mentioned.

Hygrothermal properties are important to ensure the CEBs will have the expected durability and will not have adverse impacts on indoor air quality (eg mould formation) (Mukhopadhyaya et al 2002) (Nguyen et al. 2017). Equally the impact of CEBs on thermal comfort (RH, temperature and surface condensation) (Fantucci et al. 2017) (BS 5250:2011+A1:2016) are important considerations for occupant acceptance, particularly given previous stigmatisation of earth-based housing.

The quality of residential material using local soil as the main constituent of construction, while utilizing agricultural waste ash for partial stabilization in the country for sustainable and comfortable environment can be determined by two criteria. The quality of the material for the type of building required and the potential design strategies required.

The quality of material can be analysed by checking the mechanical and hygrothermal property of the material in a laboratory. The mechanical strength is to ensure that material can carry the load it will be exposed to from dead load, live load of users, external load etc. the mechanical strength for compressed earth blocks to be analysed includes compressive strength and bulk density of the material.

The hygrothermal properties relate to indoor air quality and are also required to ensure the comfort of the users in the space. The tests required includes water absorption coefficient, moisture absorption test, water vapour transmission, moisture buffering test and thermal conductivity test. Improvement of the property of the material would also mean the reduction of energy required to keep the user of the space comfortable. To analyse the hygrothermal property of the material in depth, hygrothermal simulation based on the laboratory results is required.

The parameters affecting hygrothermal and thermal performance were identified such as building location in relation to climate and surrounding buildings, orientation, shelter from rain (ie roof), moisture from indoor activities. The assessment criteria for mould growth risk were defined (Sadovský and Koronthályová 2017) (Fedorik & Illikainen, 2013), (ISO 13788:2012 (Gradeci et al. 2018)

Potential wall structures which can incorporate CEBs are considered in relation to potential interstitial condensation and mould growth. The most suitable wall design for tropical savanna climate (Aw) in Nigeria is the option of masonry wall with cavity to prevent driving rain from going into the inner skin of the wall. The wall could be having full cavity or partially filled cavity with insulation.

This literature review has revealed a lack of research on CEBs with RHA as a cement substitute and its effect on the resulting hygrothermal properties and impact on indoor air quality and thermal comfort of the resulting building. It has also revealed little data on the mechanical properties of CEBs with RHA as a cement substitute.

3 Research Methodology

This chapter describes the activities carried out at various stages of the research project in order to achieve the objectives of the study. Section 3.1 describes the relevant research strategies used from the inception to the conclusion of the research. Section 3.2 describes the processes adopted in this research for production and testing of materials used for manufacturing CEBs, and the production of the experimental CEBs. Section 3.3 describes the tests carried out on the CEBs to ascertain their mechanical, physical and durability properties. Section 3.4 describes the simulation to test the hygrothermal performance of the wall material. Section 3.5 describes the method applied to develop the building design optimised for CEBs in the local climate and to compare the thermal comfort arising from using CEBs versus concrete blocks.

3.1 Research Framework

The current study concentrates on a means to provide affordable and sustainable residential houses for low-income earners in Nigeria. The construction techniques, materials and design process are to ensure that the construction process has less negative impact on the earth for present and next generation. Figure 3.1 illustrates the theoretical framework adopted in the study for providing affordable and sustainable residential houses using compressed earth blocks partially stabilized with rice husk ash. The steps employed to achieve the required material property is described in this section.

1. Provision of affordable and sustainable residential houses: there have been different research methods carried out across the globe to ensure affordable and sustainable buildings in areas such as the design method, construction methods, building materials used for building construction, policy of the industry, and some other methods. This research focused on providing affordable and sustainable material for wall construction. The use of locally available material using simple methods for production and material that does not adversely affect the environment for this generation and future generation to come.
2. Compressed earth block: it is a traditional masonry material technique that requires the use of the local soil, it can be stabilized to improve it is mechanical and hygrothermal property and requires minimal energy and simple methods for production.
3. Raw materials: the local soil of the area is laterite. Laterite is major material required for production of compressed earth blocks. It has high content of clay and this causes moulded material to have high tendency to shrink and cause cracking when dried. The characteristics of shrinkage and cracking can be resolved by reducing the clay content and stabilizing the soil. To reduce the clay content ratio,

there would be addition of sandy soil to the mix and to stabilize the soil, ordinary Portland cement and rice husk ash would be mixed in varying ratio. Rice husk ash would be prepared according to achieve the require amorphous silica content.

4. Production of CEBs: The material laterite, sandy soil, ordinary Portland cement and rice husk are mixed in varying ratio. The laterite soil and sand soil mix ratio remain a constant ratio, while the ordinary Portland cement is gradually reduced and replaced with rice husk ash. There are two types of blocks produced which included the solid and hollow blocks. The blocks are cured for a duration of 14, 21 and 28 days.
5. Evaluation of mechanical and hygrothermal properties of CEBs: the varying ratio of the blocks are laboratory tested in to ensure the blocks meet the required mechanical property required for the building type. Blocks that meet the required mechanical test are further tested to ensure it meets the hygrothermal property required for masonry unit. The most suitable CEB mixes are selected for further evaluation.
6. Evaluation of hygrothermal behaviour of wall structure (mould growth) and thermal comfort: the property of wall material is analysed using numerical simulations. The hygrothermal behaviour of the wall for mould growth was analysed using WUFI and the thermal comfort level of the wall was analysed using Design Builder. Four sets of mix ratio are selected from the laboratory test as the most suitable to proceed for further evaluation, the properties from the laboratory test are then inputted to WUFI to analyse the hygrothermal behaviour of the wall structure in the selected climate. The best mix ratio based on the studied conditions are selected for further test to ensure thermal performance of the wall meets the requirement. The use of simulation for this aspect was chosen rather than in situ measurement techniques because of time and cost constraint of the research. The simulation of the wall material is based on weather data from previous decade and assumed conditions, while in situ measurement would have been based on real condition of the place at the time.

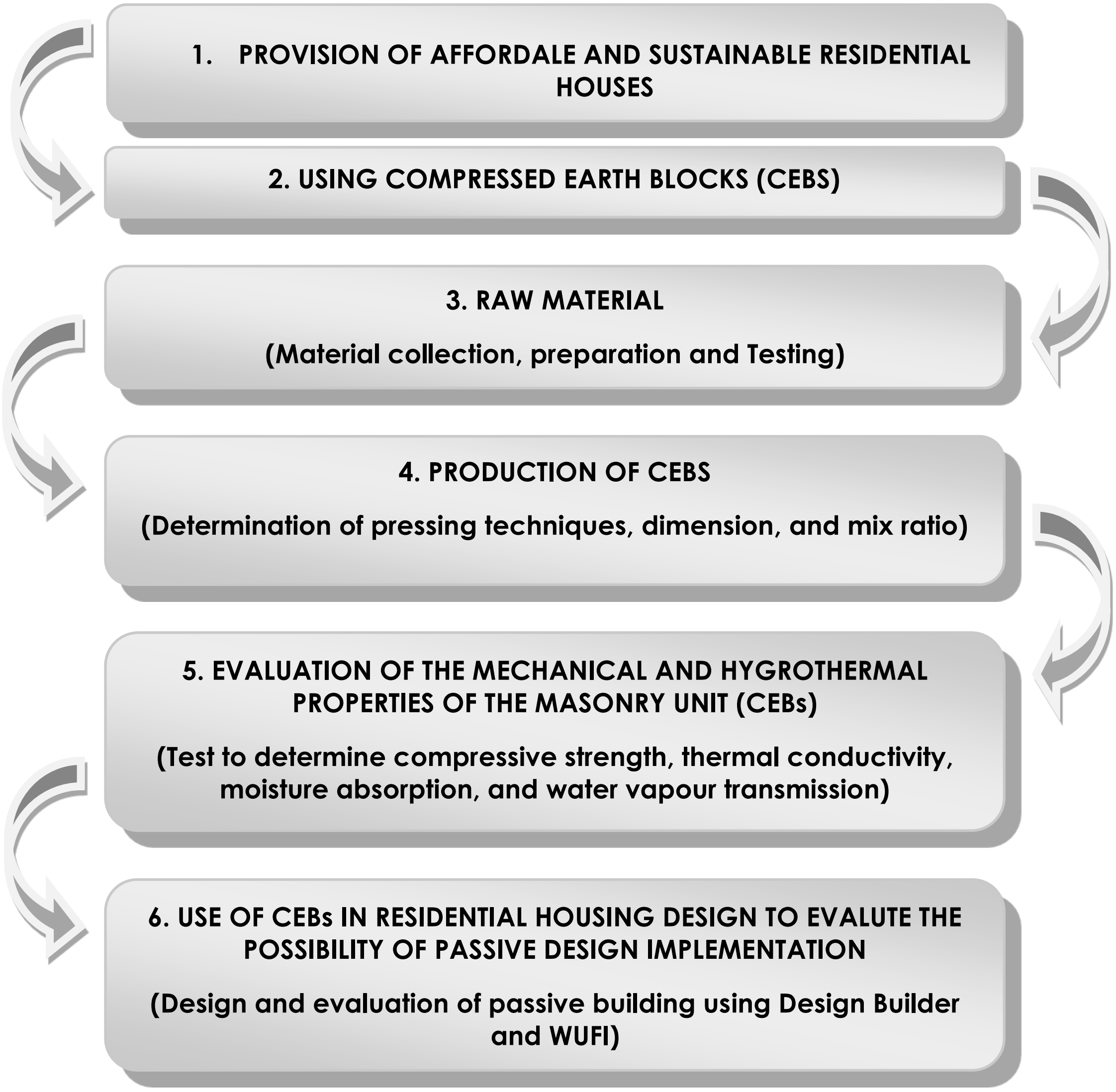


Figure 3.1, Theoretical framework for providing affordable and sustainable residential houses

3.2 Production of CEBs and testing of the component materials

3.2.1 Raw material collection preparation and test

This section describes in detail the process used to obtain the raw materials, test them and manufacture CEBs from them. The main material used for construction was earth material (laterite). The selection of soil for engineering purpose (CEBs) required several steps before it was deemed appropriate. The following characteristic was used to determine the soil selection in accordance to British standard (BS, EN ISO 14688-1:2018; EN ISO 14688-2:2018). The characteristic of the soil was appropriate for sustainable construction:

a. the soil must be natural to the area
b. the soil should not have organic matter
c. the soil particle had to be smaller than 63mm.
d. the soil had to stick together when wet and moulded
e. coarse soil could have sand

f. fine soil could include silt and clay soil

3.2.1.1 Raw material collection

The materials used to produce the experimental CEBs include laterite (clay), sharp sand, Ordinary Portland Cement (OPC), rice husk ash, and water. All the materials were sourced locally, the exact locations are indicated in the following information.

a. Soil Type: Combinations of clay soil, silt, sand or gravel are commonly used to produce CEBs. To improve binding due to poor soil type, stabilizers are used to enhance the property of soil type available (Mostafa, 2016). Laterite (clay) soil is rich in iron oxide, silica, alumina which can be gotten from weathering of rocks with colour generally red, yellow and brown. It is the predominant soil in Nigeria (Adam & Agib, 2001; Mostafa & Uddin, 2016b) and was extracted in Ogun state as shown in Figures 3.2 and 3.3. Laterite has poor workability, low shear strength, high compressibility and poor bearing capacity as a result of the property of clay. Stabilization will reduce soil compressibility, improve workability and soil drainage characteristic. Production usually requires stabilizer such as lime, cement, straw, bitumen and pozzolans. Attempts are being made to avoid cement due to its environmental impact. The large proportion of clay causes excessive shrinkage; and therefore, requires an addition of sand to make it suitable for CEB. A small test sample of laterite soil and stabiliser was first test without the addition of sand, the compressive strength was poor so further test was not conducted for this batch. For this study, laterite was therefore combined with sharp sand to achieve soil with an appropriate ratio of components to form bricks.

The laterite was taken from an excavation site close to CEB production site (Ilaro) along the Oja-Odan road, Ilaro, Ogun State, Nigeria. Sharp sand was collected from a local stream along the Oja-Odan road, Illaro, Ogun State, Nigeria. Samples of the laterite and sharp sand were collected to carry out standard procedure test to determine Atterberg limits, and porosity.

b. Cement: The 42.5 grade Dangote Ordinary Portland Cement (OPC) brand manufacture in Ogun state (location shown in Figure 3.3) is popularly used for building construction in Nigeria and was purchase from a retailer along Oja-Odan Road, Ilaro Ogun State, Nigeria for the stabilisation of laterite in this research.

c. Rice Husk: The rice husk was obtained from a rice milling factory along Lagos - Abeokuta Expressway, Ogun State (location shown in Figure 3.3). This was used to make rice husk ash for the stabilisation of laterite in this research.

d. Water: Potable water from a borehole at the production site was used to mix the material after batching.

Figure 3.2: green outline highlighting the location of Ogun state on the map. (d-maps.com, 2020)

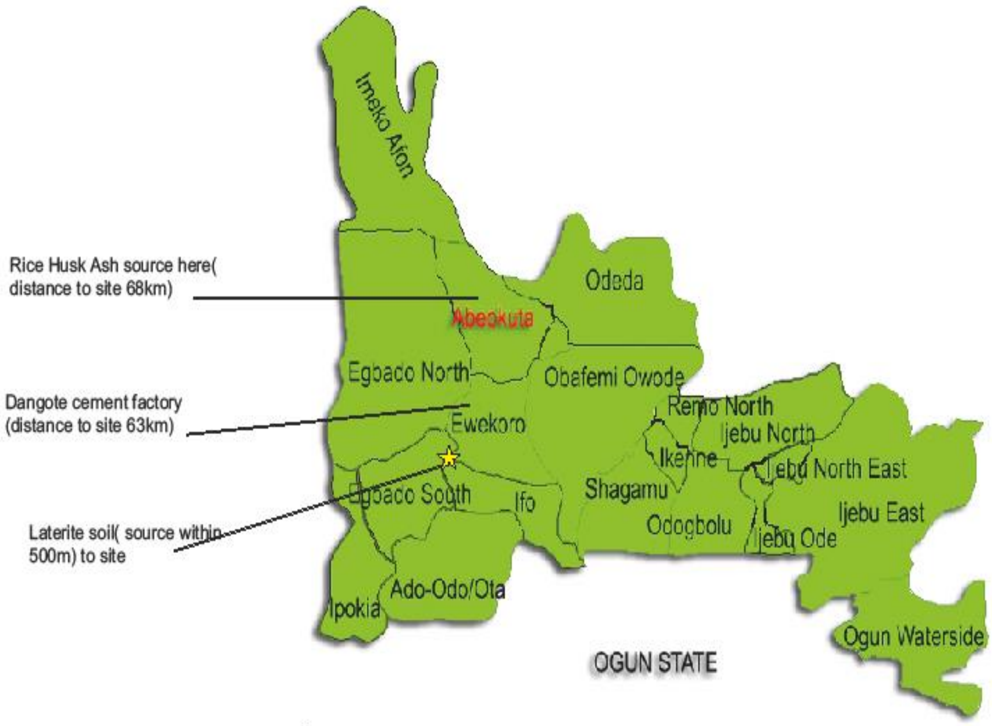


Figure 3.3: Map of Ogun state and location of site, location and distance of materials to site.

3.2.1.2 Raw material preparation

Each material required preparation before being used to produce CEBs. The preparation process for each material is described in this section.

a. **Soil Type**: The excavated soil was air dried on a flat surface, pulverised and passed through sieve. Laterite was sieved with a minimum and maximum sieve mesh size of 0.063mm and 63mm respectively to ensure the appropriate grain were attained (Akinwunmi et al 2019). Similarly, the sharp sand was subjected to sieving through mesh size between 2mm and 0.425mm to attain the appropriate grain sizes (Mostafa, 2016). The sieved soil was spread across a large surface area where they were air dried for a week.

b. **Rice Husk Ash (RHA)**: The rice husk was charred before subjected to combustion for a period of 3 – 4hrs at temperatures of 550-700ºC in a furnace to obtain Rice Husk Ash (RHA). The treatment was to ensure the RHA retains its high amorphous silica content (Alsubari et al, 2016; Chiang et al, 2009; Ganesan et al, 2008; Sore et al, 2016). The process of carrying out the burning of the rice husk ash was challenging, as a large combusting device to burn the rice husk at the required temperature wasn't available.

   i. At Covenant University the combustion furnace was damaged and the part that was to be fixed wasn't available in the country, so it was to be ship into the school from the buyer. The only combustion furnace available was too small to burn the amount that would be required for the partially replacement needed in the soil mix.

   ii. There was also an enquiry of the device at Nigeria Building and Road Research Institute Nigeria (NBRRI) but the furnace available to burn at controlled temperature was damaged and the other furnaORDIce did not have enough temperature control.

   iii. There was an enquiry of the furnace at National Agency for Food and Drug Administration (NAFDAC), the furnace available was small and can only burn 50 g of rice husk at a time per day as the furnace would take a few hours to cool down before another batch can be put in to burn.

Finally, the burning process of rice husk ash had to be done with a private sculptor that had a large furnace. The burning process took about three weeks to be completed as the furnace had to be cooled for 36 hours after each batch before it could be removed from the furnace.

3.2.1.3 Raw material testing - Earth

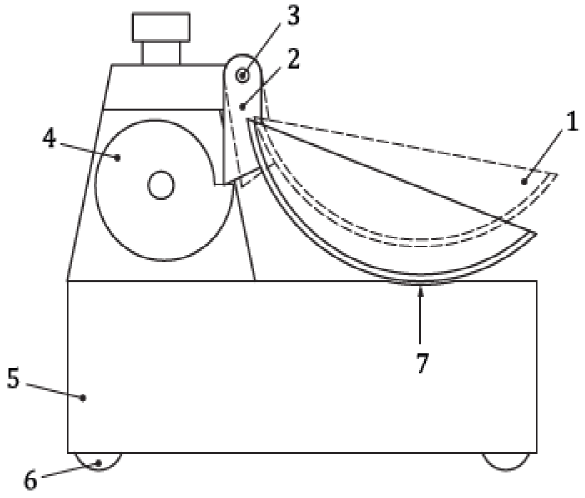
The principal purpose of testing soil is to understand the soil behaviour in terms of its compressibility, strength and permeability. The soil behaviour can then be predicted based on the characteristics of the soil particle size, shrinkage property, soil composition, soil bulk density and other test. For soil to be deemed adequate for engineering purpose, soil needs certain particle distribution, plasticity index, moisture content and bulk density. A range of tests was carried out to analyse the raw materials and ensure that they are suitable for making CEBs.

Atterberg limit test: The soil composition used for engineering purpose are describe in soil fraction. The soil fraction for the purpose of CEBs is composed of primary and secondary fraction. Primary fraction of the soil determines the engineering properties of the soil which can be given as basic of plasticity. The secondary fraction helps to modify the engineering properties of the soil. The test carried out ensure the soil can be categorized appropriated (i.e. sandy Gravel, sandy is the secondary fraction and gravel is the primary fraction of the soil). Silt and clay react differently in the presence of water. The Atterberg limit test defines the plastic and liquid limits and includes a linear shrinkage test. These tests are described below and were conducted according to (BS, EN ISO 17892-12:2018).

A. **Liquid limit:** It is minimum percentage of moisture required by a soil to cover 12.7mm distance after 25 blows along the bottom of a groove in a liquid limit device. The liquid limit testing apparatus(Figure 3.4) includes porcelain evaporating dishes approximately 114 mm in diameter; pulverizing apparatus- mortar and rubber covered pestle, sieve (0.425mm); spatula (about 75mm long and 19mm wide); balance sensitive to 0.01g; watering bottle with distilled water; drying tare with covers such as cans with lids; and mechanical liquid limit device (consisting of brass cup and carriage, grooving tool and gauge, oven, and desiccator).

Description of device

- Specimen cup: the cup has to be made of brass or stainless steel. The surface has to be smooth and replaced when there is damage on the surface
- Carriage: the carriage is secured and adjusted to 10mm height of the cup drop.
- Cam or crank: the crank shall be able to raise the cup easily continuously to its maximum height by rotating it at least 180^o.
- Grooving tool: a flat curved non-corroding metal tool.



KEY

1. Specimen cup
2. Hanger
3. Carriage with pin
4. Cam or crank
5. Base
6. Rubber feet

Figure 3.4; liquid limit device: BS EN ISO 17892-12:2018

Preparation of specimen

- Measure fine soil sample: 200g of fine soil to an accuracy of 0.1% of the mass, or 0.01g (whichever is greater). The soil must be less than 0.4mm particle size (soil particles larger than 0.4mm are removed). Soil used in these tests does not need to be oven dried;

Where it is not possible to remove large particles by sieving, the wet separation method is used:

- Put soil in a jar and add distilled water to cover the soil sample and then stir until it becomes a slurry;
- Pour slurry soil sample through a 0.4mm or nearest size sieve (a large aperture guard sieve may be used to protect the sieve);
- Dry the sample that is retained in the sieve 110 ± 5^{o}C. Weigh the dried material to an accuracy of 0.1g or 0.1% (whichever is greater). This is the reference mass ($m_{r.}$);
- Allow the sample that passed through the sieve to settle and pour off the clear water;
- The sample is allowed to dry in a oven of not more than 50^{o}C until it becomes a firm paste (stirring occasionally to prevent premature edge/surface drying);

Determination of liquid limit by the Casagrande method

i. Place the firm paste in the device.
ii. The soil was chopped, stirred and kneaded to attain uniformity.
iii. Enough soil was poured into the cup of the liquid limit device and then spread to avoid bubbles.
iv. The soil was equally divided in the cup using a grooving tool, it was cut in a single stroke.

v. The crank was turned for about 2 revolutions per second without holding the base. The number of blows required for the groove cut to occur were recorded. NB - the closure of the gap on the soil should be by soil flow not by soil slide across the face of the cup.

vi. Crank rotation was stopped as soon as the groove has closed over a length of 10mm. The number of crank rotations (blows) were recorded, if it did not meet the requirements stated in Table 3.1, the test result was repeated with minor adjustments to water content as required.

Table 3.1- Casagrande test requirements (BS EN ISO 17892-12:2018)

	Number of blows (rotation)
Range of number of rotations	15-40
Number of rotations for liquid limit	25
Maximum difference between two successive reading	2

vii. A sample (15g) was taken from the soil in the cup to determine its moisture content. This was done by finding the difference between the mass of wet soil sample from the cup and the mass of the soil sample after drying in the oven for 18 – 24 hours at 110±5^{o}C;

viii. The procedure (i-vii) was repeated four more times.

ix. The percentage of water content was calculated using Equation 3.1 and the liquid limit was calculated from Equation 3.2.

Equations

i. water content (W) of liquid limit test (BS EN ISO 17892-12 2018):

$$w = \frac{m_1 - m_2}{m_2 - m_c} \times 100 = \frac{m_w}{m_d} \times 100$$

… Equation 3.1

ii. liquid limit test:

$$W_L = W\left(\frac{N}{25}\right)^{0.25}$$

(GTM-7, 2015) … Equation 3.2

Where:

N= number of blows

W= moisture content

W_L = liquid limit

B. **Plastic limit**: It is the moisture content in the soil between the plastic and semi-solid state of the soil. It is measured by rolling a 3mm stick soil sample on glass surface until it begins to crumble,

Apparatus

- Mixing plate: it's a smooth, flat, clean surface used to roll the threads. It's usually made of glass of about 100mm thick with square dimension of 300mm.
- Rod or gauge: it's a rod of 3mm to 3.5mm or a gauge with opening equal to be used to check the size of thread made.

Determination of plastic limit

i. the remainder of the sample from the liquid limit test machine was retrieved.
ii. take 15g to 20g of the retrieved soil sample and plate on the mixing plate.
iii. allow the paste to dry partially until it has reached plastic state.
iv. mould the sample into a ball and roll into an ellipsoidal shape.
v. divide the portion into three.
vi. each portion should be rolled into ellipsoidal shape of 6mm first.
vii. the ellipsoidal shape was rolled into a uniform thread of 3mm diameter through the length.
viii. the thread was broken into 6 pieces and squeezed back together into a uniform rod.
ix. place the pieces into a suitable container and place a lid on it.
x. repeat step 4-9 until the thread crumbles and the soil can no longer be rolled into a thread.
xi. the moisture content of the crumbled soil was determined by finding the difference between the mass of the wet crumbled soil sample from the cup and the mass of the crumbled soil sample after drying in the oven for 18 – 24 hours at 110±5ºC and calculate using Equation 3.3;
xii. the percentage plastic limit was calculated using Equation 3.4.

Equations

- Moisture content for plastic limit test

$$moisture\ content(W_P) = \frac{mass\ of\ water}{weight\ of\ dry\ soil} x100$$ (GTM-7, 2015) Equation 3.3

- Plasticity index (L_p) (BS EN ISO 17892-12 2018)

$L_p = w_L - w_P$ … Equation 3.4

Where:

w_L is the liquid limit

w_P is the plastic limit

Plasticity index should be between 15-30

C. **Linear shrinkage**: In soil with moisture content equivalent to the liquid limit, linear shrinkage is the decrease in length of the soil when it has been exposed to drying, (Adam & Agib, 2001; ASTM, Standard D 4318 2005). The procedure is described below:

- A mould of size 600mm x 40mm x 40mm was greased.
- The mould was slightly over-filled with moist soil with caution to ensure there was no air bubble.
- A spatula was used to level the soil to the horizontal surface of the mould.
- The mould was placed in the oven for 18 – 24 hours at 110±5ºC for drying.
- The oven could cool before the mould was removed and the longitudinal shrinkage was measured; The measured value was expressed as percentage to the original length; and
- The percentage linear shrinkage was determined by the expression in Equation 3.5.

Equation

- Linear shrinkage of soil

$$linear\ shrinkage = \frac{LS}{L} \times 100$$ (ASTM, Standard D 4318 2005) … Equation 3.5

Where:

LS= Longitudinal shrinkage of the soil (mm)

L= Length of the mould (mm).

3.2.1.4 Raw material testing - RHA

The RHA sample was exposed to monochromatic radiation over a varying incident angle range in an x-ray diffraction device. This caused an interaction with the RHA atoms. The spectra are characterised by the chemical composition and the phases of RHA developed. This technique provided phase identification (i.e. amorphous or crystalline), along with phase quantification, percentage crystallinity, crystallite size and unit cell. The x-ray diffraction device at Cardiff University can collect high resolution data at low temperature to systems that can probe structures up to 900^0C under 10 different atmospheres of reactive gases.

The RHA samples were obtained using two different methods in order to establish which was the most suitable for high amorphous silica content

Method 1

The rice husk ash used for the test was gotten form Abeokuta, Ogun state. The rice husk was first charred to remove the moisture and organisms from the waste using a local burning method in a local mud pot. The colour of the husk changed from cream to black and the husk reduced to about half its size in mass. The charred husk was then combusted in a furnace for about 2-3 hrs at temperature ranging from 550-780ºC. The furnace was left to cool for about 24 hrs before the RHA was brought out of the furnace. The colour of the resulting rice husk ash was whitish grey colour.

Method 2

The rice husk was combusted directly in the furnace for $2^1/_2$ hrs- 4hrs. The colour of the rice husk changed from cream to whitish grey. The furnace was fed with the same quantity of husk used in ‘method 1’, the burning of the hush took a long time and cost more because the mass of the husk has not been reduced from the charring step which removes moisture and organisms. The second method was introduced to reduce the time of production process.

3.2.2 Compressed Earth Block (CEBs) production

Compressed earth block (CEB) is produced by mechanical compaction. Besides being made locally by semi-skilled labour. CEB has possibility of attaining adequate thermal and acoustic properties. It requires less energy compared to bricks and concrete thus making it affordable and at the same time sustainable (Sekhar C & Nayak, 2018). The study serves dual purposes. Reduction of construction cost through reduction of the quantity of OPC and substitution with cheaper waste product, RHA. In CEB, the environmental impact of producing OPC is major and the cost of production and purchasing is a concern in the production of a sustainable and affordable building walls.

3.2.2.1 CEB Mix ratios

The cement content used was in accordance with the recommended ratio for the wet climate (Sekhar and Nayak, 2018). All the blocks required for one mix ratio was made in one single mix to ensure the same mix was achieved was made for each individual block within a batch.

Six different mix ratios were used to produce 162 solid and 108 hollow CEBs to test the best mixture ratio. The solid CEBs are to be used for exterior and load bearing walls, as these walls will be exposed to environmental climate and structural loads. The production of hollow blocks was used to reduce the raw material needed to make interior walls as these are not exposed to environmental climate and are not load bearing. The mix ratio variables included Laterite, Sharp Sand, OPC, RHA and Water. Each mix ratio was grouped and labelled accordingly. The control mixes for solid CEBs adopted ratio 11:7:2 for Laterite, Sharp Sand and OPC. While the hollow CEBs adopted ratio 13:5:2 for Laterite, Sharp Sand and OPC. The mix ratio for hollow CEBs differed from the solid because the formation of the hollow block required more laterite.

The experimental CEBs were intended to explore the replacement of OPC with RHA. For this reason, the proportions of laterite and sharp sand were identical to the control mix. The OPC component was replaced with 10%, 20%, 30%, 40% and 50% of RHA respectively for both block shapes – this is detailed in Table 3.3.

3.2.2.2 Production of solid and hollow CEBs

For each CEB mix, the respective proportions of laterite, sharp sand, ordinary Portland cement and Rice Husk Ash, were measured and mixed thoroughly with a shovel in order to achieve homogenous mixtures as shown in Figure 3.5. Thereafter, the respective mixes were each filled in (290 × 140 × 95) mm mould, placed in the mortar interlocking press (also illustrated in Figure 3.5) to produce solid and hollow CEBs. Consequently, two types of CEB (i.e. solid and hollow) of the specifications shown in Table 3.2 were produced.

The manual production method was used for this study because the equipment is light, sturdy, low cost, simple to manufacture and repair and could be easily purchased in Nigeria for about $500- $800. A more detailed description of the process follows:

a. Measuring and mixing of required proportions materials (i.e. laterite, sand, OPC, RHA and water). Wetting with water was done to ensure workability and binding of the materials.

b. The mix was poured into the mould of the mechanical pressing machine in Figure 3.5. manual Pressure was applied manually for a few seconds for uniform compaction; and

c. afterwards the blocks were extruded and placed for curing.

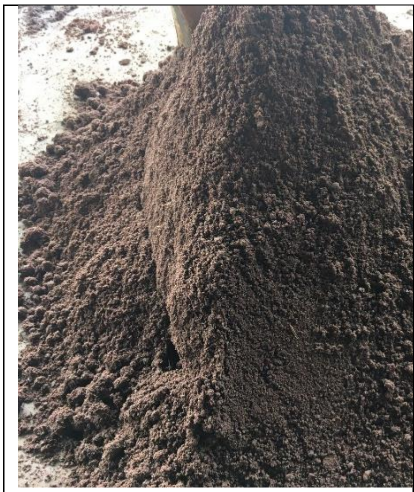
	
Materials before molding	CEBs pressing machine

Figure 3.5, material mix before moulding and CEBs mould

Production of blocks was carried out in Nigeria; the blocks were manufactured by some laboratory technologists at Covenant University and Illaro Polytechnic.

Table 3.2 Physical characteristics of the experimental CEBs

Characteristic	**Types of CEBs**	
	Solid CEB	**Hollow CEB**
Mix Ratio of Laterite, Sharp Sand and Cement for the experimental compressed earth blocks	11:7:2	13:5:2
Size of Block	(290 × 140 × 95) mm^3	(290 × 140 × 95) mm^3
Radius of hollow in the block	Not applicable	22.5mm
Surface area of the block	$0.0406m^2$	$0.039\ m^2$
Volume of the block	$0.00386m^3$	$0.00371m^3$

3.2.2.3 Curing

The blocks were manufactured in Nigeria, which experiences high temperature, high relative humidity and (at some time of the year) high rainfall. The blocks produced for affordable building are made externally which means the blocks need to be protected when produced and when curing process occurs. The blocks were laid as shown in Figures 3.6 and 3.7 after compaction. The blocks were kept in a controlled environment (23±5^oC and

90%RH) during curing. Extreme shrinking and cracking were prevented by covering the blocks with a 1mm thick tarpaulin sheet to control the rate of moisture desorption. Watering of blocks was done with a spray bucket at least twice daily to ensure adequate occurrence of hydration reactions (Adam & Agib, 2001). Sets of blocks were cured for 14, 21 and 28 days. After curing, the blocks were then stored in a dry room in preparation for the subsequent tests. The production and curing incorporated the procedure for clay masonry units according to British standard (BS, EN 771-1:2011+A1:2015).

Table 3.3a, Composition of mix for CEBs – Solid

Shape	**CODE**	**Laterite proportion**	**Sharp sand proportion**	**Stabilizer proportion**		**Curing time (days)**
				OPC	RHA	
Solid	S/0 RHA* 0% RHA	11	7	2*	-	14
						21
						28
	S/0.2 RHA 10% RHA	11	7	1.8	0.2	14
						21
						28
	S/0.4 RHA 20% RHA	11	7	1.6	0.4	14
						21
						28
	S/0.6 RHA 30% RHA	11	7	1.4	0.6	14
						21
						28
	S/0.8 RHA 40% RHA	11	7	1.2	0.8	14
						21
						28
	S/1 RHA 50% RHA	11	7	1.0	1.0	14
						21
						28

** Control sample*

Table 3.3b, Composition of mix for CEBs – Hollow						
Hollow	% RHA	13	5	2*	-	14
						21
						28
	H/0.2 RHA 10% RHA	13	5	1.8	0.2	14
						21
						28
	H/0.4 RHA 20% RHA	13	5	1.6	0.4	14
						21
						28
	H/0.6 RHA 30% RHA	13	5	1.4	0.6	14
						21
						28
	H/0.8 RHA 40% RHA	13	5	1.2	0.8	14
						21
						28
	H/1 RHA 50% RHA	13	5	1	1	14
						21
						28

** Control sample*

Samples of the experimental hollow and solid compressed earth blocks produced in this study are shown in Figures 3.6 and 3.7, respectively.

Figure 3.6. Samples of experimental solid CEBs produced in this study

Figure 3.7. Samples of experimental* hollow *CEB produced in this study

3.3 Compressed earth blocks (CEBs) testing

The key factor of interest is the effect which the RHA stabiliser has on the mechanical, hygrothermal and thermal properties of the CEB. The relevant tests are described in sections 3.3.1 to 3.3.8.

3.3.1 Bulk density of Compressed earth block

The density of a block measures how closely packed the particles of are. Higher block density indicates more closely packed particles and better compaction. The procedure adopted for the bulk density determination is accordance to British standard (BS, EN 772-4: 1998) described below.

For each block shape, mix ratio and curing option:

a. three blocks were selected randomly from the solid block samples cured for 14 days for each mix ratio.

b. the blocks were weighed separately with a digital weighing balance and recorded to an accuracy of 0.1% of their mass.

c. An average of their mass was taken using Equation 3.6.

d. The volume of the blocks was derived as shown in Equation 3.7.

e. The mean block density was calculated as shown in Equation 3.8.

f. Steps a-e were repeated for each curing condition and for hollow blocks

Equations

- Average of mass of sample blocks (m)

$$average\ mass\ of\ sample\ blocks = \frac{mass\ 1 + mass\ 2 + mass\ 3 + mass\ n}{number\ of\ blocks\ (n)}$$ Equation 3.6

- Volume of the block (V)

$$volume\ of\ block = length\ x\ breadth\ x\ height$$ Equation 3.7

- Mean bulk density (ρ)

$$mean\ bulk\ density = \frac{mass\ 1}{volume\ 1} + \frac{mass\ 2}{volume\ 2} + \frac{mass\ 3}{volume\ 3}$$ Equation 3.8 (BS, EN ISO 17892-2:2014)

3.3.2 Compressive strength of Compressed earth block

Compressive strength is a basic mechanical property measurement necessary to test the quality of experimental CEBs as masonry unit in compression. Inadequate strength of the masonry unit (CEBs) will lead to failure of the structural masonry wall (Berto. L et al, 2005; Gumaste et al, 2007). The failure of the unit can lead to cracks and weakness which can cause the ingress of water or moisture into the structure which reduces the interior comfort level (Berto. L et al, 2005). Cracking in masonry is a major problem that leads to abandonment of a structure or in extreme cases collapse of the structure.

The blocks were tested based on the standards for fired clay bricks in British standard (BS, EN 772-1:2011+A1:2015) for each block shape, mix ratio and curing option:

Apparatus

The machine will have adequate strength to crush the entire test specimen and conform to Table 3.4 and Figure 3.8. The machine shall have two steel bearing platens. The deflection of the platen surface shall be less than 0.1mm measure over 250mm. the surface of the platen shall be hardened, or the face-case hardened. The platen shall align freely with the surface of the specimen and shall be held by friction or tilting during loading. The bearing of the platen shall be larger than the surface of the specimen.

Table 3.4, Maximum permissible error/repeatability of compressive test

Maximum permissible repeatability of forces as percentage of indicated force (%)	Maximum permissible mean of error of forces as percentage of indicated force (%)	Maximum permissible error of zero force as percentage of maximum force range (%)
2	±2	±0.4

Figure 3.8, Image of compressive strength test on CEB

Preparation of the samples for test

a. Cure specimen under sack kept damp throughout the curing period at relative humidity greater than 90%
b. Weigh the samples to an accuracy of 0.1% of their mass
c. Conditioning before testing:
   Air dry conditioning involves:
   - Storing in the laboratory (conditions defined in Table 3.5) until constant mass is reached when the consecutive mass weight of the sample 24 hours apart is less than 0.2% of the total mass.

Alternatively, dry the specimen in an oven at 105°C ±5°C for at least 24 hours and cool at room temperature for 4 hours.

Table 3.5, Condition of CEBs in a laboratory

Temperature	Greater than or equal 15°C
Relative humidity	Less than or equal to 65%

Procedure for determination of compressive strength of CEBs

a. three blocks were selected randomly from the solid block samples cured for 14 days from the controlled mix ratio.
b. The gross area (mm^2) of the surface of the sample shall be calculated by multiplying the length and the width of the specimen. Equation 3.9 was used for solid CEBs and Equation 3.10 was used for hollow blocks.
c. Wipe the surface of the machine clean to remove loose grits from the bed of the specimen. Alig the specimen to the centre of the platen so uniform load can be applied across the surface.
d. Application of force perpendicular to the CEBs was gradually increased until failure or a visible crack occurs.
e. The Force at the point of failure for each block was recorded.
f. The compressive strength of the blocks was calculated using Equation (3.9).
g. The mean compressive strength of the blocks was calculated from Equation (3.10).
h. steps a – g was repeated for the block samples cured for each combination of curing and mix ratio; and
i. steps a – h was repeated for hollow block samples.

Equations

- cross section area of the block

$cross\ sectional\ area\ (A) Solid\ block = length\ x\ breadth$ Equation 3.9

$$cross\ sectional\ area\ (A_H) Hollow\ block =$$

$(lenght_1\ xbreadth_1) - 2(length_2 xbreadth_2)$ Equation 3.10

- compressive strength of the blocks (f_b) (BS, EN 772-1:2011+A1:2015)

  Compressive strength $(MPa) = \frac{P}{A}$ ... Equation 3.11

  Where P= Force at point of failure

- mean compressive strength of the blocks

$$\text{mean compressive strength} =$$

$$\frac{C_1+C_2+C_3+C_n}{\text{number of compressive strength}}$$ …………. Equation 3.12

3.3.3 Water absorption Capacity of compressed earth block

Principle:

Water absorption is the quantity of water in kg absorbed by a unit of block when fully immersed in water for duration of 24 hours. Water absorption rate is expressed as a percentage of the weight of the dry unit. The water absorption rate of the block samples was determined in accordance with British standard (BS, EN 772-21:2011) highlighted in the procedure below for each block shape, mix ratio and curing option:

Apparatus

- Water tank large enough to soak the samples, with base slightly raised, so that water encounters all the surfaces of the samples
- Ventilated oven to maintain temperature of 105±5°C
- Weighing device to accuracy of 0.1% of dry mass

Procedure

a. Three blocks were selected randomly from the solid block samples cured for 14 days from the controlled mix ratio.
b. The sample was dried in the oven at temperature of 105±5°C until constant mass is reached. Constant mass is reached when two consecutive mass measures taken 24hrs apart are within 0.2% of the total mass. Allow to cool to room temperature before weighing.
c. The blocks were weighed separately with a digital weighing balance and their weights were recorded.
d. The blocks were fully submerged in water for 24±0.5 hours.
e. The blocks were removed from the water and the surface of the blocks were dried with damp cloth.
f. The damp blocks were weighed with a digital weighing balance separately and their weighs were recorded.
g. The water absorption rate was calculated from Equation 3.13 to the nearest 1%.
h. The mean water absorption rate was calculated from Equation 3.14.
i. Steps a – h was repeated for the block samples cured for 21 and 28 days for each mix ratio: and
j. Steps a – i was repeated for hollow block samples

Equations

- Water absorption capacity/rate (BS, EN 772-21:2011):

$$\text{Water absorption rate } W_S = \frac{M_s\text{-}M_d}{M_d} \text{ x } 100\ldots\ldots.. \qquad \text{Equation 3.13}$$

M_s is mass of sample soaked and M_d mass of sample when dried.

- mean water absorption rate:(BS, EN 772-1:2011+A1:2015)

$$\text{mean of water absorption} = \frac{W_{S1}+W_{S2+}W_{S3+}\ldots.W_{Sn}}{\text{number of samples}}\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 3.14}$$

3.3.4 Water absorption coefficient of compressed earth block

The British standards defines water absorption coefficient as the mass of water absorbed by a material per surface area and per square root of time. The British standard (BS, EN ISO 15148:2002+A1:2016) specifies the procedure described below for the determination of water absorption coefficient. Consequently, the procedure was adopted in this study for a selected solid blocks mix ratio cured for 28 days, further test was abandoned for hollowed blocks as it didn't meet the requirement for mechanical strength:

a. Three blocks were selected randomly from the solid block samples cured for 28 days from the controlled mix ratio.

b. The blocks were weighed separately with a digital weighing balance and their weights were recorded.

c. The area of the horizontal surface to be partially immersed in water was calculated by the expression in Equation 3.9.

d. The blocks were placed in separate PVC containers over small PVC studs to ensure the blocks did not touch the surface of container.

e. The water level was maintained during the test at 5±2mm above the base of the test block samples as shown in Figure 3.9.

f. The block samples were removed after 20 minutes and blotted with dry cloth to remove excess water on their surfaces.

g. The block samples were weighed, and the new masses were recorded.

h. Steps d – g were repeated several times allowing immersion in water to continue for 1 hour, 2 hours, 4 hours, 8 hours, 12 hours, 18 hours and 24 hours;

i. The change in mass per area was calculated as expressed in Equation 3.15,

j. The water absorption coefficient was calculated as expressed in Equation 3.16, and 3.17.

k. Steps a – j was repeated for the block samples cured 28 days for each mix ratio.

Equations

- Change in mass (BS, EN ISO 15148:2002+A1:2016):

$$change\ in\ mass(\Delta \mathrm{mt}) = (\mathrm{mt} - \mathrm{mi})/\mathrm{A} \quad \text{… Equation 3.15}$$

The change in mass shall be plotted against $\sqrt{t}$. The graph plotted could either be straight or curved. The water absorption coefficient is dependent on the shape of the graph.

- Straight graph equation represents a sample with no water on top of surface after longest immersion time (illustrated in Figure 3.10) (BS, EN ISO 15148:2002+A1:2016):

$$WAC\ (\mathrm{Aw}) = (\Delta \mathrm{mtf} - \Delta \mathrm{m0})/\sqrt{\mathrm{tf}}_{t_f} \quad \text{… Equation 3.16}$$

Where:

$\Delta m_{tf=}$ the value of Δm on the straight line at time t_f, in kg/m^2;

Δm_0 is the mass at time zero on the graph that cuts the vertical axis when the line is extended,

t_f is the duration in seconds.

- Water absorption coefficient (WAC) when the graph is curved represents a sample with water on top of surface after a period of immersion (illustrated in Figure 3.11) (BS, EN ISO 15148:2002+A1:2016):

$$WAC(\mathrm{Aw}, 24) = \Delta \mathrm{mtf}/\sqrt{86400} \quad \text{… Equation 3.17}$$

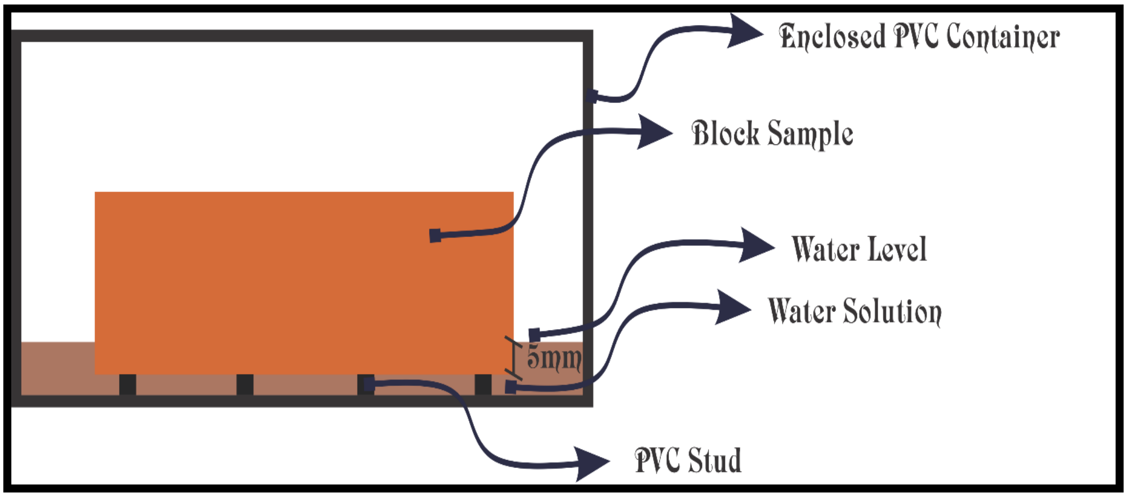


Figure 3.9 Section of Water Absorption Coefficient test set up

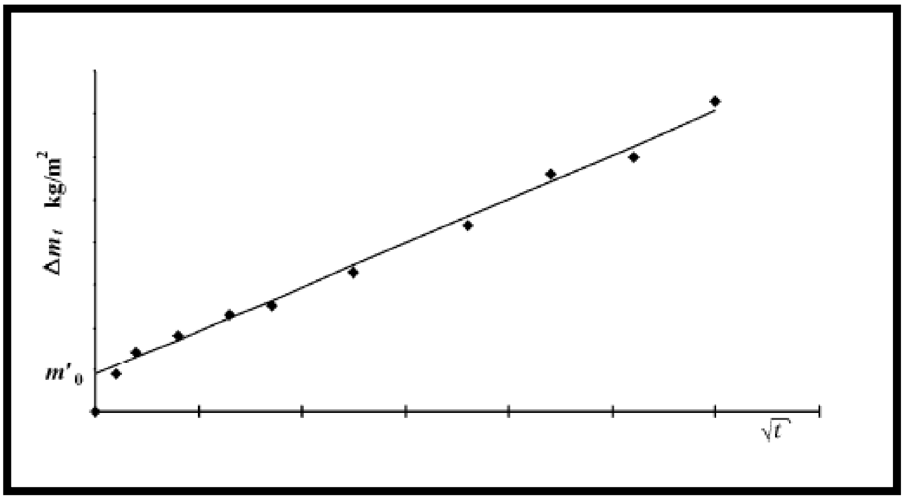


Figure 3.10, Change of mass per area vs square root of immersion time - This represents a sample which did not develop water on the top surface even after the longest immersion time

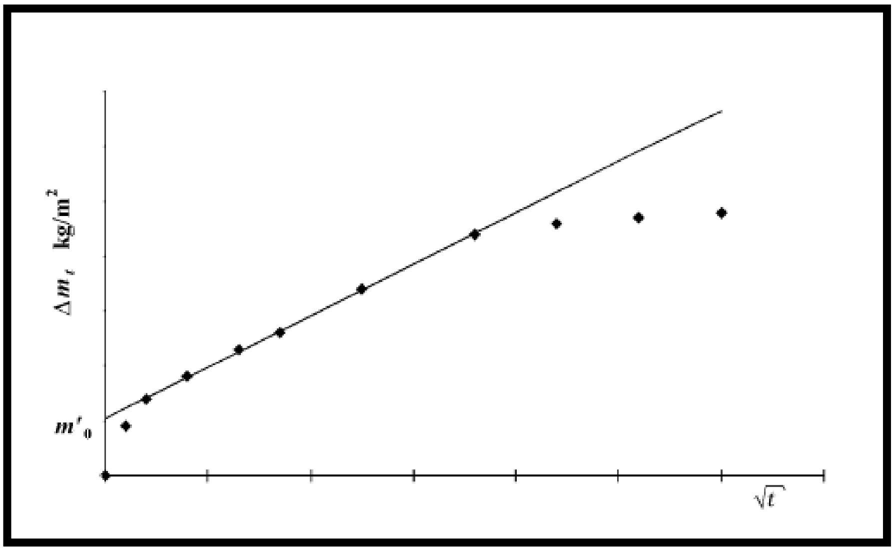


Figure 3.11 Change of mass per area vs square root of immersion time - This represents a sample which developed water on the top surface

3.3.5 Water vapour transmission

The British Standard (BS, EN ISO 12572:2016) describes the procedure for the determination of water vapour transmission. The block samples were subjected to different conditions in order to determine the density of water flow rate, water vapour resistance, water vapour permeability, and water vapour resistance factor. The procedures described below were followed for a selected solid block mix ratio cured for 28 days:

Procedure

a. Three block samples were selected randomly from the solid block samples cured for 28 days from a mix ratio.

b. The block samples were conditioned by keeping them in controlled environment at a temperature and relative humidity of 23±5^{o}C and 50±5% respectively.

c. The block samples were sealed with waterproof tapes at all sides to leave the top and bottom exposed.

d. The blocks were weighed, and their weights were recorded.

e. The area of the exposed surfaces was calculated from equation (3.9)

f. The block sample was placed over a dry cup 0% (calcium chloride) in such a way that the bottom surface of the block was exposed and sealed from exposure to the external conditions, the overhanging part of the block was sealed with waterproof tape.

g. The sample in step f was placed in an airtight PVC container containing aqueous salt solution (Magnesium nitrate) to control the relative humidity to 50% as shown in Figure 3.12. The temperature was maintained at 23±1^{o}C;

h. The block sample was weighed every 24 hours until the difference in masses of five consecutive readings was within ±5% of the running mean value of the block sample weight.

i. Steps e – h was repeated for other two blocks.

j. The mass change rate was determined by the expression in Equation 3.18.

k. The density of water vapour flow rate was calculated from Equation 3.19.

l. The water vapour permeance was calculated from Equation 3.20.

m. The water resistance was calculated from Equation 3.21.

n. The water vapour permeability was calculated from Equation 3.22.

o. The water vapour resistance factor was determined by from Equation 3.23.

p. The water vapour permeability of air was calculated from Equation 3.24; and

q. Steps a – p will be repeated for the block samples cured 28 days for other mix ratio.

Equations

- Change of mass rate for water vapour transmission (BS, EN ISO 12572:2016):

$$\Delta \dot{m}_{12} = \frac{m_2 - m_1}{t_2 - t_1}$$

… Equation 3.18

Where:

m_2 is the mass of the test assembly at time t_2, in kg

m_1 is the mass of the test assembly at time t_1, in kg

t_1 and t_2 are successive time in seconds.

Δm_{12} is the mass per time for a single determination, given as kg/s

- Water vapour flow rate through specimen (G) is the mean of five consecutive Δm_{12}
- Density of water vapour flow rate for water vapour transmission (g) (BS, EN ISO 12572:2016):

$$g = \frac{G}{A}$$

… Equation 3.19

Where:
A is area from Equation 3.9
G is water vapour flow rate

- Water vapour permeance for water vapour transmission (W_P) (BS, EN ISO 12572:2016):

$$W_P = \frac{G}{A\Delta p}$$ … Equation 3.20

The value of Δp_V (water vapour pressure difference across specimen) shall be calculated from the mean of the measure temperature and relative humidity over the course of the test.

Note: for temperature greater than 0^oC, vapour pressure on either side of the specimen can be calculated as (BS, EN ISO 12572:2016):

$$p = \phi . 610{,}5 . e^{\frac{17{,}269.\theta}{237+\theta}}$$ …Equation 3.20a

Where:

ϕ is relative humidity

θ is temperature (°C)

- Water vapour resistance (Z) for water vapour transmission (BS, EN ISO 12572:2016):
  Z = 1/w … Equation 3.21
  Where:
  w is water vapour transmission

- Water vapour permeability (δ) for water vapour transmission (BS, EN ISO 12572:2016):
  δ = w.d … Equation 3.22
  Where:
  w is water vapour transmission
  d is mean thickness of specimen (m)

- Water vapour resistance factor (μ) for water vapour transmission (BS, EN ISO 12572:2016):

$$\mu = \frac{\delta \mathrm{air}}{\delta}$$

… Equation 3.23

Where:

$$\delta_{\mathrm{a}} = \frac{0{,}086\ p_0}{R_{\mathrm{D}} \cdot T \cdot p} \left(\frac{T}{273} \right)^{1{,}81}$$

… Equation 3.23a

R_D is the gas constant of water vapour = 462 x 10^{-6} Nm/mg.K

- Water vapour permeability of air for water vapour transmission:

$$g_{air} = \frac{\Delta \boldsymbol{p} . \delta_{\boldsymbol{air}}}{\mu . \boldsymbol{d}}$$

… Equation 3.24

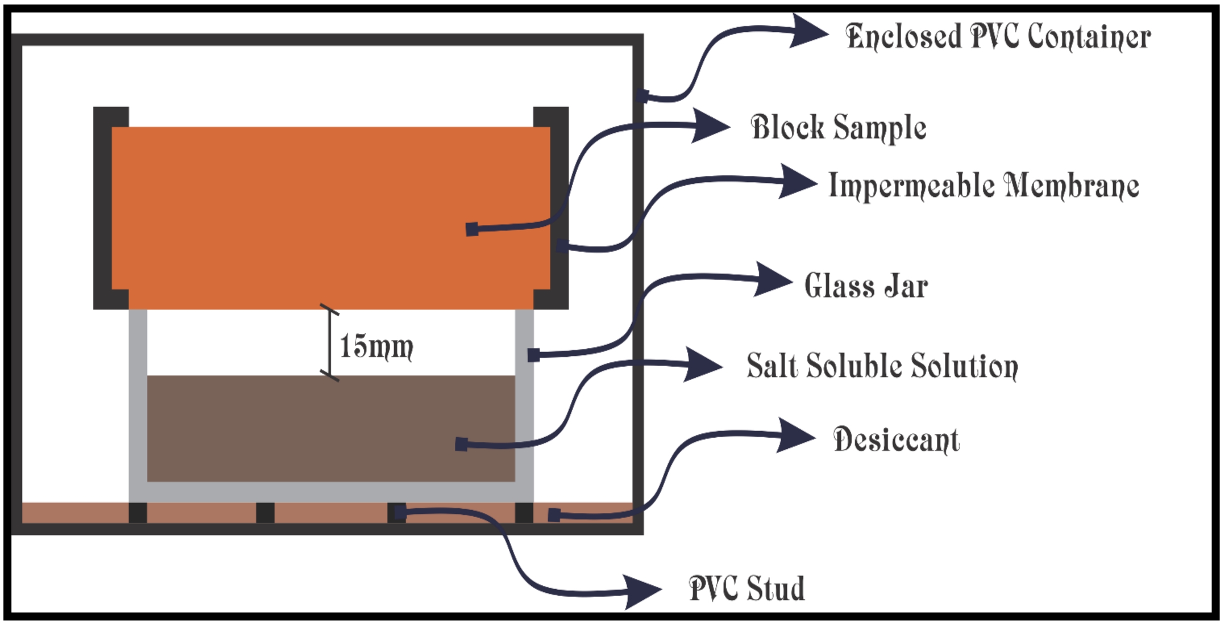


Figure 3.12: Section of Water vapor transmission setup

3.3.6 Moisture absorption

The British Standard for moisture absorption determination described below was in accordance to (BS, EN ISO 12571:2013). The block samples kept at varying relative humidity levels were used to determine the moisture absorption. The procedures used are as follows for a selected solid block mix ratio cured for 28 days:

a. Three block samples were selected randomly from the solid block samples cured for 28 days from a mix ratio.

b. The block samples were conditioned by keeping them in controlled environment at a temperature and relative humidity of 27±5°C and 50±5% respectively.

c. All sides of the block samples excepting the bottom side were sealed with waterproof tape.

d. The blocks were weighed separately, and their weights were recorded.

e. The area of the exposed side (i.e. bottom) was calculated from equation 3.9.

f. A cup was conditioned with an aqueous salt solution (magnesium chloride) to keep it at a relative humidity of 33%.

g. The block sample was placed over the conditioned cup in such a way that the entire bottom surface of the block covers the cup from exposure to the external conditions and the overhanging part of the block is sealed with water proof tape as shown in Figure 3.13;

h. The mass of the block sample was taken at 24 hours interval until the constant mass was attained (i.e. when the difference in masses of three consecutive readings were within less 0.1% of the total mass of the block sample).

i. Step f was repeated to attain a relative humidity of 55%, 75% and 85% respectively.

j. Step g – h was repeated for the same sample with condition cup of relative humidity of 55% (magnesium nitrate), 75% (sodium chloride) and 85% (potassium chloride) respectively.

k. The moisture content of the block sample was determined by the expression from equation (3.25).

l. Steps a – k was repeated for the block samples cured 28 days for other mix ratio.

Equations

- Moisture content for moisture absorption (u) (BS, EN ISO 12571:2013):

$$u = \frac{m - m_0}{m_0}$$ … Equation 3.25

Where:

m is specimen at equilibrium with corresponding relative humidity

m_o is the mass of the specimen after drying

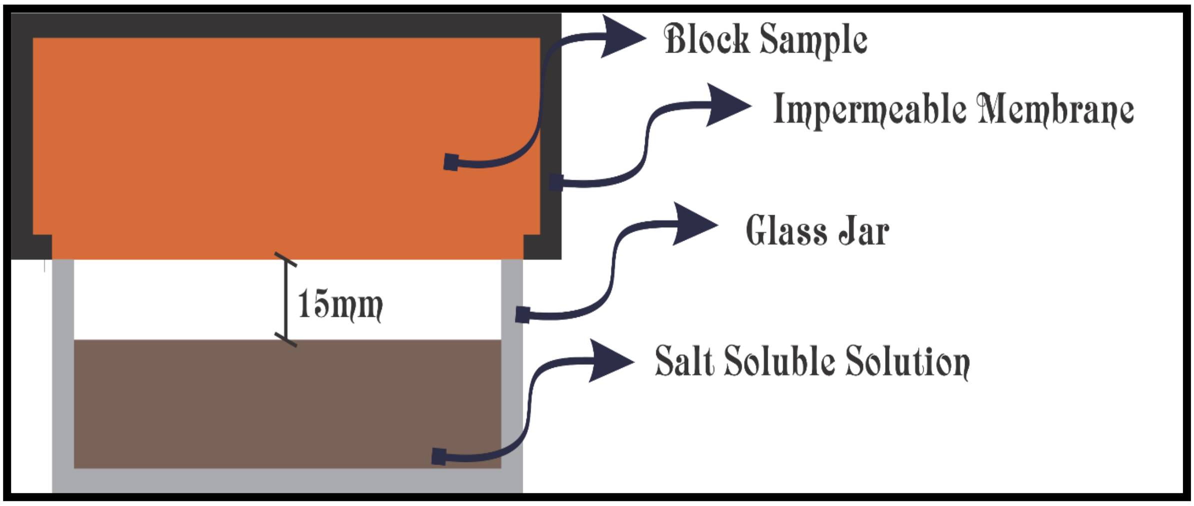


Figure 3.13: Section of Moisture Absorption setup

3.3.7 Moisture buffering

The moisture buffering test was done according to the NORDTEST work group process (McGregor et al, 2014; Rode et al, 2005; Zhang et al, 2017). The block samples were tested at varying relative humidity level to determine the moisture buffering. The procedures used are as follows for a selected solid block mix ratio cured for 28 days:

a. Three block samples were selected randomly from the solid block samples cured for 28 days from a mix ratio.

b. The block samples were conditioned in controlled environment at a temperature and relative humidity of 23±5ºC and 50±5% respectively.

c. The block samples were sealed at all sides with a waterproof tape except the bottom that was left exposed.

d. The blocks were weighed separately, and their weights were recorded.

e. The area of the exposed side is calculated with the expression from the equation (3.26).

f. A cup was conditioned with an aqueous salt solution (magnesium chloride) to keep it at a relative humidity of 33%.

g. The block sample was placed over the conditioned cup in such a way that the entire bottom surface of the block covers the cup from exposure to the external conditions and the overhanging part of the block is sealed with water proof tape as shown in Figure 3.14;

h. The mass of the block sample was taken after 8 hours of exposure.

i. Step f was repeated to attain a relative humidity of 75% (sodium chloride).

j. Step g was repeated for the same sample with condition cup kept at a relative humidity of 75%.

k. The mass of the block sample was taken after 16 hours of exposure.

l. The mass of the block sample was taken at 8 hours interval until the constant mass was attained (i.e. when the difference in masses of three consecutive readings was within less 0.1% of the total mass of the block sample.

m. The moisture buffering of the block sample was calculated from equation (3.27).

n. Steps a – l was repeated for the block samples cured 28 days for other mix ratio

Equations

i. Moisture effusivity for moisture buffering test (b_m) (Rode et al. 2005, (Rode et al, 2007)):

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \frac{\partial u}{\partial \varphi}}{p_s}}$$

…Equation 3.26

Where:

$\delta_{p=}$ water vapour permeability (BS, EN ISO 12572:2016)…Equation 3.22

$\rho_{O=}$ dry density = dry weight/volume …Equation 3.26b

du = moisture content change = mean of mass change of last 3 cycles= mean (mass release +mass intake + mass release) OR mean (mass intake +mass release +mass intake)

dφ = relative humidity difference

ii. Moisture buffer value for moisture buffering test:

$$MBV_{ideal} \approx \frac{G(t)}{\Delta RH} = 0.00568.\,p_s.\,b_m.\sqrt{t_p}$$ …..Equation 3.27

ΔRH= change in relative humidity between the low humidity (33%) and high humidity (75%) exposed to the samples

G_t= accumulated moisture uptake

$$G(t) \approx 0.568 \cdot b_m \cdot \Delta p \sqrt{t_p}$$

… Equation 3.27a

t_p= time (between the last three cycles)

p_s= saturation vapour pressure of air

$$p_s = \phi.\,610{,}5.\,e^{\frac{17{,}269.\theta}{237+\theta}}$$ … Equation 3.20a

b_m = Moisture effusivity for moisture buffering test (Equation 3.26)

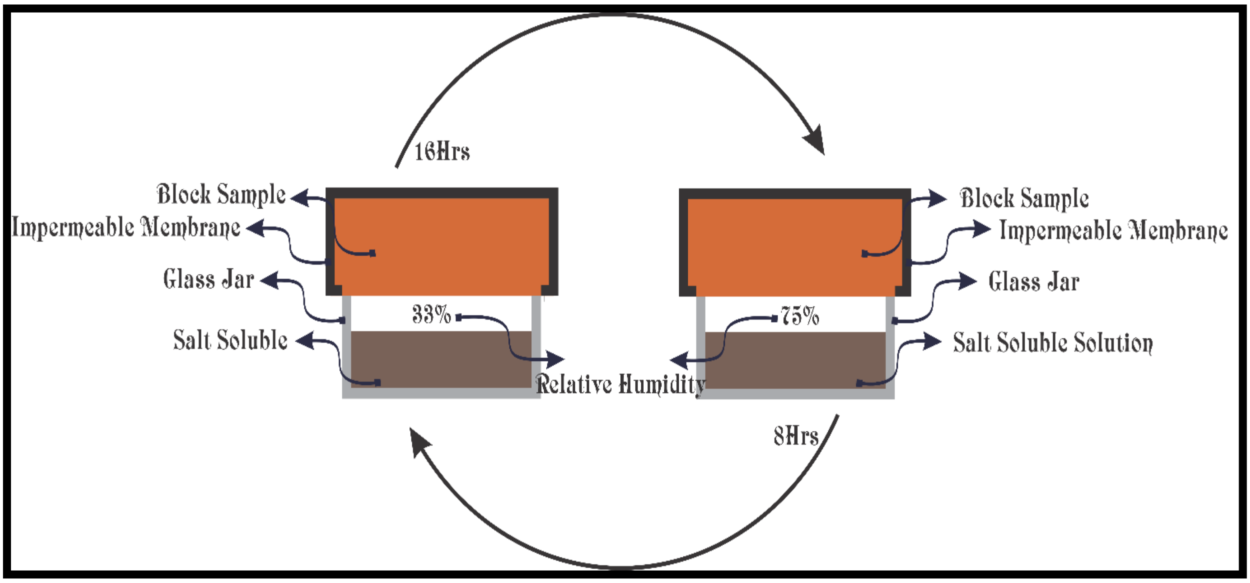


Figure 3.14: Section of Moisture buffering setup

3.3.8 Thermal conductivity

Thermal conductivity is defined as the amount of heat per unit time per unit area conducted through a plate of unit thickness of a given material, with the faces of the plate differing by one unit of temperature. The methodology from the standard (BRE, Report 2014; BS, EN 1934:1998) and BRE Report "In-situ measurements of wall U-values in English housing" . The thermal performance of a wall expressed in terms of the U-value is the amount of heat loss or gained by the wall structure. The procedures described below were followed for the determination of the thermal conductivity of the experimental compressed earth blocks

Principle:

The principle for thermal performance of CEBs was achieve by construction of masonry wall, the wall was surrounded with hot box using heat flux meter. The heat flow meter is used to create two environmental condition for steady state of the materials. The masonry wall is exposed to hot and cold environmental temperature for a selected solid block mix ratio cured for 28 days:

Procedure for determination of thermal conductivity:

a. hollow block samples were selected randomly from the solid block samples cured for 28 days from each mix ratio.
b. the block samples were used to construct a wall using a cement- sand mortar mix with a thickness of 12-15mm in a hot box as shown in Figures 3.15 - 3.18.
c. heat was generated using an electric heater inside the hot box on one side of the wall for two weeks. A controller was used to keep the internal temperature to 33+-2^{o}C

d. heat flux plate and a thermistor were fixed on the side of the wall receiving the heat generated from the heater while external sensors were placed on the other side of the wall.
e. the heat flux plate, and thermistor were connected to a data logger that recorded the temperature, relative humidity and heat flow every 15minutes while the external sensors measured the temperature and relative humidity at the same frequency.
f. after the test, experimental data was collected by connecting the data logger and external sensor to the computer.
g. the heat flux and thermal conductivity values of the block samples were determined by the expression in equation (27) and (28).
h. In order to calculate the U-value, the construction of a hot-box using the samples of CEB RHA mix sample to make a wall in the hot box was required in Figures 3.15 and 3.16. Heat flux plate were to be fixed to the wall. The wall and the heat flux plates are protected in a guarded hot box (BRE 2014)

Equations

$k = \frac{\mathrm{q\ x\ d}}{\mathrm{T1 - T2}}$ (BS, EN ISO 22007-1:2017)
……………………………………………………………………… Equation 3.28

Where:

k is thermal conductivity of the material (W/m.K)

q is the quantity of heat passing through a unit area (W/m^2)

d distance between the two sides (m)

T1 is the temperature on the warmer side (^{o}C)

T2 is the temperature on the cooler side (^{o}C)

And to get the value of q of material.

$q = \frac{\mathrm{Q}}{\mathrm{A}}$ (BS, EN ISO 22007-1:2017)
……………………………………………………………………… Equation 3.29

Where:

Q is the quantity of heat passing through the base area of the sample (W)

A is the base area of the sample (m^2)

The value q is gotten directly from the data logger in the case of this test

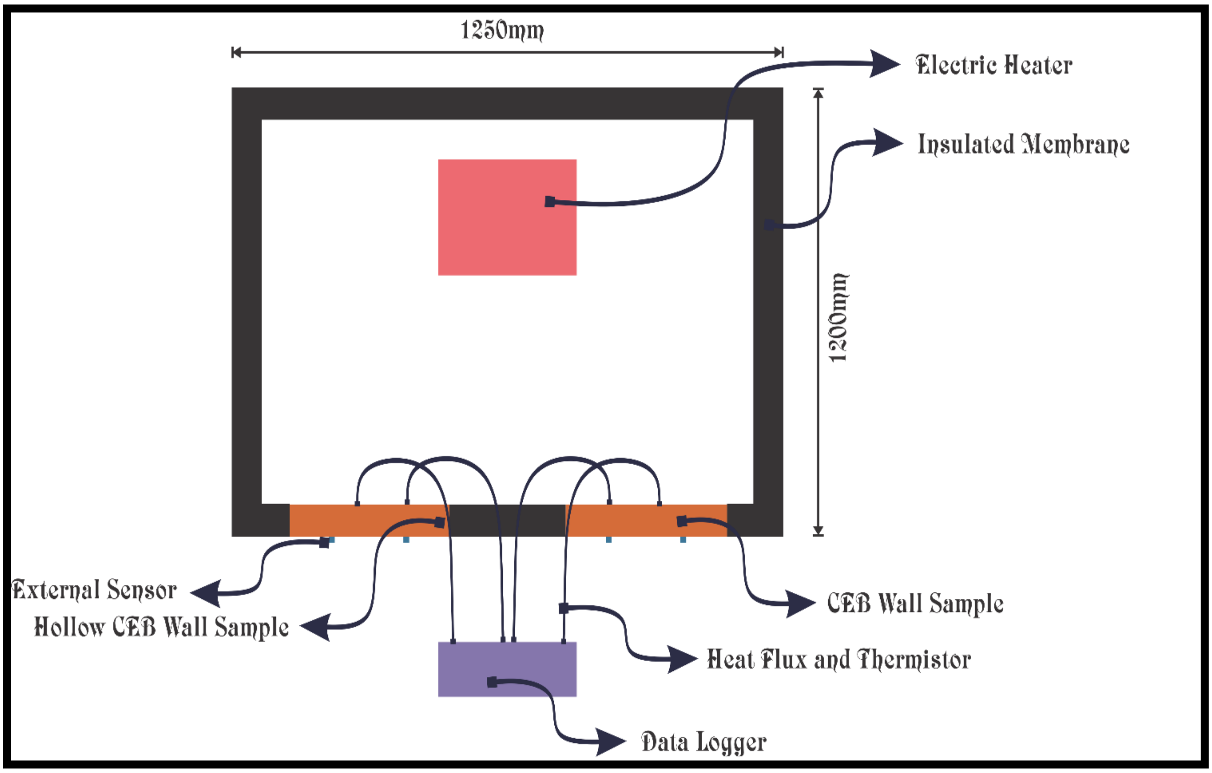


Figure 3.15: section of in-situ thermal test with CEB blocks exposed to laboratory environment

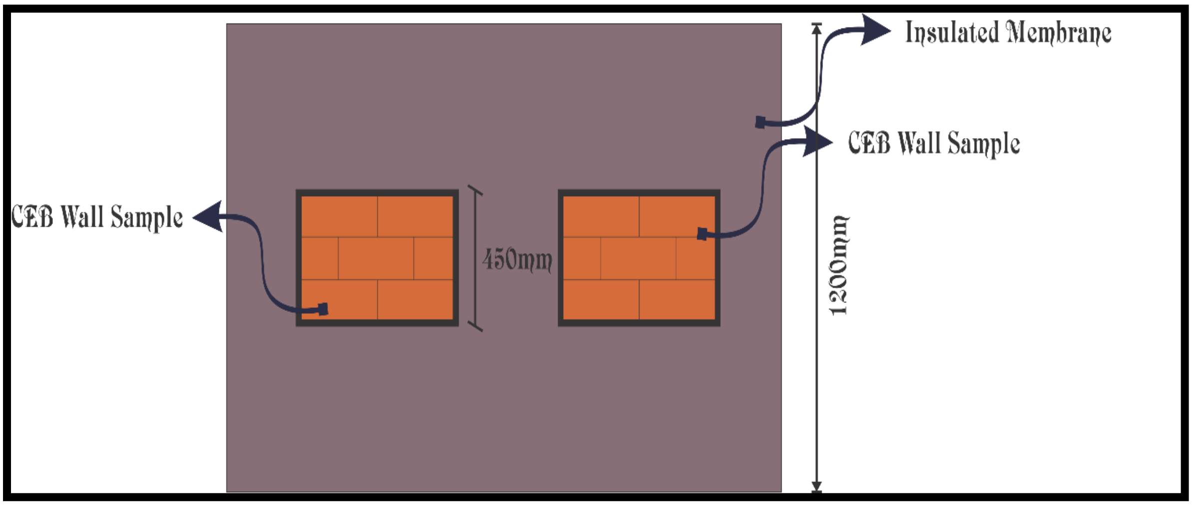


Figure 3.16: Elevation of in-situ thermal test with CEB blocks exposed to laboratory environment.

Equipment:

The in-situ thermal test was constructed using sheet plywood and insulated using expanded polystyrene (EPS) see Figures 3.17 and 3.18. The In-situ box was constructed by Mr Gbadamosi Ibrahim Abiodun and Mr Mathew Oladele Bamidele. It was able to carry out testing of two different mix sample simultaneously. The size of the box was designed with a length of 120cm, a width of 125 cm and a height of 120 cm. the cavity of the wall constructed had a width of 0.15cm. The in- situ box was heated electrically. The thermal conductivity test was performed with the inner temperature at 36±5^{o}C while the external temperature of the room remained at 26±2^{o}C.

Figure 3.17: External view of the in-situ thermal test

Figure 3.18: Internal view of the in-situ thermal test

The specimen is located in-between the box and room, so is exposed to two different environmental conditions. The box is hot inside and the heat flows to the cool outside of the building envelop. The thermal property can then be measured by measuring the heat flux (W/m^2) on both sides of the wall (using the circular plates shown in Figure 3.19). The temperature and relative humidity were measured every second using a sensor attached to the heat flux in Figure 3.19. The average per minute was recorded by the data logger (Eltek 851L datalogger in Figure 3.20). The running mean values were then calculated using equations 3.28 and 3.29 to calculate the thermal conductivity (W/m.K) and quantity of heat passing through a unit area of the material (W/m^2).

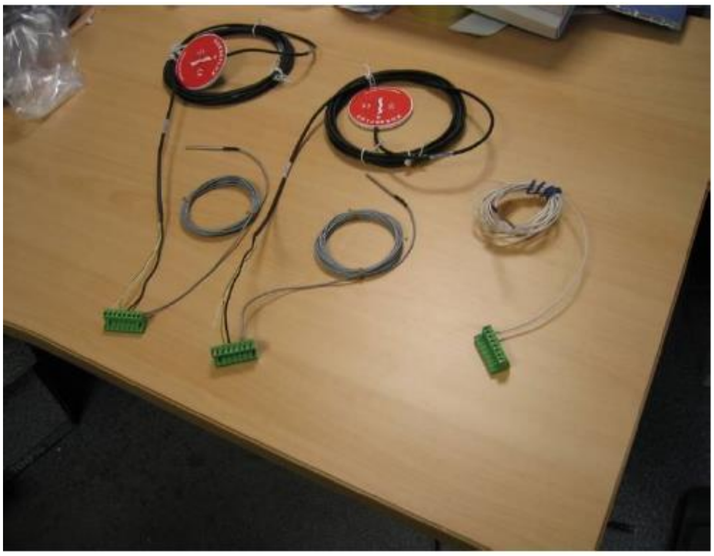


Figure 3.19. Heat flux sensor and thermistor

Figure 3.20. Data logger

3.4 Simulation of Wall System

3.4.1 Modelling for interstitial condensation and assessing risk of mould growth development on selected CEB compositions

After analysing the tests described in Section 3.3 to eliminate any curing/RHA composition combinations which are not suitable for use, a selection of usable CEBs compositions were selected. WUFI Pro 5.3 was used for the dynamic simulation of hygrothermal analysis. Mould formation was further studied by exporting the result from WUFI pro 5.3 to WUFI bio to study the amount of mould growth in mm in a year.

The selection of WUFI pro was as a result of the following considerations:

a. High accurate hygrothermal behaviour result for materials measured over a long period measured against the real climatic condition of the country
b. It allows hygrothermal simulation of interior space to be measured against different standards.
c. Material data for other materials that are required for solid wall system are included in WUFI library (Vertal' et al. 2018)
d. it is a standard tool for assessing hygrothermal performance of one dimension building cross section. It focuses on single or multiple assemblies of walls and roofs that are subjected to external and internal conditions.
e. It allows the customization of material properties
f. It allows the change or calculation of climate data file for the internal space from the external climate imported.

Data from moisture buffering, water vapour transmission, water absorption coefficient, water absorption rate, moisture absorption, bulk density and thermal conductivity of the material tests were required for simulation.

Processes required for WUFI Pro 5.3 simulation

There are three stages in setting up the simulation. These involve the component, the controls, and the climate and are described below.

i. Component

a. **Assembly:** the wall size and wall system are designed for each material in the wall. The material property can also be adjusted accordingly. The wall design is shown in section 2.8.1

b. **Orientation, inclination, and height of the wall:** orientation was chosen based on the most prevalent wind direction. Inclination is vertical for a wall. The wall height was based on a medium rise building (4 storeys).

c. **Surface coefficient:** heat resistant of different types of building structure was given in the tool, so selection of external wall was chosen. The selection of short-wave radiation absorptivity was brick, clay, cream and glazed was chosen as the most similar from the options for the simulation of Compressed earth blocks walls. The other parameters were left at the default values.

d. **Initial condition:** the initial moisture component to be calculated in the component was for each layer of the wall system proposed. The initial relative humidity was the as typically built (60-80%) and initial temperature of 23ºC.

ii. **Controls:**

a. **Calculation period and profiles:** the start date and the end date are selected. The simulation process was investigated for 1 year, and in some cases 3 years

b. **Numerics**: it allows the selection of the mode of calculation which typically includes heat transport, moisture transport and temperature.

iii. **Climate:**

a. **Outdoor (external side):** selection of weather file for simulation of WUFI/ WAC format from Meteonorm. This format is necessary to analyse the driving rain direction in the location selected. The rain factor was calculated according to the ASHRAE standard 160, with the wall exposed by a medium level and the wall below a steep slope room for southern climate (Aw) of Nigeria. The data from Lagos was used (as detailed in Section 3.4).

b. **Indoor (internal side):** two internal condition were selected. The first one represented the indoor climate for areas like kitchen and bathroom with moisture content resulting from the high relative humidity of about 85% by selecting the sine curves. The other for areas with "normal" climate condition like living room, dining rooms, bedrooms, by selecting EN 15026. The indoor climate in EN 15026 was calculate from the external climate.

Process required for WUFI bio simulation.

WUFI bio is an add-on tool that can be used in connection with results from WUFI Pro to analyse mould growth in the building. It is important to study different boundary conditions that may potentially be experienced within the interior space of the building. The tool studies the boundary conditions compared with growth conditions that are typical for mould growth to thrive. It compares the critical water content and the water content that would support the germination of spores. The analysis tells if the material used for wall is wet enough to grow mould. The internal temperature, the relative humidity and substrate quality are required for analysis. The mould spores that are close to the wall surface change water content as the temperature and the relative humidity change. Biological activity begins and the spores germinate at the point at which water content reaches the critical.

Limitations to the tools are highlighted below:

- It can only simulate for interior spaces.
- Influence of other factors such as pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered.

A variety of available substrates for mould growth in building simulation include the following:

Substrate class 0: it refers to possible any mould growth in the building.

Substrate class I: it refers to mould growth in bio-utilizable substrates, such as wallpaper, plaster boards, etc.

Substrate class II: it refers to less bio-utilizable substrate with porous structure such as plaster, earth blocks, mineral building material, wood, etc. This is the category of substrate to be used for the earth wall that is analysed. The internal temperature and relative humidity for mould growth at this stage is 25-30ºC and 80%, respectively.

Substrate class K: it refers to fungi growth that leads to possible health risk to the users of the space and building that has nutrient within. The internal relative humidity is higher than 80% and temperature 25- 30%

Mould index for classification with WUFI bio

There are seven possible classifications of mould growth. These are:

0: No growth

1: Some growth visible under microscope

2: Moderate growth visible under microscope, coverage more than 10%

3: Some growth seen visually; thin hyphae found under microscope.

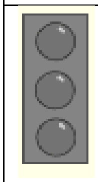
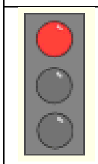
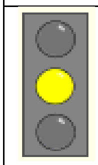
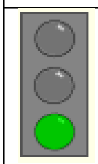
4: Visual coverage more than 10%

5: Cover more than 50%

6: Tight coverage, 100%

The results of the analysis are shown as traffic light colours and implications are highlighted in Table 3.6.

Table 3.6 WUFI Bio traffic light indicators

Traffic light signal	Implication of the light on building materials
	This is shown when the analysis is done for less than 1 year.
	Mould growth on wall surface is more than 200mm/year. The material of wall with this result is not acceptable.
	Mould growth on the wall surface is between 50mm/year and 200mm/year. The materials need to be studied further for it to be acceptable for usage
	Mould growth on the wall surface is below 50mm/year. The value is usually acceptable.

3.4.2 Simulation for thermal comfort performance

The bioclimatic analysis of Lagos, Nigeria was developed to develop an appropriate schematic unit house for CEBs and Nigeria climate. The passive design strategies implemented for CEBs wall material was used for compared with concrete blocks with similar U- value to understand the thermal comfort level of the users of the space.

3.4.2.1 Climatic Analysis

Climatic design responds to the climate of the area and acknowledges the topography of the area. The climatic classifications present across Nigeria were identified in Section 2.3.1 and used to identify relevant design strategies. However, more detailed climatic analysis is useful to ensure an appropriate design strategy is being followed. The following climatic analysis was carried for Lagos state in the south (Aw).

i. Weather data was obtained from Meteonorm 7v7.3.3 for Lagos located at 6.5^0N/3.5^0E – tropical savannah climate (Aw) which covers the largest area of Nigeria (compared to the other three climates present). The data was based on the 1991-2010 period for radiation, while temperature was from 2000-2009.

ii. The Adaptive Comfort Model in ASHRAE Standard 55-2010 was chosen as the most suitable from the options available. This was considered appropriate due to the focus on eliminating mechanical service systems to reduce the amount of energy required to service the building over its lifetime. This fits well with the expected living conditions of the occupants. This model considers that the occupants of the space can make adaptations (e.g., adjust their clothing and open or close the windows) in response to the external climate conditions.

iii. The weather file was visualised using Climate Consultant to obtain the following and represented in Table 5.17:

1. Monthly diurnal averages: this indicates daily temperature variations in relation to solar radiation.
2. Wind: wind speed and direction.
3. Psychrometric chart: bioclimatic chart with simplified weather data was presented in Section 2.3.1. Climate consultant helps visualize more detailed climate data. This enables comparison of the periods of comfort created by the relevant passive strategies.

Basic design decisions were made based on the climatic data.

3.4.2.2 Simulation for thermal performance

The final simulation was to compare the thermal performance of the RHA stabilised CEBs in comparison to modern masonry components. Design builder Version 6 is widely accepted as an appropriate dynamic simulation tool for thermal analysis (Mahmoud, 2020; Srisamranrungruang, 2020) and was selected for this analysis. Like WUFI, Design Builder utilises real climate data. The data from Lagos (as detailed in Section 3.4) was used.

Occupant parameters were specified as:

- Number of occupants – 4, (average occupants of a home in Nigeria)
- Clo level – 0.5-1, (typical short and shirt or trouser and shirt based on the climate)
- Activity level – Dining room, eating.
- Occupancy pattern – mealtimes, 7-10am, 12-3pm, 6-9 pm

As this investigation was testing the thermal response to the wall materials, a simplified structure was used:

- double glazed windows (U-value of 3.0 $W.m^2.K^{-1}$) were positioned on north and south facades to minimise solar gains and roof overhang of 0.9m for additional shading,
- building height of 3.5m,

- roof - clay tile (U-value of 0.25 $W.m^2.K^{-1}$) and pitch of 30^0 to facilitate rainwater removal,
- natural ventilation,
- floor area of $360m^2$. It's size for residential house.

Two material options were tested:

a. Concrete as a typical modern material (wall type EP) (U-value of 1.19)
b. CEB with 20% RHA in an EP wall type (described in Section 5.1.15) (U-value of 1.219). This material was chosen as it meets it has adequately provided a scenario that provides adequate air quality required in the climate considered, the factors are discussed in section 6.3.

Two structure shapes were tested:

The area of the building tested was $360m^2$. The rectangular shape building is the most suitable to ensure easy penetration of air into the building space. The two different shapes are to understand the change of comfort level when the building is less compact to a larger difference between the length and breadth.

a. 24x15m (area to volume ratio of 0.50238) oriented with long dimensions facing North/South.
b. 36x10m (area to volume ratio of 0.54127) oriented with long dimensions facing North/South.

Both shaped were intended to facilitate natural ventilation.

Two window wall ratios (WWR) were tested:

a. 40%- according to Mahoney chart the window to wall ratio for the climate can fall between 40-80%. To reduce the area of window area exposed to sun radiation, reduction of window is necessary to reduce the U-value.
b. 60%

These material options were analysed for occupant thermal comfort by checking the number of hours of comfort in the house for a year. The intention of this analysis is to determine whether occupant comfort is being adversely affected using CEBs in comparison with typical modern materials.

4. Laboratory Test Results

This chapter presents the results of laboratory testing on raw materials (laterite and rice husk ash) in Section 4.1

In section 4.2 the results of laboratory testing of mechanical (4.2.1 bulk density, 4.2.2 compressive strength) and hygrothermal (4.2.3 water absorption, 4.2.4 water absorption coefficient, 4.2.5 water vapour transmission, 4.2.6 moisture absorption, 4.2.7 moisture buffering, 4.2.8 thermal conductivity) properties are presented for:

- Solid and hollow CEBs
- CEBS with OPC partially replaced with RHA at 0%, 10%, 20%, 30%, 40%, and 50%
- Curing times of 14, 21 and 28 days.

These results will be discussed in Chapter 6.

4.1Testing of raw materials used for CEB production.

This section categorises the earth in relation to the Unified Soil Classification and its linear shrinkage. It also assesses the phase composition of the silica within the RHA for its suitability.

4.1.1 Atterberg limit test for laterite soil

The process of determining the parameters which define the Atterberg limits of a laterite soil was described in section 3.2.1.3. The properties of local laterite earth for liquid limit, plastic limit, plastic index and linear shrinkage are presented in Table 4.1.

Table 4.1 Properties of laterite sample used for making the experimental CEB

Property	Mean ± SD
Liquid limit	43.30 ± 4.679
Plastic limit	16.06 ± 5.586
Plasticity index	27.24 ± 4.376
Linear shrinkage	6.50 ± 0.990

Plotting the results of laterite properties (Table 4.1) in the unified soil classification chart (Figure 4.1) showed that the laterite sample corresponds to soil classification CL. Description of soil classes highlighted in Table 4.2 indicated the laterite sample is classified in the category of clays. The Soil CL is inorganic clay of low to medium plasticity, gravelly, sandy and silty clays. The results of liquid limit as shown in Figure 4.1 suggest that the soil has low plasticity.

Table 4.2 Description of the unified soil classification with laterite classification highlighted

Fine grained soils (50%+ passes no. 200 sieve)	Silts	Low plasticity (liquid limit <50)	ML	Inorganic silts, clayey silts of low to medium plasticity
		High plasticity (liquid limit 50+)	MH	Inorganic silts, micaceous or diatomaceous silty soils, elastic silts
	Clays	**Low plasticity (liquid limit <50)**	**CL**	**Inorganic clays of low to medium plasticity, gravelly, sandy, and silty clays**
		High plasticity (liquid limit 50+)	CH	Inorganic clays of high plasticity, fat clays, sandy clays of high plasticity
	Organic silts and clays	Low plasticity (liquid limit <50)	OL	Organic silts and clays of low to medium plasticity, sandy organic silts and clays
		High plasticity (liquid limit 50+)	OH	Organic silts and clays of high plasticity, sandy organic silts and clays
Organic soils		Primarily organic matter (dark in colour and organic odor)	PT	Peat

The findings about the laterite soil are discussed further in Section 6.1.1.(Hind K.J, 2007)

4.1.2 Phase identification of silica in RHA

Two methods of processing rice husk in order to achieve ash with an appropriate silica content were trialled. The method used for production of the rice husk ash was shown in section 3.2.1.3

X-ray diffraction (XRD) was used to calculate the percentage of amorphous silica within the RHA. The XRD analysis was carried out by the School of Chemistry, Cardiff University.

The X-ray diffraction trace for RHA prepared using Method 1 (pre-charred) is shown in Figure 4.1. While the trace for RHA prepared using Method 2 (furnace only) is shown in Figure 4.2. The percentage of amorphous silica indicated by the X-ray diffraction traces are presented in Table 4.3.

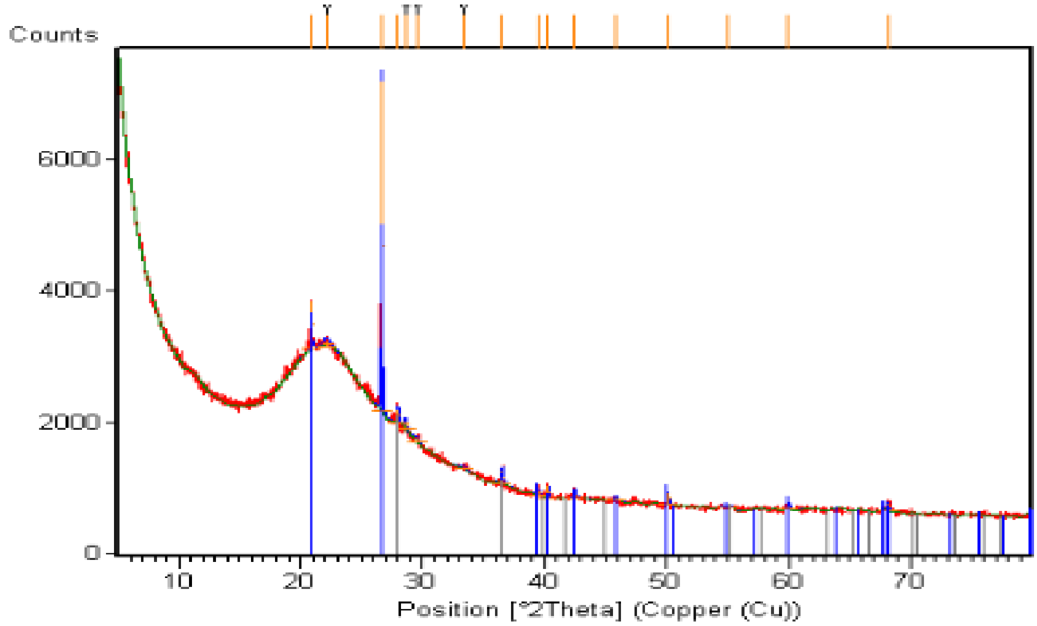


Fig 4.1- 80% SiO_2(xrd analysis software) – Method 1

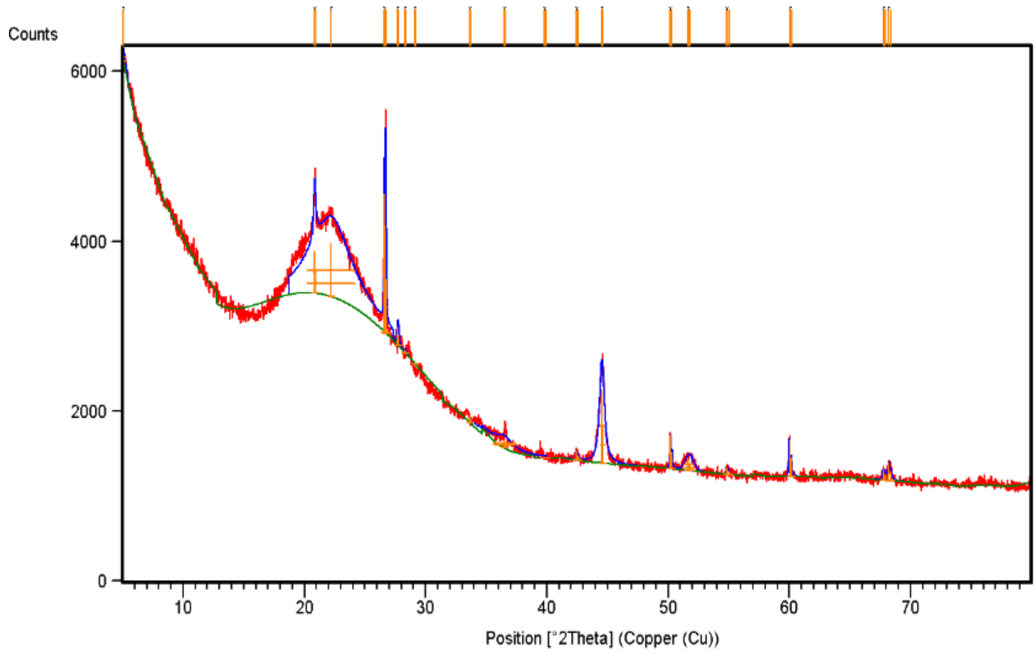


Fig 4.2- 96% SiO_2 (xrd analysis software) – Method 2

Table 4.3 Percentage amorphous silica contents of experimental Rice Husk Ash (RHA) samples at different combustion times

RHA produced from:	Combustion duration (hr)	Silica (%)
Method 1 (Fig 4.1)	2-3	80%
Method 2 (Fig 4.2)	2.5 -4	96%

Both methods produced ashes containing amorphous silica contents adequate for pozzolan chemical reaction when used for stabilization. Combusting the rice husk for a longer period at the applied temperature (i.e. 550 to 780ºC) as in Method 2, resulted in ash that contained higher amount of silica, but incurred an energy penalty for using the furnace for a longer period.

The findings about RHA are discussed further in Section 6.1.2.

4.2 Mechanical and Hygrothermal properties of the Experimental CEBs

The results of the laboratory tests on the experimental CEBs are presented in this section.

The different types (solid vs hollow), curing periods and RHA compositions were expected to influence the mechanical and hygrothermal properties of the CEBs. These properties were tested and are reported in the following sections of Chapter 4. As hollow blocks were only intended for internal use, these were not tested for hygrothermal properties.

4.2.1 Bulk density of experimental CEBs

The methodology used to determine bulk density of the CEBs was described in section 3.3.1. The results of bulk density of the experimental solid and hollow CEBs with varying levels of RHA cured for 14, 21 and 28 days are presented in Tables 4.4 and 4.5, respectively. As three samples were tested for each condition the mean and standard deviation (SD) are presented. The mean bulk density values ranged from 1738.0 ± 34 to 1935.9 ± 51 kg/m^3 in solid CEBs, and from 1753.9 ± 66 to 1977.9 ± 29 kg/m^3 in hollow CEBs.

The mean bulk density values of the solid CEBs and duration of curing are shown in Table 4.4 and Figure 4.3 (abbreviated y-axis to illustrate this point).

Table 4.4. Bulk density of solid CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Bulk density (kg/m^3) Mean ± SD
S/0 RHA	14	0	100	1891.8 ± 14
0% RHA	21	0	100	1790.7 ± 57
	28	0	100	1768.2 ± 40
S/0.2 RHA	14	10	90	1885.7 ± 12
10% RHA	21	10	90	1816.6 ± 16
	28	10	90	1855.5 ± 19
S/0.4 RHA	14	20	80	1916.0 ± 28
20% RHA	21	20	80	1738.0 ± 34
	28	20	80	1783.8 ± 26
S/0.6 RHA	14	30	70	1860.7 ± 41
30% RHA	21	30	70	1782.0 ± 28
	28	30	70	1777.7 ± 27
S/0.8 RHA	14	40	60	1935.9 ± 51
40% RHA	21	40	60	1782.0 ± 31
	28	50	60	1756.1 ± 29
S/1 RHA	14	50	50	1800.2 ± 43
50% RHA	21	50	50	1791.5 ± 39
	28	50	50	1824.4 ± 49

Table 4.5. Bulk density of hollow CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Bulk density (kg/m^3) Mean ± SD
H/0 RHA	14	0	100	1797.1 ± 12
	21	0	100	1826.8 ± 36
	28	0	100	1977.9 ± 29
H/0.2 RHA	14	10	90	1911.3 ± 49
	21	10	90	1852.0 ± 50
	28	10	90	1768.3 ± 48
H/0.4 RHA	14	20	80	1844.8 ± 28
	21	20	80	1782.7 ± 68
	28	20	80	1873.5 ± 48
H/0.6 RHA	14	30	70	1812.4 ± 89
	21	30	70	1792.0 ± 55
	28	30	70	1949.1 ± 45
H/0.8 RHA	14	40	60	1831.3 ± 99
	21	40	60	1789.9 ± 35
	28	50	60	1753.9 ± 66
H/1 RHA	14	50	50	1784.5 ± 50
	21	50	50	1808.8 ± 23
	28	50	50	1786.3 ± 49

Results presented in Table 4.6 (below) depict the effect of RHA and duration of curing on the bulk density of CEB for solid blocks. Considering the influence of curing - the mean bulk density values were highest in blocks cured for 14 days (1881.7 ±47.57 kg/m^3), lowest in blocks cured for 21 days (1775.4 ±32.80 kg/m^3), while values for blocks cured for 28 days curing were 1793.3 to ±39.15 kg/m^3. Considering the influence of RHA content – the lowest (1790.7± 64.53 kg/m^3) mean bulk density value was recorded at S/0.6 RHA (30%) inclusion, while the highest (1852.6 ± 34.64 kg/m^3) was found at S/0.2 RHA (10%) inclusion.

Table 4.6. Effect of RHA inclusion and curing duration on the bulk density of solid CEBs

RHA (%)	Bulk Density (kg/m^3)			
	Day 14	Day 21	Day 28	Mean ± SD
S/0 RHA	1891.8	1790.7	1768.2	1816.9 ±65.83
S/0.2 RHA	1885.7	1816.6	1855.5	1852.6 ± 34.64
S/0.4 RHA	1916.0	1738.0	1783.8	1812.6 ±92.43
S/0.6 RHA	1860.7	1733.6	1777.7	1790.7± 64.53
S/ 0.8 RHA	1935.9	1782.0	1750.1	1822.7 ± 99.35
S/1 RHA	1800.2	1791.5	1824.4	1805.4 ± 17.05
Mean ± SD	1881.7 ±47.57	1775.4 ±32.80	1793.3 ±39.15	

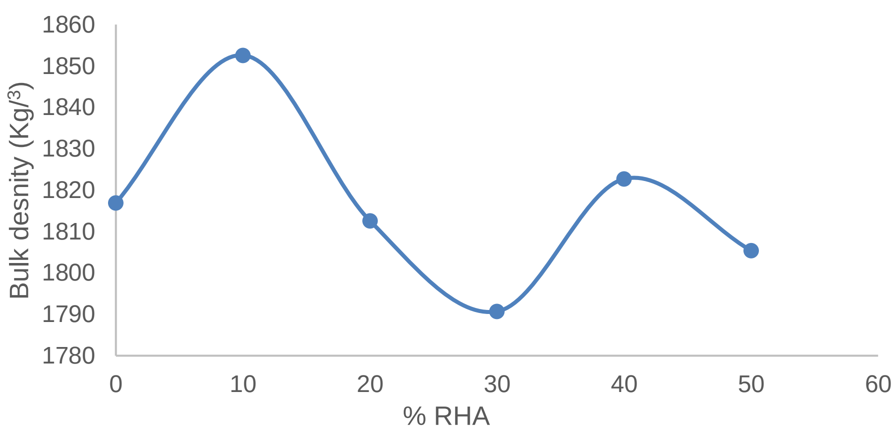


Figure 4.3 Effect of RHA inclusion on bulk density of experimental Solid CEBs

The results for hollow CEBs are shown in Table 4.7 and Figure 4.4. Considering the influence of curing – the mean bulk density values ranged from (low) 1808.37±24.4 kg/m^3 in block cured for 21 days to (high) 1851.5±88.21 kg/m^3 in block cured for 28 days. Considering the influence of RHA content - the lowest was recorded for H/0.8 RHA (40% RHA) with values 1791.7±27.38 while the highest was recorded for H/0 RHA (0% RHA - control block) with 1867.3±68.55.

Table 4.7. Effect of RHA inclusion and curing duration on the bulk density of hollow CEBs

RHA (%)	Bulk Density (kg/m³)			
	Day 14	Day 21	Day 28	Mean ± SD
H/0 RHA	1797.1	1826.8	1977.9	1867.3 ±68.55
H/0.2 RHA	1911.3	1852.0	1768.3	1843.9 ± 50.80
H/0.4 RHA	1844.8	1782.7	1873.5	1833.7 ± 32.81
H/0.6 RHA	1812.4	1790.0	1949.1	1850.5 ± 60.90
H/ 0.8 RHA	1831.3	1789.9	1753.9	1791.7 ± 27.38
H/1 RHA	1784.5	1808.8	1786.3	1793.2 ± 9.5
Mean ± SD	1830.23 ±41.41	1808.37 ±24.4	1851.5 ±88.21	

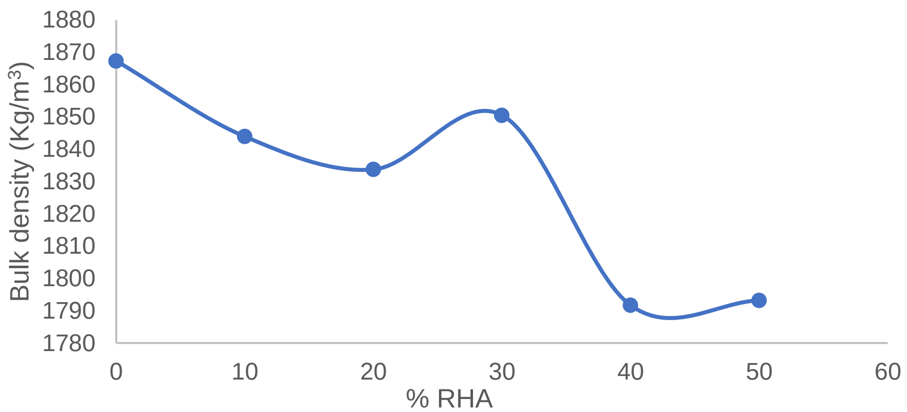


Figure 4.4 Effect of RHA inclusion on bulk density of experimental Hollow CEBs

For solid blocks, the bulk mean density of blocks cured for 14 days was found to be higher than those cured for longer periods; however, this finding did not hold for hollow blocks. There was no clear difference relating to RHA content for solid or hollow blocks. Nor was there a clear difference in the bulk mean density between solid and hollow blocks.

The findings related to bulk density are discussed further in Section 6.2.1.1.

4.2.2 Compressive strength of experimental CEBs

The methodology used to determine compressive strength of the CEBs was described in section 3.3.2. The results of compressive strength of the experimental solid and hollow CEB with varying levels of RHA at different curing duration are presented in Tables 4.8 and 4.9, respectively. Mean values of compressive strength ranged from 2.39 ± 0.3 N/mm^2

being the lowest and 6.39 ± 0.5 N/mm^2 being the highest in the solid CEB. In case of hollow CEB 0.61 ± 0.1 N/mm^2 and 2.68 ±0.1 N/mm^2 were least and highest values, respectively.

The results indicate that the solid CEBs were stronger than the hollow type.

Table 4.8. Compressive strength of solid CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Compressive strength (N/mm^2) Mean ± SD
S/0 RHA	14	0	100	4.86 ± 0.4
	21	0	100	4.21± 0.3
	28	0	100	5.34 ± 0.6
S/0.2 RHA	14	10	90	4.61± 0.2
	21	10	90	5.83± 0.2
	28	10	90	6.39 ± 0.5
S/0.4 RHA	14	20	80	3.92 ± 0.2
	21	20	80	4.26 ± 0.3
	28	20	80	4.08 ± 0.3
S/0.6 RHA	14	30	70	4.08 ± 0.4
	21	30	70	3.89 ± 0.5
	28	30	70	3.12 ± 0.4
S/0.8 RHA	14	40	60	3.63 ± 0.1
	21	40	60	3.58 ± 0.3
	28	50	60	2.99 ± 0.2
S/1 RHA	14	50	50	2.39 ± 0.3
	21	50	50	3.84 ± 0.1
	28	50	50	3.22 ± 0.4

Table 4.9. Compressive strength of hollow CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Compressive strength (N/mm^2) Mean ± SD
H/0 RHA	14	0	100	2.22 ± 0.4
	21	0	100	2.30 ± 0.4
	28	0	100	2.68 ±0.1
H/0.2 RHA	14	10	90	2.61 ±0.6
	21	10	90	2.45 ± 0.2
	28	10	90	2.45 ±0.2
H/0.4 RHA	14	20	80	1.46 ± 0.1
	21	20	80	1.53 ± 0.1
	28	20	80	1.92 ± 0.1
H/0.6 RHA	14	30	70	1.38 ± 0
	21	30	70	1.46 ±0.1
	28	30	70	1.46 ± 0.1
H/0.8 RHA	14	40	60	1.30 ± 0.3
	21	40	60	1.38 ± 0
	28	50	60	1.30 ± 0.1
H/1 RHA	14	50	50	0.61 ± 0.2
	21	50	50	0.61 ± 0.1
	28	50	50	0.84± 0.3

Mean values of compressive strength of experimental CEBs cured from 14 to 28 days for solid blocks are shown in Table 4.10. Considering the influence of curing – the mean compressive strength ranged from (low) 3.92±0.873 N/mm^2 in blocks cured for 14 days to (high) 4.27 ±0.803 N/mm^2 in blocks cured for 21 days. However, the difference in the compressive strength between different curing periods was not clear.

Considering the influence of RHA content - the results show that the values varied from (low) 3.15±0.732 N/mm^2 for the group with 50% RHA inclusion to (high) 5.61±0.910 N/mm^2 for the group with 10%RHA inclusion. The group having 10% RHA inclusion has a higher compression strength than the groups with higher RHA inclusions and were comparable to CEBs stabilised using OPC only.

Table 4.10. Effect of RHA inclusion and curing duration on the compressive strength of experimental solid CEBs

RHA (%)	Compressive Strength (N/mm^2)			
	Day 14	**Day 21**	**Day 28**	**Mean ± SD**
0	4.86	4.21	5.34	4.80±0.567
10	4.61	5.83	6.39	5.61±0.910
20	3.97	4.26	4.08	4.10±0.146
30	4.08	3.90	3.12	3.70±0.510
40	3.63	3.58	2.99	3.40±0.356
50	2.39	3.85	3.22	3.15±0.732
Mean ± SD	3.92±0.873	4.27 ±0.803	4.19 ±1.393	

Figure 4.5 illustrates the trend in the compressive strength of the solid CEBs as affected by the RHA inclusion. The picture depicted suggests that inclusion of RHA in the mix caused the reduction of strength by almost half.

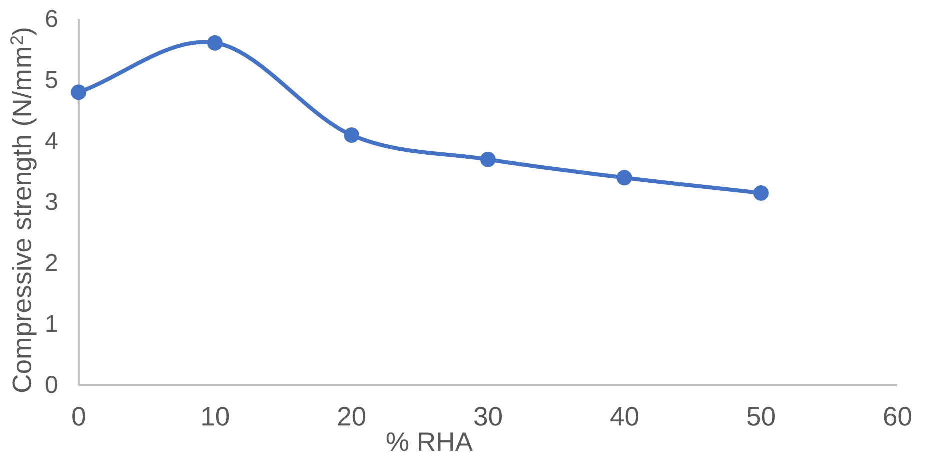


Figure 4.5 Effect of RHA inclusion on compressive strength of experimental solid CEBs

Mean values of compressive strength of experimental CEBs cured from 14 to 28 days for hollow blocks are shown in Table 4.11. Considering the influence of curing - the mean compressive strength was least (1.6±0.65 N/mm^2) after 14 days curing and highest (1.78 ±1.393 N/mm^2) after 28 days of curing. However, the difference in the compressive strength between different curing periods was not clear.

The results show that the values varied with varying levels of RHA inclusion in the mix. The group having 10% RHA inclusion recorded the highest value (2.40 ± 0.17 N/mm^2) while the group with 50%RHA inclusion had the least value (0.69±0.09 N/mm^2). The group having 10% RHA inclusion has a higher compressive strength than the groups with higher RHA inclusions and was comparable to CEBs stabilised using OPC only. The group with 50% RHA had a compressive strength which was lower than all other groups tested. The group with 40% RHA had a compressive strength which was lower than all other groups tested apart from those containing 50% RHA. Although there was an overlap in the compressive strength results from groups containing 20 and 30% RHA, the overall trend that increased RHA proportion reduces the compressive strength appears to hold true for hollow blocks.

Table 4.11. Effect of RHA inclusion and curing duration on the compressive strength of experimental hollow CEBs

RHA (%)	Compressive Strength (N/mm^2)			
	Day 14	Day 21	Day 28	Mean ± SD
0	2.22	2.30	2.68	2.40 ± 0.17
10	2.61	2.45	2.45	2.50 ± 0.07
20	1.46	1.53	1.92	1.63 ± 0.17
30	1.38	1.46	1.46	1.43 ± 0.03
40	1.30	1.38	1.30	1.33 ± 0.03
50	0.61	0.61	0.84	0.69 ± 0.09
Mean ± SD	1.60 ±0.65	1.62 ±0.61	1.78 ±1.393	

Figure 4.6 illustrates the trend in the compressive strength of the hollow CEBs as affected by the RHA inclusion.

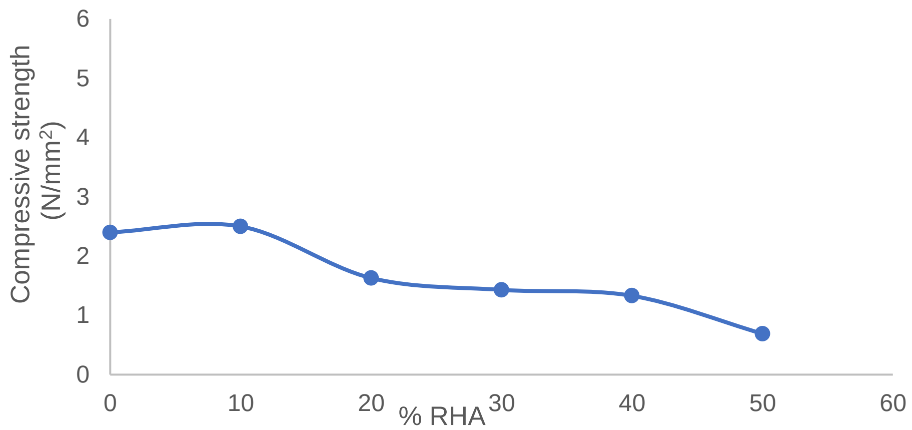


Figure 4.6 Effect of RHA inclusion on compressive strength of experimental hollow CEBs

For curing periods of 14 and 21 days, the solid blocks show a higher compressive strength than hollow blocks. There is not a difference in compressive strength for blocks cured for 28 days for solid and hollow blocks. Considering RHA content, the “solid” version of each RHA content has a higher compressive strength than the “hollow” version with the same RHA content.

The findings for compressive strength are further discussed in Section 6.2.1.2.

4.2.3 Water Absorption Capacity of experimental CEBs

The methodology used to determine water absorption capacity was described in Section 3.3.3. The results of water absorption capacity of the experimental solid and hollow CEB with varying levels of RHA at different curing duration are presented in Tables 4.12 and 4.13, respectively. Mean values of water absorption capacity ranged from 5.25 ± 0.16 % to 9.66 ± 2.29% in solid CEB, and from 4.26 ± 0.93% to 7.96 ± 1.48% in hollow CEB.

Table 4.12. Water absorption capacity of solid CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Water absorption capacity (%) Mean ± SD
S/0 RHA	14	0	100	5.25 ± 0.16
	21	0	100	7.43 ± 0.45
	28	0	100	8.75 ± 0.47
S/0.2 RHA	14	10	90	5.40 ± 0.54
	21	10	90	8.89 ± 0.24
	28	10	90	5.88 ± 1.07
S/0.4 RHA	14	20	80	5.60 ± 0.65
	21	20	80	9.66 ± 2.29
	28	20	80	5.95 ± 0.82
S/0.6 RHA	14	30	70	6.88 ± 0.48
	21	30	70	9.67 ± 1.23
	28	30	70	7.90 ± 1.82
S/0.8 RHA	14	40	60	4.31 ± 0.87
	21	40	60	8.51 ± 1.99
	28	40	60	9.17 ± 2.29
S/1 RHA	14	50	50	7.68 ± 0.65
	21	50	50	9.43 ± 1.03
	28	50	50	7.43 ± 0.83

Table 4.13. Water absorption capacity of hollow CEBs produced with varying partial replacement of OPC with RHA

Code	Duration of curing (days)	RHA (%)	OPC (%)	Water absorption capacity (%) Mean ± SD
H/0 RHA	14	0	100	6.07 ± 1.46
	21	0	100	7.38 ± 0.47
	28	0	100	5.84 ± 1.66
H/0.2 RHA	14	10	90	5.34 ± 1.60
	21	10	90	5.24 ± 0.77
	28	10	90	6.16 ± 0.35
H/0.4 RHA	14	20	80	4.26 ± 0.93
	21	20	80	6.70 ± 1.17
	28	20	80	6.59 ± 0.42
H/0.6 RHA	14	30	70	6.61 ± 1.39
	21	30	70	8.03 ± 0.25
	28	30	70	6.99 ± 1.13
H/0.8 RHA	14	40	60	6.83 ± 0.89
	21	40	60	7.40 ± 1.00
	28	50	60	8.47 ± 1.53
H/1 RHA	14	50	50	7.96 ± 1.48
	21	50	50	6.71 ± 1.14
	28	50	50	7.15 ± 0.23

The mean water absorption capacity of the test solid CEB samples presented in Table 4.14 revealed that the lowest (4.31 ± 0.87%) and the highest (9.66 ± 2.29%) values were obtained at 14 and 21 days of curing, respectively. Also, the least value (6.76±1.59%) and the highest value (8.20±0.91%) were recorded in blocks that had 10% and 50%, respectively.

Table 4.14 Water absorption capacity of solid CEBs with varying RHA levels cured for 14, 21 and 28 days

RHA (%)	Water Absorption Capacity (%)			
	Day 14	Day 21	Day 28	**Mean ± SD**
0	5.25	7.43	8.75	7.14±1.44
10	5.40	8.99	5.88	6.76±1.59
20	5.60	9.99	5.95	7.18±1.99
30	6.88	9.67	7.90	8.15±1.14
40	4.31	8.51	9.17	7.33±2.15
50	7.68	9.48	7.43	8.20±0.91
Mean ± SD	5.85±1.11	9.01±0.85	7.51±1.26	

Figure 4.7 illustrates the trends in the water absorption capacity of the solid CEBs as affected by RHA inclusion. However, none of the RHA compositions performed differently from the control sample (0% RHA). Similarly, there was no clear difference in water absorption capacity between different curing periods.

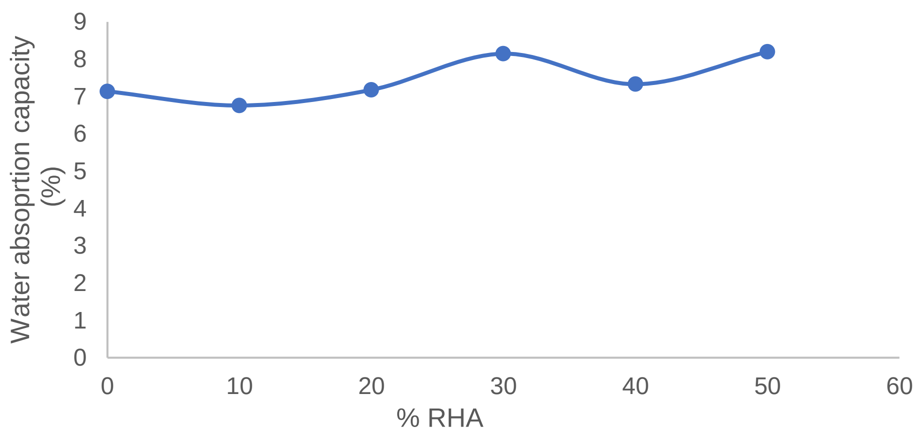


Figure 4.7 Effect of RHA inclusion on water absorption capacity on experimental Solid CEBs

The mean water absorption capacity of the test hollow CEB samples presented in Table 4.15 revealed that the lowest (5.85±1.11%) and the highest (9.01±0.85%) values were obtained at 14 and 21 days of curing, respectively. Also, the least value (6.76±1.59) and the highest value 8.20±0.91%) were recorded in blocks that had 10% and 50% RHA, respectively

Table 4.15 Water absorption capacity of hollow CEBs with varying RHA levels cured for 14, 21 and 28 days

RHA (%)	Water Absorption Capacity (%)			
	Day 14	Day 21	Day 28	**Mean ± SD**
0	6.07	7.38	5.84	6.43 ± 0.78
10	5.34	5.24	6.16	5.58 ± 0.41
20	4.26	6.70	6.59	5.85 ± 01.13
30	6.61	8.03	6.99	7.21 ± 0.60
40	6.83	7.40	8.47	7.57 ± 0.68
50	7.96	6.71	7.15	7.27±0.52
Mean ± SD	6.18±1.17	6.91±0.87	6.87±0.84	

Figure 4.8 illustrates the trends in the water absorption of the hollow CEBs as affected by RHA inclusion. The group having 10% RHA inclusion has a lower water absorption capacity than the groups with 40% or higher RHA inclusions. However, there was no clear difference in water absorption capacity between different curing periods.

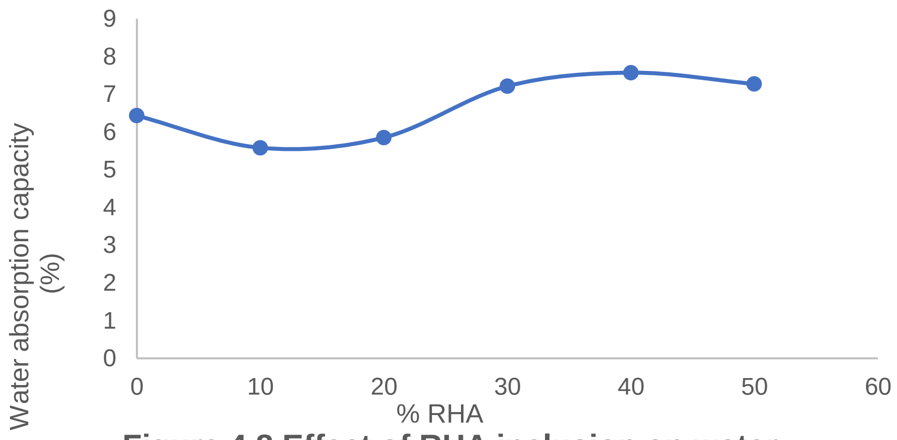


Figure 4.8 Effect of RHA inclusion on water absorption capacity on experimental hollow CEBs

The findings for water absorption capacity are further discussed in Section 6.2.1.3.

4.2.4 Water Absorption coefficient of Compressed Earth Blocks

The methodology used to determine the water absorption coefficient was described in Section 3.3.4. Solid blocks which had been cured for 28 days were tested. This test was not applied to hollow blocks intended for internal use. The results are presented in Tables 4.16 to 4.22 and Figures 4.10 to 4.15.

The plots (Figures 4.9 – 4.14) were all curvilinear; hence the water absorption coefficients were calculated using Equation 3.15 and 3.17.

i. The results of partial immersion of the block sample S/0 RHA are shown in Table 4.18. The square root of time (secs) is plotted against change in mass of the surface area $\Delta m_t/A$ (kg/m^2) in Figure 4.9.

Table 4.16 Water Absorption Coefficient for sample S/0 RHA

Time		$\sqrt{t}$ (secs)	Mass change mean ± SD	Δm_t (kg)	$\Delta m_t/A$ (kg/m^2)
(hr)	(secs)				
Initial	0	0	7.20 ± 0.04	0	0
1/3 (20 mins)	1200	34.64	7.35 ± 0.04	0.1	3.57
1	3600	60.00	7.61 ± 0.02	0.37	13.21
2	7200	84.85	7.63 ± 0.02	0.39	13.93
4	14400	120.00	7.8 ± 0.09	0.62	22.14
6	21600	146.97	7.8 ± 0.08	0.64	22.86
12	43200	207.9	8 ± 0.00	0.76	27.14
18	64800	254.56	8 ± 0.00	0.76	27.14
24	86400	293.94	8 ± 0.00	0.76	27.14

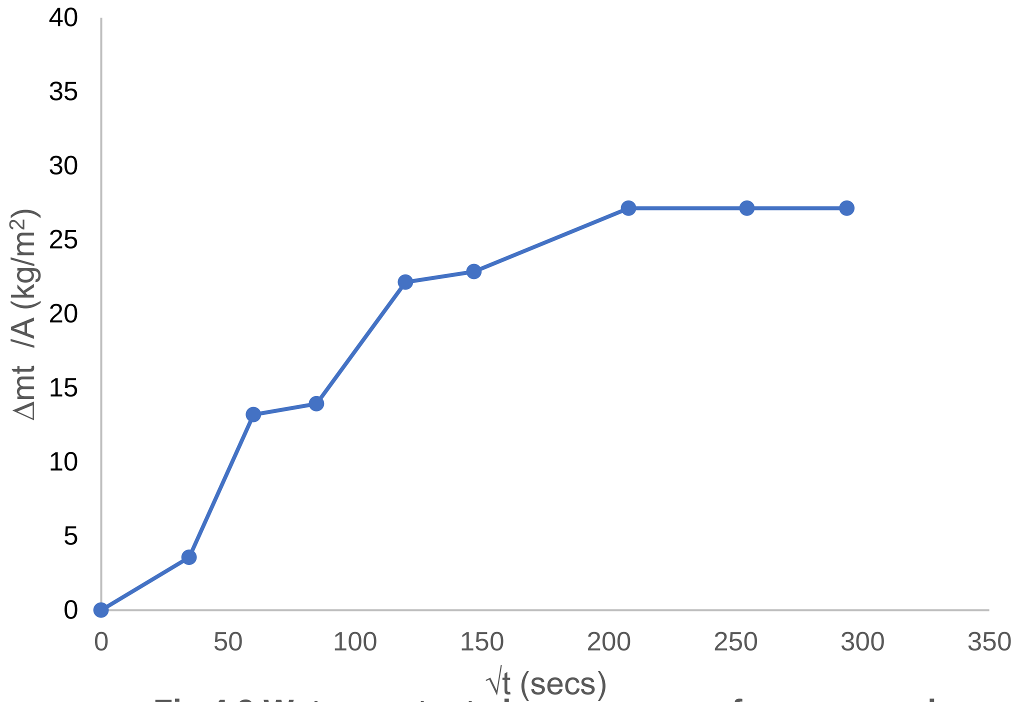


Fig 4.9 Water content change over surface area and square root of time in 24 hrs (control, S/0 RHA)

Using equation 3.17, Water coefficient for S/0 RHA (Control)= 0.09 kg/m^2 s$^{1/2}$

Table 4.17 Water Absorption Coefficient for sample S/0.2 RHA

Time (hr)	Time (secs)	√t (secs)	Mass change mean ± SD	Δm_t (kg)	Δm_t /A (kg/m^2)
Initial	0	0	7.35 ± 0.04	0	0
1/3 (20 mins)	1200	34.64	7.55 ± 0.04	0.2	7.14
1	3600	60.00	7.75 ± 0.02	0.38	13.57
2	7200	84.85	7.8 ± 0.00	0.45	16.07
4	14400	120.00	7.85 ± 0.00	0.5	17.86
6	21600	146.97	7.93 ± 0.02	0.58	20.71
12	43200	207.9	8.10 ± 0.05	0.78	27.86
18	64800	254.56	8.15 ± 0.00	0.8	28.57
24	86400	293.94	8.15 ± 0.00	0.8	28.57

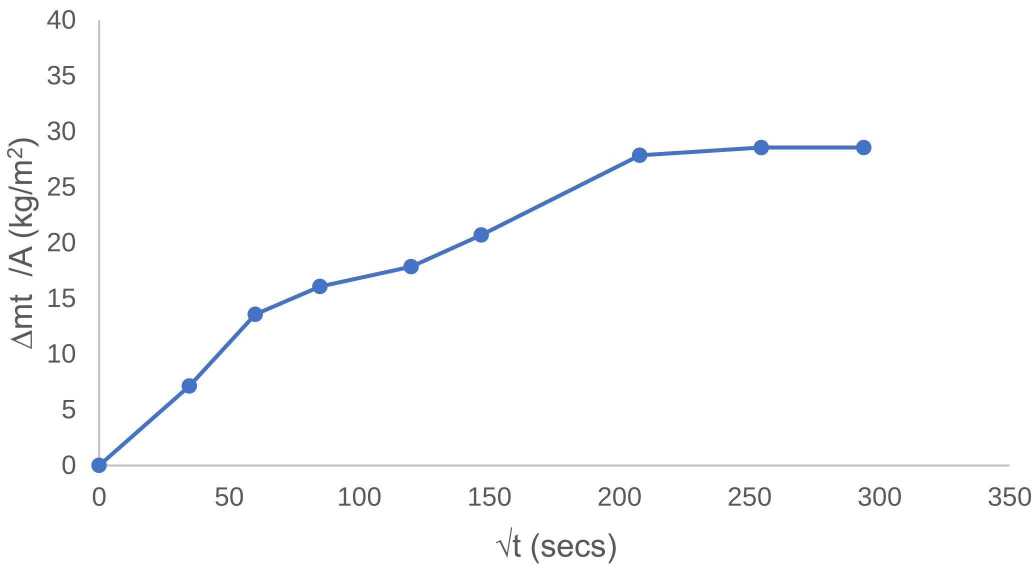


Fig 4.10 Water content change over surface area and square root of time in 24 hrs (S/0.2 RHA)

Using equation 3.17, Water coefficient for S/0.2 RHA (Control)= 0.10 kg/m^2 s$^{1/2}$

Table 4.18 Water Absorption Coefficient for sample S/0.4 RHA

Time (hr)	(secs)	√t (secs)	Mass change mean ± SD	Δm_t (kg)	Δm_t /A (kg/m^2)
Initial	0	0	6.98 ± 0.06	0	0
1/3 (20 mins)	1200	34.64	7.15 ± 0.04	0.17	6.07
1	3600	60.00	7.31 ± 0.08	0.34	12.1
2	7200	84.85	7.45 ± 0.04	0.47	16.8
4	14400	120.00	7.57 ± 0.09	0.59	21.1
6	21600	146.97	7.61 ± 0.02	0.64	22.9
12	43200	207.85	7.8 ± 0.00	0.82	29.3
18	64800	254.56	7.82 ± 0.02	0.84	30
24	86400	293.94	7.82 ± 0.02	0.84	30

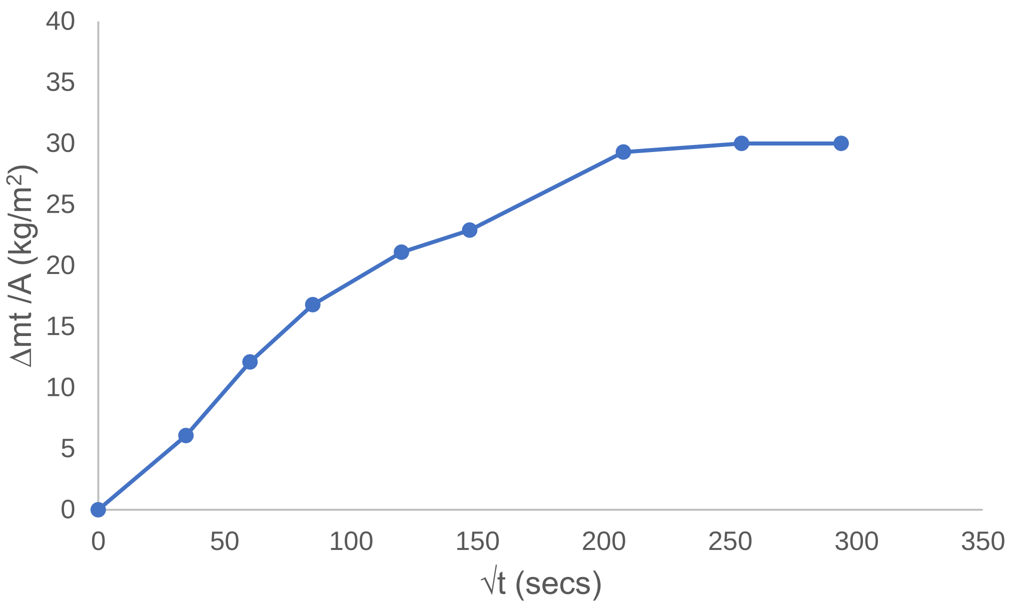


Figure 4.11 Water content change over surface area and square root of time in 24 hrs (S/0.4 RHA)

Using equation 3.17 Water coefficient for S/0.4 RHA (Control)= 0.10 kg/m^2 s$^{1/2}$

Table 4.19 Water Absorption Coefficient for sample S/0.6 RHA

Time (hr)	Time (secs)	√t (secs)	Mass change mean ± SD	Δm_t (kg)	$\Delta m_t/A$ (kg/m^2)
Initial	0	0	6.65 ± 0.04	0	0
1/3 (20 mins)	1200	34.64	6.97± 0.02	0.32	11.43
1	3600	60.00	7.13 ± 0.02	0.48	17.14
2	7200	84.85	7.20 ± 0.00	0.55	19.64
4	14400	120.00	7.28 ± 0.02	0.63	22.5
6	21600	146.97	7.33 ± 0.02	0.68	24.29
12	43200	207.85	7.37 ± 0.04	0.72	25.71
18	64800	254.56	7.38 ± 0.02	0.73	26.07
24	86400	293.94	7.50 ± 0.04	0.85	30.36

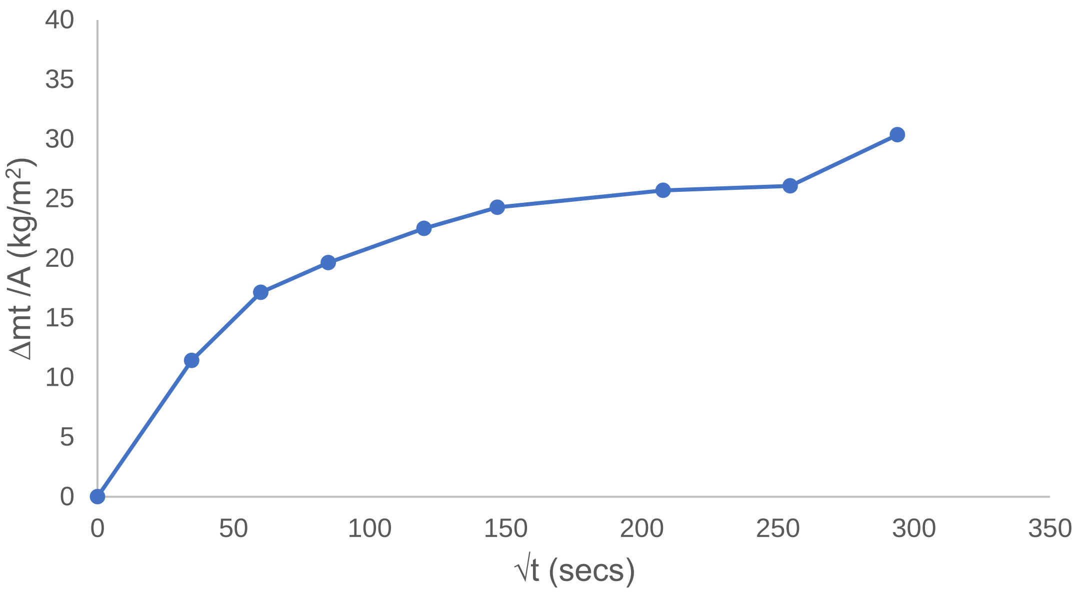


Figure 4.12 Water content change over surface area and square root of time in 24 hrs (S/0.6 RHA)

Using equation 3.17 Water coefficient for S/0.6 RHA (Control)= 0.10 kg/m^2 s$^{1/2}$

Table 4.20 Water Absorption Coefficient for sample S/0.8 RHA

Time		√t (secs)	Mass change mean ± SD	Δm_t (kg)	Δm_t /A (kg/m^2)
(hr)	(secs)				
Initial	0	0	6.63 ± 0.05	0.00	0
1/3 (20 mins)	1200	34.64	6.97± 0.02	0.34	12.14
1	3600	60.00	7.11 ± 0.02	0.49	17.50
2	7200	84.85	7.26 ± 0.02	0.64	22.86
4	14400	120.00	7.38 ± 0.05	0.75	26.79
6	21600	146.97	7.41 ± 0.02	0.79	28.21
12	43200	207.85	7.53 ± 0.04	0.90	32.14
18	64800	254.56	7.56 ± 0.04	0.94	33.57
24	86400	293.94	7.60 ± 0.00	0.97	34.64

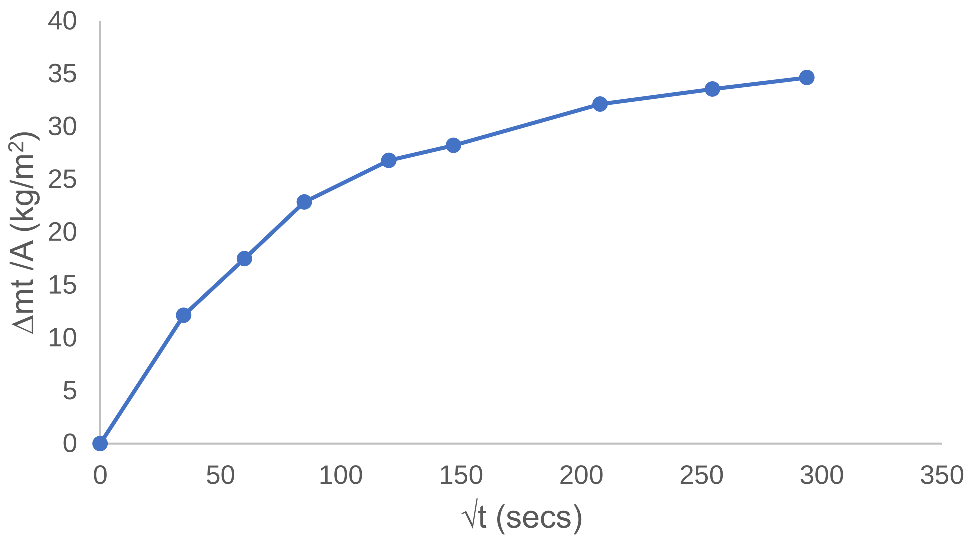


Figure 4.13 Water content change over surface area and square root time in 24 hrs (S/0.8 RHA)

Using equation 3.17 Water coefficient for S/0.8 RHA (Control)= 0.12 $kg/m^2 s^{1/2}$

Table 4.21 Water Absorption Coefficient for sample S/1 RHA

Time (hr)	Time (secs)	√t (secs)	Mass change mean ± SD	Δm_t (kg)	$\Delta m_t/A$ (kg/m^2)
Initial	0	0	6.65 ± 0.04	0.00	0
1/3 (20 mins)	1200	34.64	6.97± 0.02	0.40	14.29
1	3600	60.00	7.13 ± 0.02	0.48	17.14
2	7200	84.85	7.20 ± 0.00	0.56	20.00
4	14400	120.00	7.28 ± 0.02	0.66	23.57
6	21600	146.97	7.33 ± 0.02	0.66	23.57
12	43200	207.85	7.37 ± 0.04	0.70	25.00
18	64800	254.56	7.38 ± 0.02	0.71	25.36
24	86400	293.94	7.50 ± 0.04	0.73	26.07

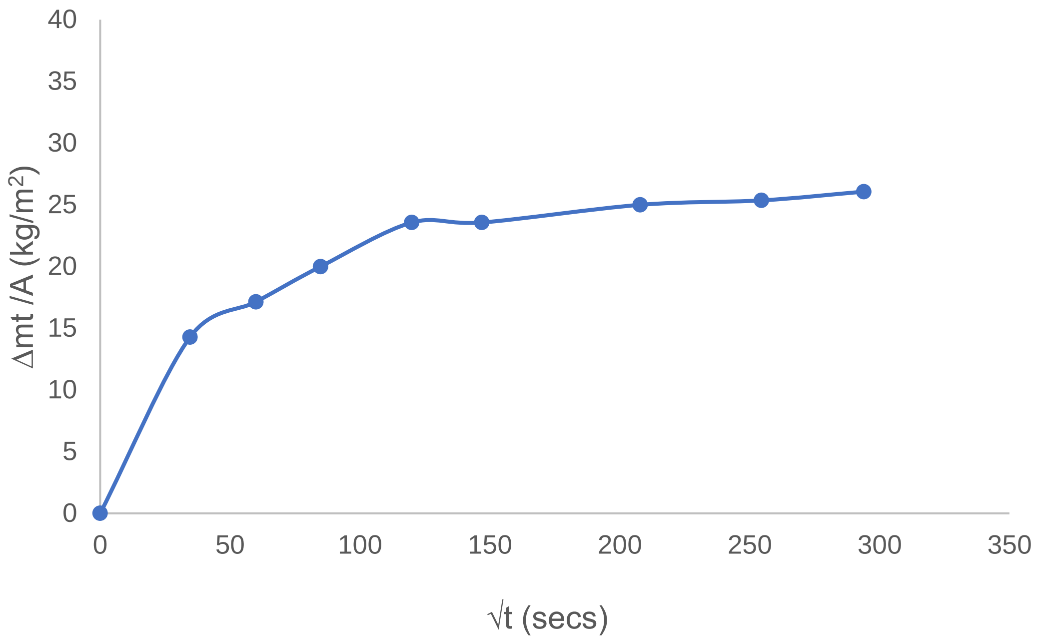


Figure 4.14 Water content change over surface area and square root time in 24 hrs (S/1 RHA)

Using equation 3.17, Water coefficient for S/0.8 RHA (Control)= 0.089 kg/m^2 $s^{1/2}$.

The water absorption coefficient of experimental CEB at different RHA inclusion levels are shown in Table 4.24. The results indicated that water absorption coefficient ranged from 0.089 (kg/m^2 $s^{1/2}$) at 50%RHA inclusion to 0.12 (kg/m^2 $s^{1/2}$) at 40%RHA inclusion. All the plots of change in mass per area against square root of time exhibited curvilinear graphs.

Table 4.22 Water absorption coefficient of experimental solid CEB at different RHA inclusion level

%RHA	Water absorption coefficient (kg/m^2 $s^{1/2}$)	Type of Graph
0	0.090	Curvilinear
10	0.100	Curvilinear
20	0.100	Curvilinear
30	0.100	Curvilinear
40	0.120	Curvilinear
50	0.089	Curvilinear

*Experiment was conducted within the laboratory temperature conditions of 25±5^{o}C

The findings for water absorption coefficient are further discussed in Section 6.2.2.1.

4.2.5 Water Vapour Transmission of Compressed Earth Blocks

The methodology used to determine the water vapour transmission was described in Section 3.3.5. Solid blocks which had been cured for 28 days were tested and control blocks were not tested, the result are to be extrapolated from literature. This test was not applied to hollow blocks which are intended for internal use.

The results of mass changes due to moisture content until equilibrium is reached for experimental CEBs with varying RHA are presented in Table 4.25. This data is then illustrated graphically in Figures 4.15– 4.19. The hygroscopic properties are then presented in Table 4.23.

Table 4.23 Changes in moisture contents in CEB at varying levels of RHA inclusion (water vapour transmission)

Time (secs)	**Moisture change (kg)**					
	0%RHA	**S/0.2 RHA**	**S/ 0.4 RHA**	**S/0.6 RHA**	**S/0.8 RHA**	**S/1 RHA**
0	-	0	0	0	0	0
86400 (24 hrs)	-	0.1	0.05	0.022	0.008	0.018
172800 (48 hrs)	-	0.2	0.068	0.036	0.018	0.026
259200 (72 hrs)	-	0.148	0.08	0.044	0.024	0.042
345600 (96 hrs)	-	0.162	0.084	0.05	0.124	0.052

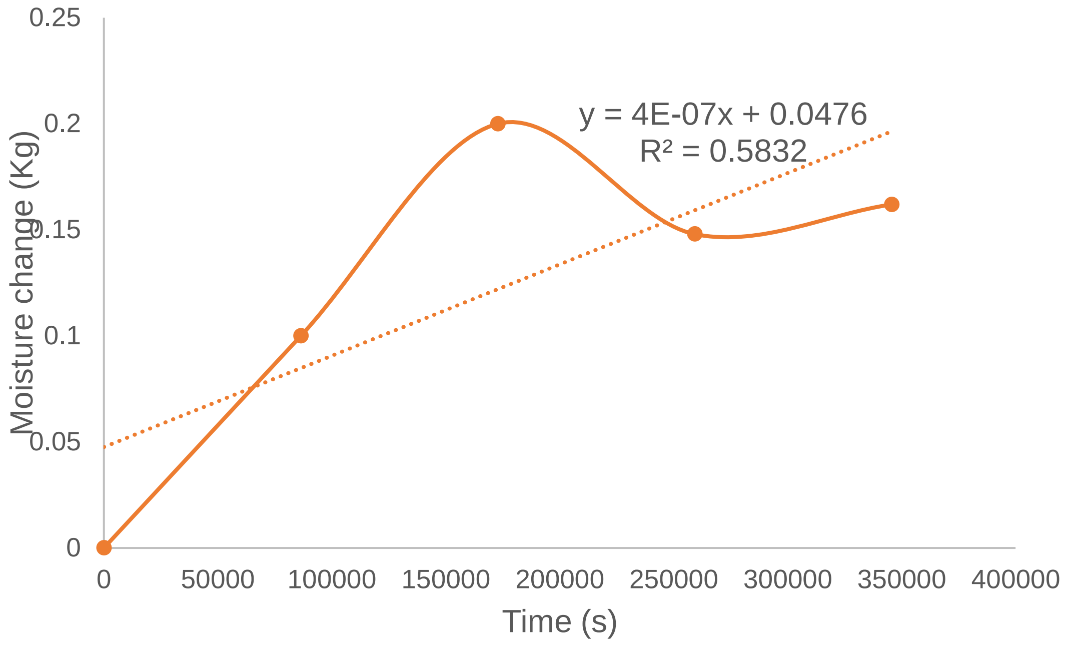


Figure 4.15 Changes in moisture contents in CEBs at 10%RHA (S/0.2 RHA) inclusion

The figure 4.15 plotted was plotted to get the slope of the moisture change until equilibrium is achieved. The slope of the figure is 4E-07

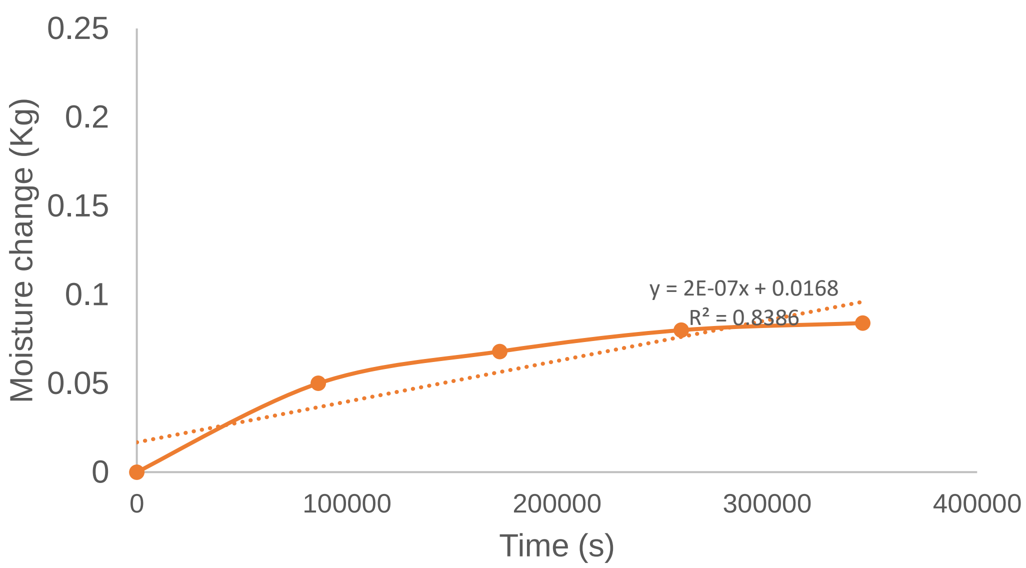


Figure 4.16 Changes in moisture contents in CEBs at 20%RHA (S/0.4 RHA) inclusion

The figure 4.16 plotted was plotted to get the slope of the moisture change until equilibrium is achieved. The slope of the figure is 2E-07

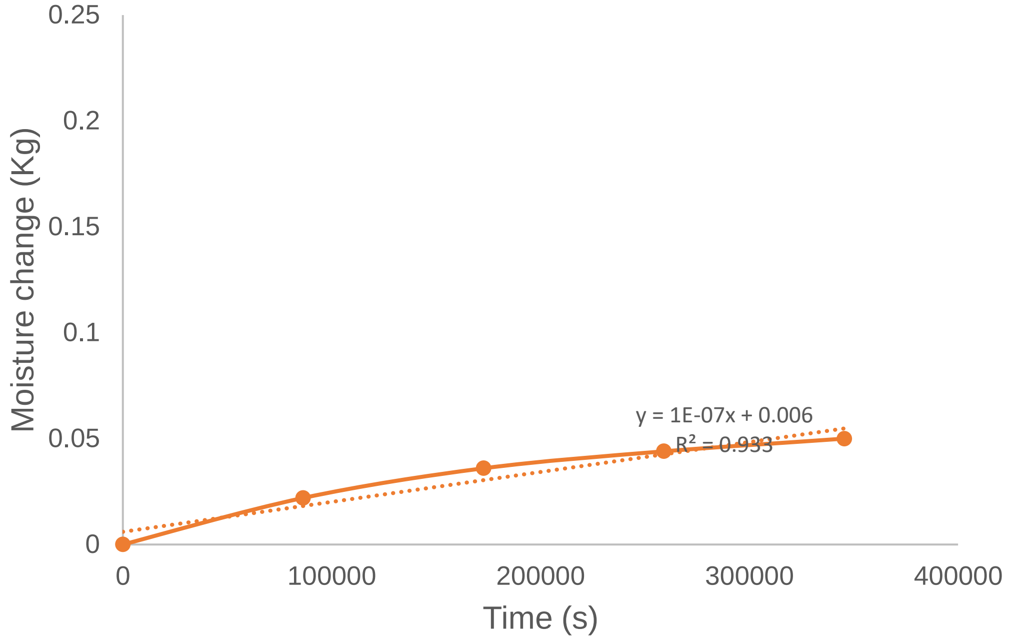


Figure 4.17 Changes in moisture contents in CEBs at 30%RHA (0.6 RHA) inclusion

The figure 4.17 plotted was plotted to get the slope of the moisture change until equilibrium is achieved. The slope of the figure is 1E-07

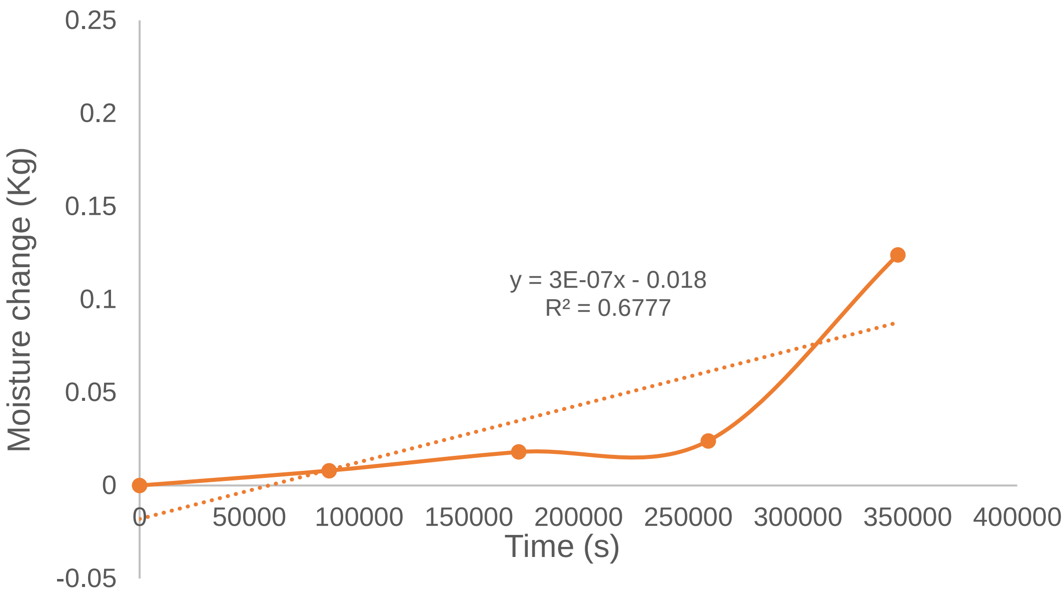


Figure 4.18 Changes in moisture contents in CEBs at 40%RHA (S/0.8 RHA) inclusion

The figure 4.18 plotted was plotted to get the slope of the moisture change until equilibrium is achieved. The slope of the figure is 3E-07

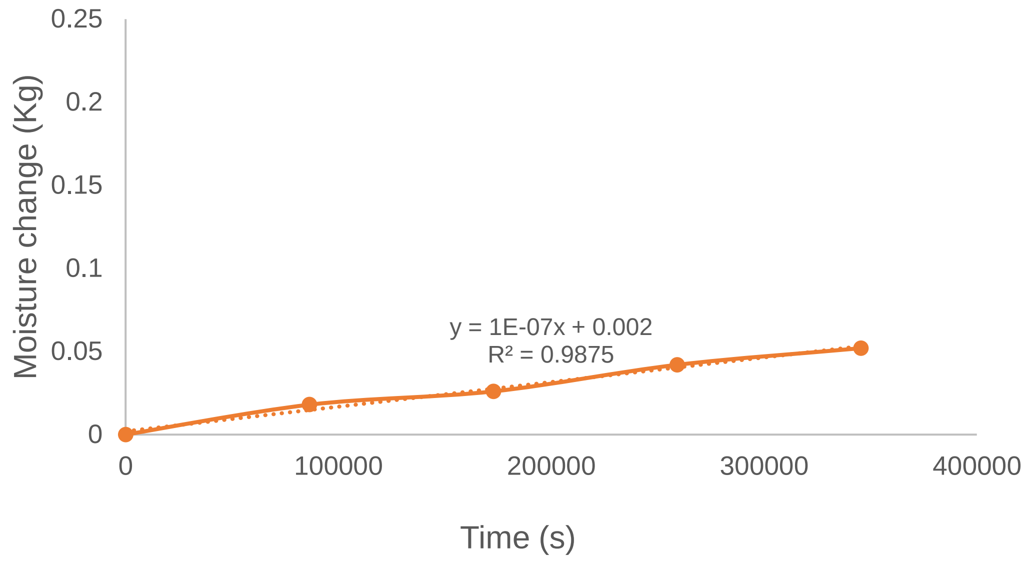


Figure 4.19 Changes in moisture contents in CEBs at 50%RHA (S/1 RHA) inclusion

The figure 4.19 plotted was plotted to get the slope of the moisture change until equilibrium is achieved. The slope of the figure is 1E-07

Density of water vapour rate, water vapour permeance, water vapour resistance, water vapour permeability of the CEB and of the air, and water vapour resistance factor were all computed, and the results are shown in Table 4.26. The results showed consistently that excepting water vapour resistance factor and water vapour permeability of air, other parameters were higher in CEB in which 10%RHA was included. Water vapour permeability of air remained constant in all the treatment groups.

Table 4.24 Hygroscopic properties of CEB at various RHA inclusion

	%RHA in the experimental CEB					
	0	**10**	**20**	**30**	**40**	**50**
Density of water vapour flow rate (kg.m^2/s)	-	1.45E-05	7.27E-06	3.75E-06	1.18E-05	3.77E-06
Water vapour Permeance (kg/m^2.s.Pa)	-	1.04E-10	5.18E-11	2.67E-11	8.41E-11	2.69E-11
Water vapour resistance (m^2.s.Pa/kg)	-	9.65E+10	1.93E+10	3.75E+10	1.19E+10	3.72E+10
Water vapour permeability of the sample (kg/m.s.Pa)	-	1.45E-11	7.25E-12	3.73E-12	1.18E-11	3.76E-12
Water vapour permeability of air (kg/m.s.Pa)	-	1.69E-10	1.69E-10	1.69E-10	1.69E-10	1.69E-10
Water vapour resistance factor	-	11.65	23.30	45.25	14.35	44.91

The findings for water absorption coefficient are further discussed in Section 6.2.2.2.

4.2.6 Moisture absorption of Compressed Earth Blocks

The methodology used to determine the water vapour transmission was described in Section 3.3.6. This test was not applied to hollow blocks which are intended for internal use. Solid blocks which had been cured for 28 days were tested. The results of absorption of moisture by the experimental CEB at the different relative humidity conditions are presented in Table 4.27. Furthermore, the equilibrium moisture content curves were plotted for the experimental CEB with and without RHA inclusion in Figures 4.20 – 4.23.

Table 4.25 Changes in moisture contents in CEB at varying levels of RHA inclusion (moisture absorption)

CEB Sample	Mean Moisture change (%)			
	33%	55%	75%	85%
S/0 RHA (0% RHA)	3.9	6.3	7.1	7.5
S/0.2 RHA (10% RHA)	3.5	6.8	7.4	8.3
S/0.4 RHA (20% RHA)	4.3	5.6	6.0	6.5
S/0.6 RHA (30% RHA)	No result			
S/0.8 RHA (40% RHA)	4.3	6.2	7.1	7.8
S/1 RHA (50% RHA)	No result			

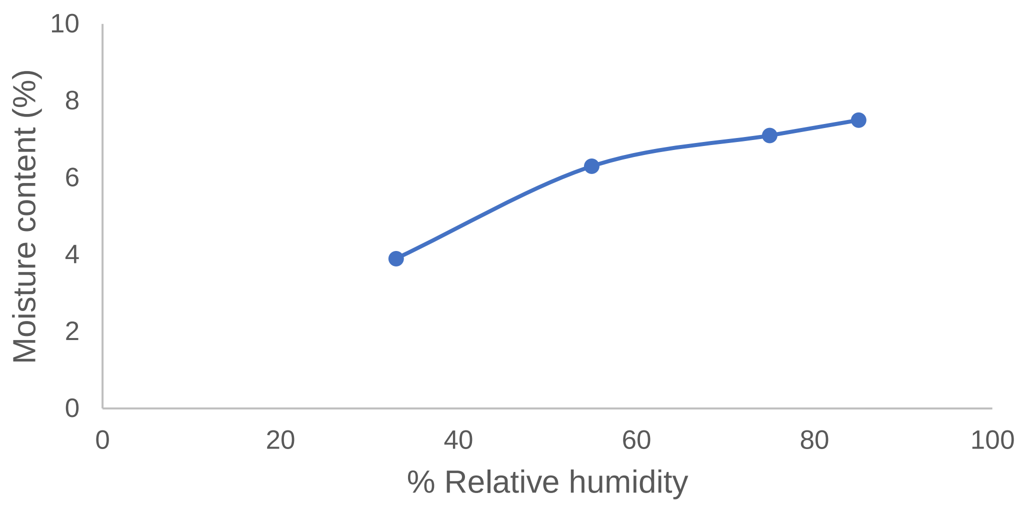


Figure 4.20:Equilibrium Moisture content curve for CEB with 0% RHA (S/0 RHA)

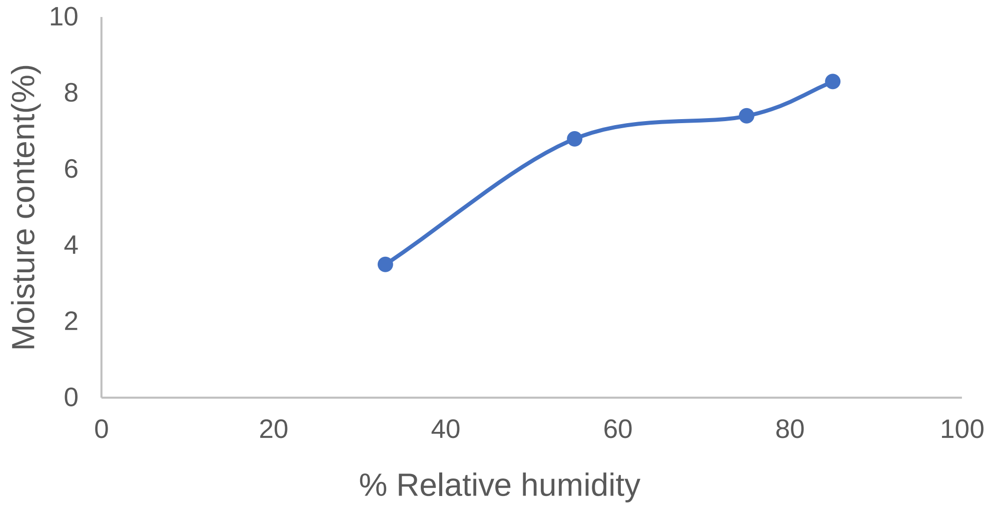


Figure 4.21:Equilibrium Moisture content curve of CEBs with 10% RHA (S/0.2 RHA)

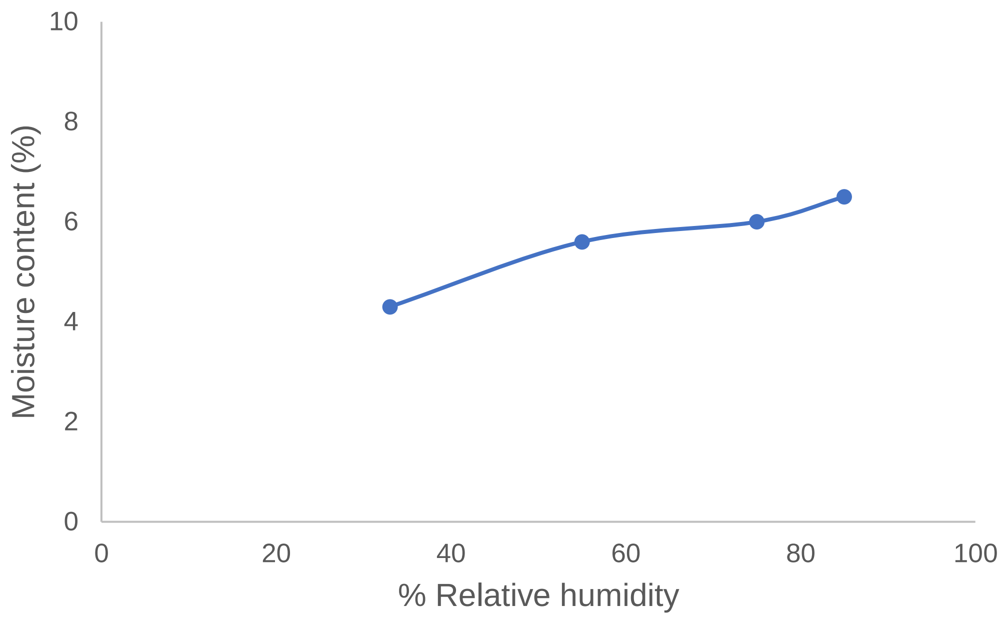


Figure 4.22: Equilibrim Moisture content curve with 20% RHA (S/0.4 RHA)

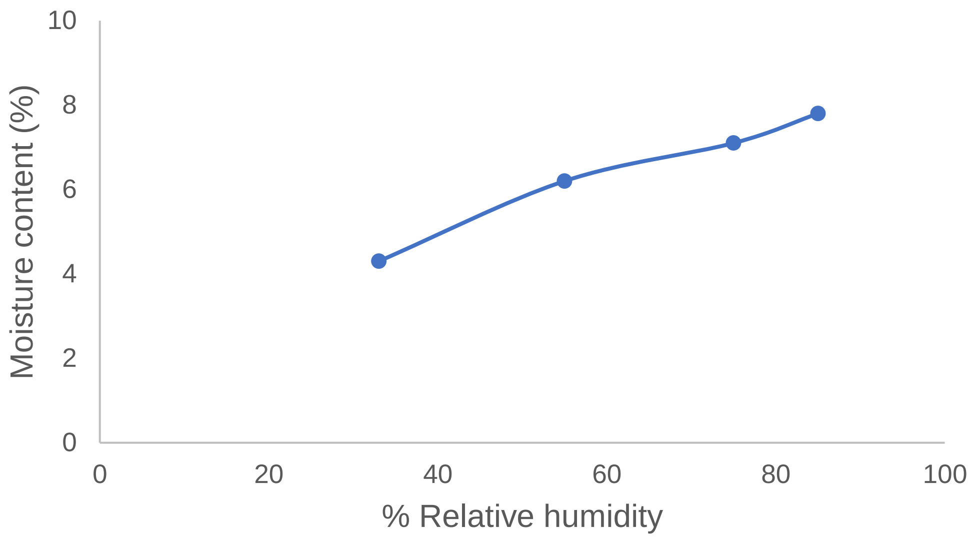


Figure 4.23: Equilibrium Moisture content curve with 40% (S/0.8 RHA)

The findings for moisture absorption are further discussed in Section 6.2.2.3.

4.2.7 Moisture Buffering of Compressed Earth Blocks

The ability of a material to properly absorb or release moisture from its structure plays a significant role in the risk of biological growth on the surface of the material (i.e. mould growth on wall surface). The effect of moisture buffering on the compressed earth blocks stabilized with ordinary Portland cement and rice husk ash was explored using the methodology described in Section 3.3.7. The results presented in Table 4.28 showed that the least moisture buffering value (1.2 g/m^2 %RH) was found in CEB with 20%RHA inclusion whereas CEB with 10%RHA inclusion had the highest value (2.1 g/m^2 %RH). The CEB with 10% RHA was classified as “Excellent” in comparison to the CEB stabilised with OPC which was classified as “Good”. CEBs stabilised with more than 10%RHA were also classified as “Good”, showing comparable performance with OPC stabilised CEBs.

Table 4.26. Influence of stabilization on moisture buffering value of CEBs

Sample CODE	MBV (g/m^2 %RH)	Classification
S/0 RHA (0% RHA)	1.8	Good
S/0.2 RHA (10% RHA)	2.1	Excellent
S/0.4 RHA (20% RHA)	1.2	Good
S/0.6 RHA (30% RHA)	No result	
S/0.8 RHA (40% RHA)	No result	
S/1 RHA (50% RHA)	1.5	Good

Tests with 30% RHA (S/0.6 RHA) and 40% RHA (S/0.8 RHA) were not carried out. However, this was not considered to be a problem as all other samples (including a sample with 50% RHA) had been classified as "Good" or better.

The findings for moisture absorption are further discussed in Section 6.2.2.4.

4.2.8 Thermal Conductivity of Compressed Earth Blocks

An in-situ thermal conductivity test was carried out as described in Section 3.3.8.

The test was carried from August –September 2018. Test of four samples with different RHA content (S/0 RHA, S/0.2 RHA, S/0.4 RHA and S/1 RHA) were taken during this period. The pair tested together consisted of 0% and 50% for the first round and the 10% and 20% for the second round. Each pair were tested for two weeks.

The result shown in Figure 4.24- 4.27 are clean library result for the duration for determining thermal conductivity value for each of the different CEBs with varying RHA. The result had to be clean because during the duration of the test, there was interrupted power supply which created a low temperature different of the internal side of the box to the external side of the box.

Figure 4.24 :Compressed Earth Block stabilized with OPC(control)

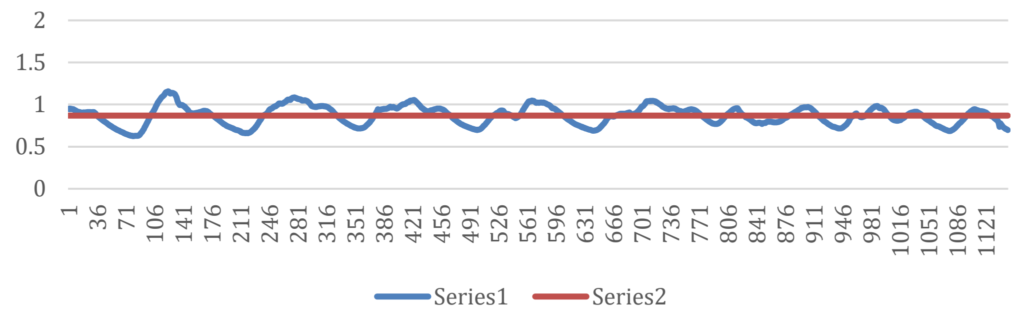


Figure 4.25 :10% RHA partially replace OPC in Compressed Earth Blocks

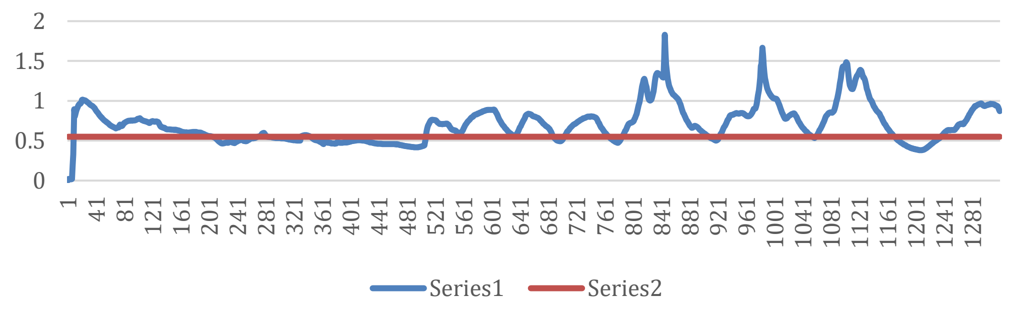
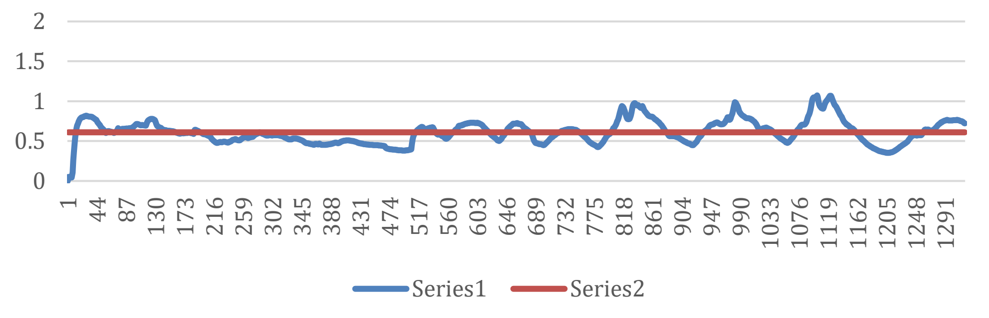
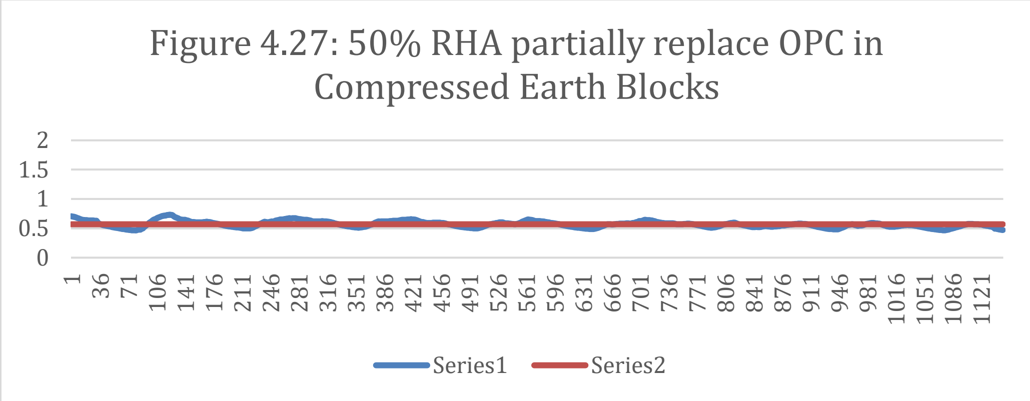


Figure 4.26: 20% RHA partially replace OPC in Compressed Earth Blocks



Key
Series1: actual running mean of the thermal conductivity test
Series 2: the average of the running mean of the thermal conductivity test
x- axis: the time
y-axis: the value of thermal conductivity (W/m.K)



Key
Series1: actual running mean of the thermal conductivity test
Series 2: the average of the running mean of the thermal conductivity test
x- axis: the time
*y-axis: the value of thermal conductivity (*W/m.K)

The results of mean thermal conductivity are presented in Table 4.29 and Figure 4.28 of the tested CEBs with varying RHA

Table 4.29: Thermal Conductivity of CEBs masonry wall with varying RHA content

% RHA	Thermal conductivity (W/m.K)	Bulk density (kg/m^3)
0%	0.87	1816.9
10%	0.55	1852.6
20%	0.61	1812.6
50%	0.57	1805.4

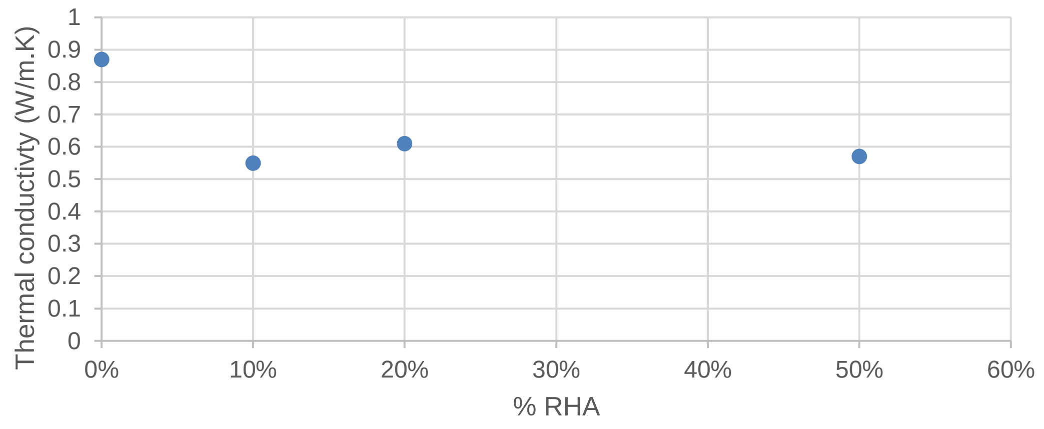


Figure 4.28: Thermal conductivity for masonry CEBs stabilized with RHA

The findings for thermal conductivity are further discussed in Section 6.2.2.5.

5. Simulation Results

This chapter reports the findings from two simulation investigations. Firstly, the simulation of mould growth and interstitial condensation is reported in Section 5.1. Then the simulation for thermal comfort performance is reported in Section 5.2.

5.1. Hygrothermal behaviour of Wall system

There are several parameters which are required for simulation of moisture content, temperature, relative humidity of the wall and mould growth. These relate to the material, the wall system, and the boundary conditions. These are detailed in Sections 5.1.

The simulation is reported in five sections: temperature gradient (Section 5.1.2), RH gradient (5.1.3), moisture content (5.1.4), mould growth (5.1.5) and total water content (5.1.6).

5.1.1. Boundaries of Simulation

5.1.1.1. Choice of Material for Simulation

In the present study, various laboratory tests were carried out on compressed earth blocks (CEBs) partially stabilized with rice husk ash (RHA). Materials used for CEB production were sourced in Nigeria. The results of the mechanical and hygrothermal tests were described in Chapter 4 of this thesis and further discussion in Sections 6.2.1-6.2.2. From these results four CEB materials were chosen for investigation, the exclusion of 40% and 50% RHA was because the materials didn't meet the requirement for hygrothermal property required. These were solid blocks with 0% RHA (as the control) and RHA contents of 10%, 20% and 30% and appropriate for external walls. The properties of the CEB materials chosen for this investigation are detailed in Table 5.1.

Table 5.1 Properties Summary of CEB materials included in simulation study

	CEBs with varying RHA Percentage			
Material property	**0%**	**10%**	**20%**	**30%**
Bulk density (Kg/m^3)	1768.2	1855.5	1783.8	1777.7
Water absorption coefficient ($Kg/m^2\ s^{1/2}$)	0.090	0.100	0.100	0.100
Moisture absorption (%)	7.5	8.3	6.5	8.0
Water vapour resistance factor	20	11.65	23.30	45.25
Thermal conductivity (W/m.K)	0.87	0.55	0.61	0.65

5.1.1.2 Wall system

A range of wall systems were considered in the literature review (Section 2.8.1). The design for the compressed earth block wall (intended to be used for affordable and sustainable design) could use two different types of wall systems. The wall system was designed bearing in the mind the following factors:

a. A cavity is required to prevent ingress of driving rain. The options for this were:
   i. masonry (CEB) external wall with plaster (EP)
   ii. masonry (CEB) external wall partially filled with insulation (NP)

   Both options (EP and NP) were chosen for further investigation because the masonry wall with cavity prevent driving rain from the inner skin of the wall.

b. The CEB thickness was determined by the typical dimensions and placement of CEBs during construction, the thickness of a typical CEBs and cavity gives a typical U-value of wall requirement in Nigeria.
c. The Option EP with external plaster is to increase the hygrothermal property of the outer skin layer. The external plaster is commonly used as the external wall finish in Nigeria. This option is illustrated in Figure 5.1.
d. The Option NP has partially filled cavity to increase the hygrothermal property of the wall. It designed to creates an extra layer of thermal insulation from external condition and the cavity to prevent driving rain form penetrating the internal skin layer. The addition MDF as insulation material was in order to use a typical insulating material and one that the cost of the material compared to Option EP is similar. This option is illustrated in Figure 5.2.

The masonry wall options were input to WUFI Pro 5.3 and are illustrated in Figures 5.1 and 5.2. These illustrations also show the assumed monitor positions on the internal and external surfaces

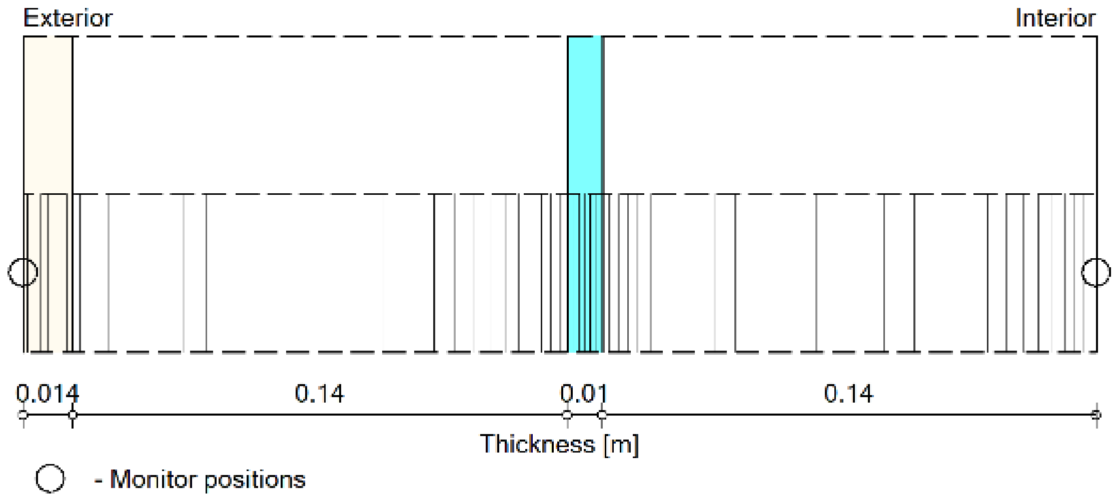


Figure 5.1 Masonry wall section EP

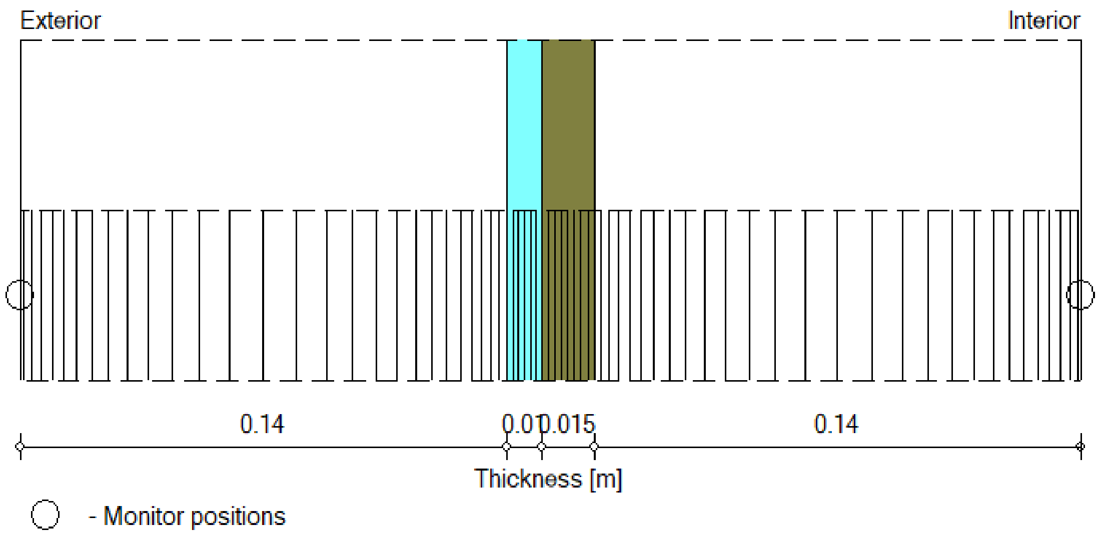


Figure 5.2 Masonry wall section NP (No external plaster)- Masonry wall with partially filled cavity.

LEGEND for Figures 5.1 and 5.2

(swatch)	External plaster	(swatch)	Medium dense fibre board
(swatch)	Air cavity	(swatch)	CEBs

Both wall conditions will be simulated for the CEB materials selected in Section 5.1.1. The walls are simulated to use for external purpose. The wall properties are described in Table 5.2.

Table 5.2 Properties of experimental CEB used for simulation study

%RHA	**Masonry wall**			
	Wall section EP-		**Wall section NP-**	
	U-value (W/m²K)	**Bulk density (kg/m³)**	**U-value (W/m²K)**	**Bulk density (kg/m³)**
0 (Control)	1.299	1768.21	1.22	1768.21
10	1.136	1855.5	1.076	1855.5
20	1.147	1783.8	1.086	1783.8
30	1.147	1777.7	1.086	1777.7

5.1.1.2. External boundary condition

The boundary condition relates to the external situation and as such relates to the climate in Lagos, Nigeria as described below. As a wall is being tested, the inclination is specified as 90º (vertical).

The image in Figure 5.3 shows the direction and annual sum of the driving rain. As South West is one of the orientations experiencing the most driving rain, this orientation is selected for testing. The minimum mean and maximum relative humidity and temperature are presented in Table 5.3 along with mean wind speed and normal annual rain sum. Simulation of the South West wall was carried out in WUFI as it's the most challenging option.

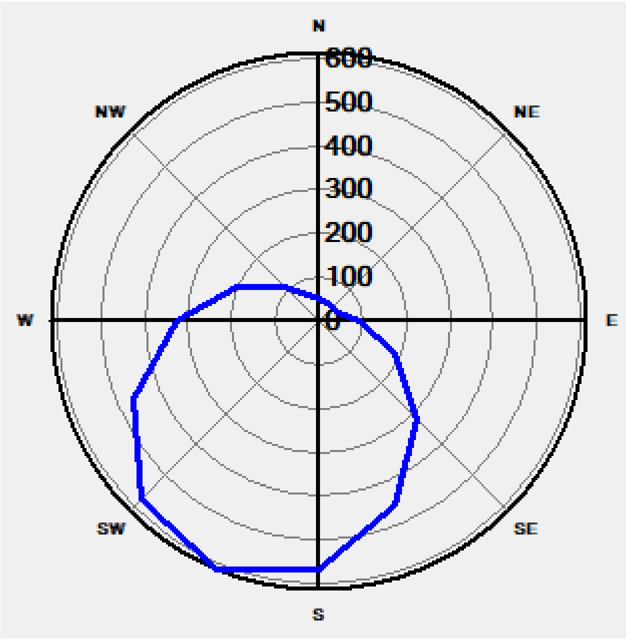


Fig 5.3 Driving rain direction

Table 5.3 External condition for simulation

Mean relative humidity (%)	85
Max. relative humidity (%)	100
Min relative humidity (%)	56
Mean wind speed (m/s)	3.94
Normal rain sum (mm/a)	100
Mean Temperature (ºC)	27.4
Max Temperature (ºC)	34.9
Min Temperature (ºC)	19.3

Table 5.4 External boundary condition of wall

Name	Description	Unit	Value
Heat resistance includes longwave radiation	External wall	(m^2K/W)	0.0588
Shortwave radiation absorptivity	Brick, clay, cream, glazed		0.36
Longwave radiation emissivity	Brick, clay, cream, glazed		0.9
Adhering fraction of rain			0.7

5.1.1.3. Internal boundary condition

Relative humidity (moisture) levels of different parts of the house differ depending on the use of the space. Spaces that are used for cooking and bathing tend to have higher moisture content compared to areas that are used for relaxation (as detailed in Section 2.4). It has been established that areas with high moisture content in the interior have a high possibility to experience mould spore germination which is known to be hazardous to the occupants of the space, deterioration and negative visualization to the interior space. The simulation of the internal space was for a typical living space such as the bedroom and more moist space like the bathroom. Consequently, the two wall systems design options using CEB for affordable and sustainable building in Lagos, Southern Nigeria (Aw) are compared in this section of the thesis.

5.1.1.4. Simulated masonry wall section

Each material was simulated for a period of one year. The result of moisture absorption, thermal conductivity, water absorption coefficient, bulk density, water vapour transmission was required from the laboratory test to be inputted into WUFI data material for simulation

The study aimed to compare the two wall design options (i.e. wall sections EP- and NP-) used for each of the compressed earth blocks proposed for affordable and sustainable building in Lagos, Nigeria (Southern Nigeria [Aw]). The wall section in Figures 5.4 and 5.5 would be used to further explain the different temperature, relative humidity, and moisture content at the different sections of the wall. The point of reference would be used to describe the mean condition of the eternal wall exposed to the internal and external conditions annually. The position in mm is described in Table 5.4.

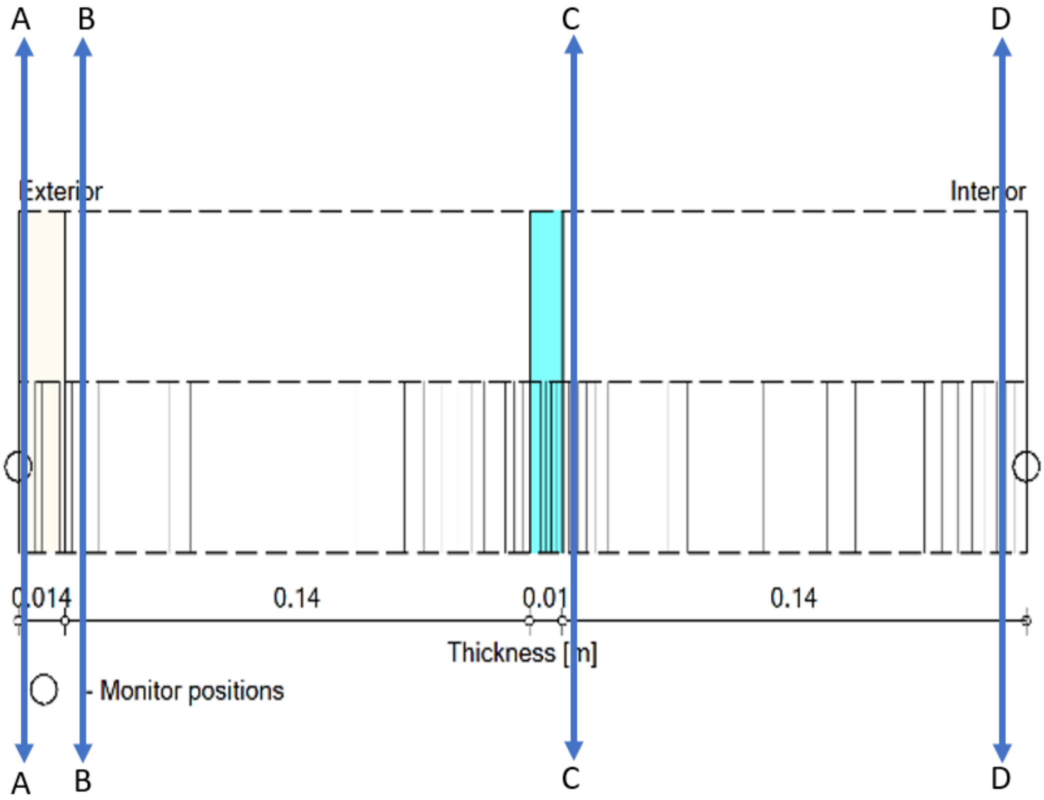


Figure 5.4: Point of reference (PR) through Wall section EP

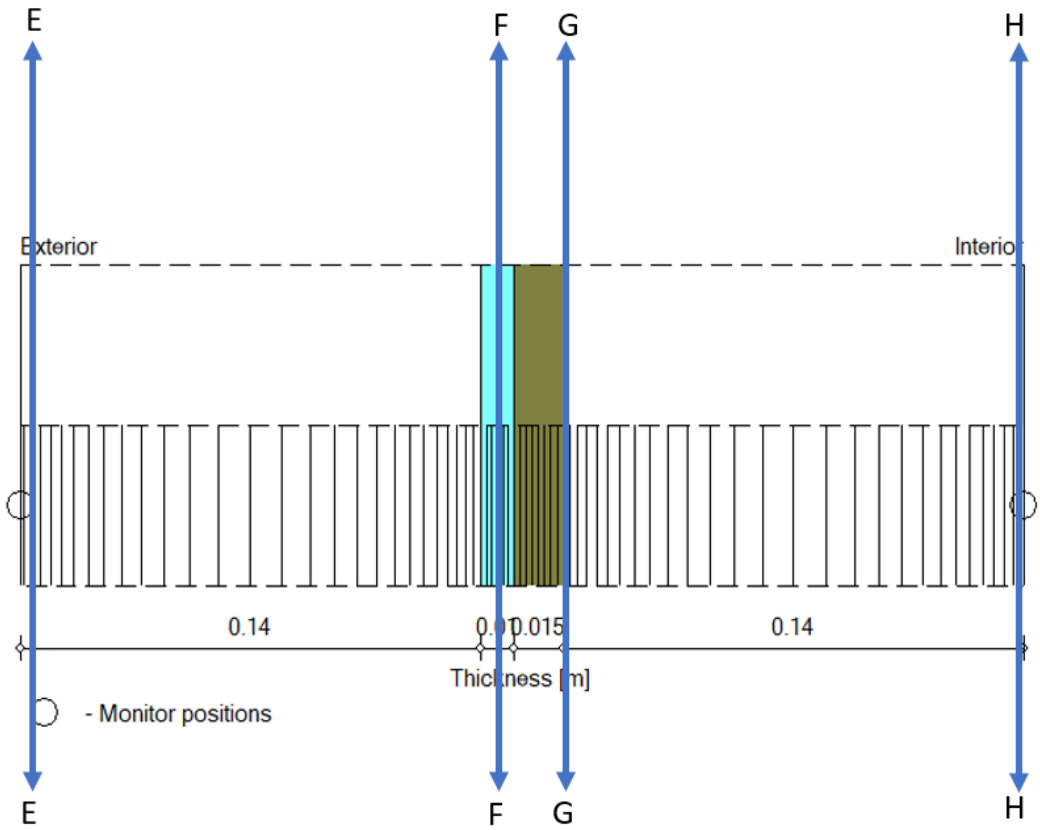


Figure 5.5: Point of reference (PR) through Wall section NP

Table 5.5 Distance of wall with varying Positions on wall

Wall section EP		Wall section NP	
Point of reference (PR)	**Position in wall section (mm)**	**Point of reference (PR)**	**Position in wall section (mm)**
A-A	0	E-E	0
B-B	14	F-F	150
C-C	164	G-G	165
D-D	300	H-H	300

5.1.1.5. Summary of Parameters to be Simulated

Table 5.6 Summary of parameter simulated on WUFI Pro

CONSTANTS	**Values**
Curing time	28 days
External wall orientation	SW wall as a result driving rain direction
Wall height	3-5 storey
Exposure of wall	Sheltered
Type of Roof	Pitch roof
External boundary	Aw, tropical savanna climate (Lagos, Nigeria)
Simulation period	1 year and 3 years
VARIABLES	
Wall material	0%,10%,20%, 30%
Wal type	Option EP and NP
Internal Relative humidity (RH) Normal RH- 50%-65% High RH- 65%-85%	Normal and High relative humidity (varying depending on use space producing varying moisture rate). Calculated from moisture load EN 15026.
Internal temperature	Calculated from external climate

5.1.2. Temperature Simulation results

The temperature gradient from external to interior surface of the wall structures in normal and high internal relative humidity (more wet areas) conditions are presented in Sections 5.1.2.1-5.1.2.4. This is discussed further in Section 6.3.

5.1.2.1. Temperature simulation of Wall Section EP – with normal internal relative humidity

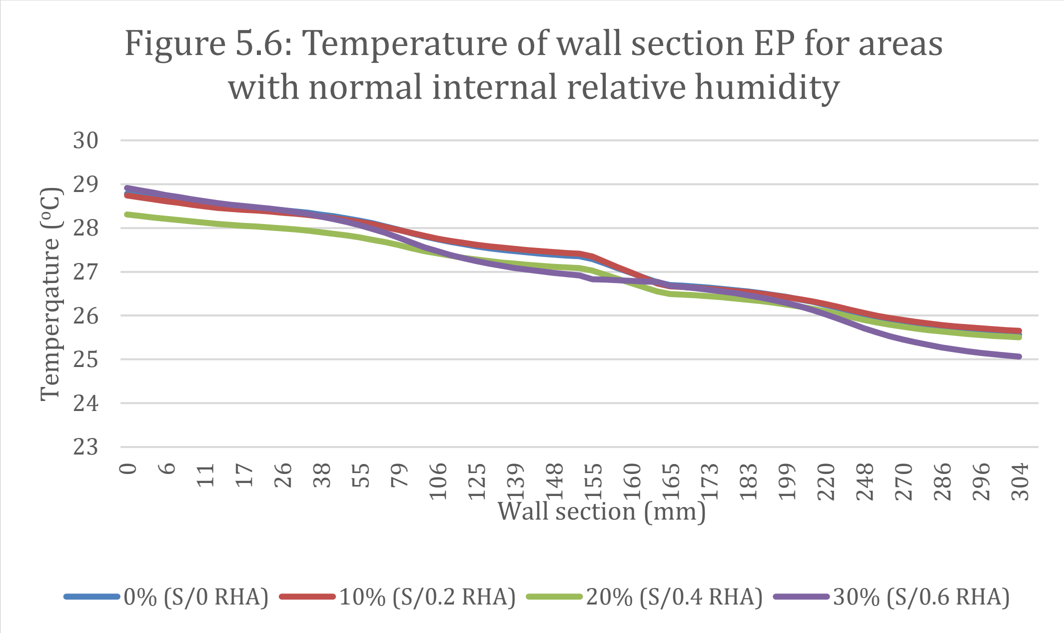
The Table of temperature shows the mean temperature at each point of reference for 1 year. The temperature values are presented in Table 5.7 in relation to the EP Wall points of reference (identified in Figure 5.1). Point of reference (PR) A-A (exterior) had temperatures which were 2.8-3.8ºC higher than the values at point of reference D-D (interior). The internal space is expected to be cooler than the external environment, as Nigeria climate experience high temperature which is not within thermal comfort range.

Wall section 30%RHA (S/0.6 RHA) had the lowest temperature value (25.1ºC) at PR D-D, while 10%RHA (S/0.2 RHA) had the highest temperature value (25.7ºC) at the same reference point. The temperature of wall section EP showed a steady decrease from the outer surface layer to the inner surface layer as illustrated in Figure 5.6.

Table 5.7: Temperature of Wall section EP at areas with normal internal relative humidity

	Temperature (ºC) at Point of Reference (PR)			
Wall section EP	A-A (ºC)	B-B (ºC)	C-C (ºC)	D-D (ºC)
0% (S/0 RHA)	28.8	28.5	26.7	25.6
10% (S/0.2 RHA)	28.7	28.4	26.7	25.7
20% (S/0.4 RHA)	28.3	28.1	26.5	25.5
30% (S/0.6 RHA)	28.9	28.5	26.7	25.1

Figure 5.6 also shows the temperature at different positions of the wall (mm from external surface).

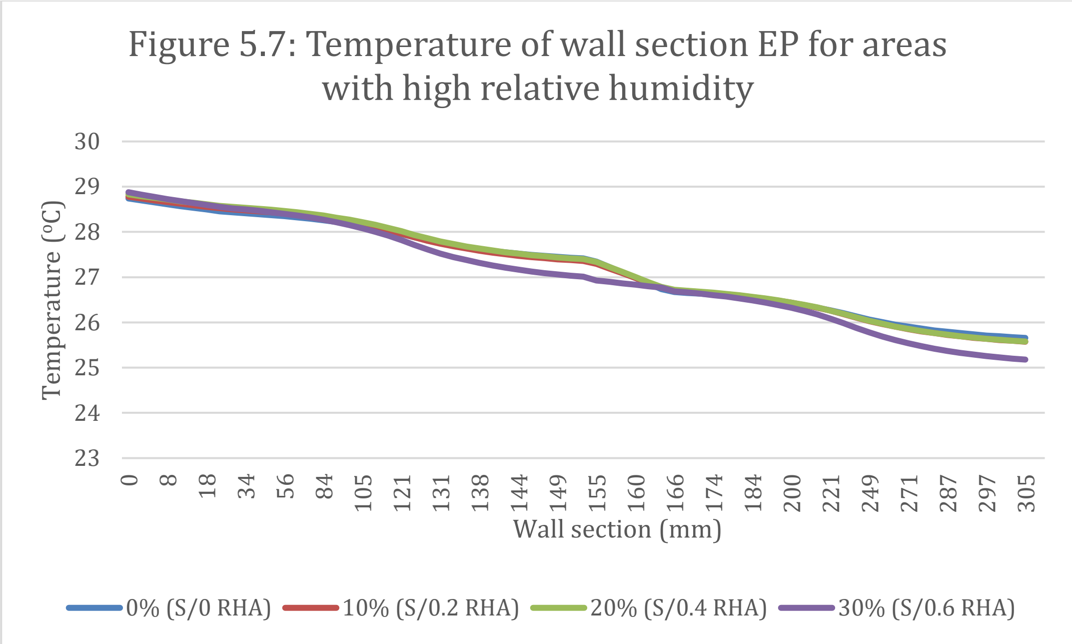


5.1.2.2. Temperature simulation of Wall Section EP – with high Internal relative humidity

The temperature values are presented in Table 5.8 in relation to the EP Wall points of reference (PR) A-A to D-D (identified in Figure 5.1). PR A-A (exterior) had temperature values which were 1.6-1.8°C higher than the inner surface temperature of the inner CEB, PR D-D. Consistently, PR A-A had higher values than test PR D-D for all the wall sections. The trend is shown in Figure 5.7. The temperature of wall section EP showed a steady decrease from the outer surface layer to the inner surface layer. Wall section 30% RHA (S/0.6 RHA) had the highest and lowest temperature values for the external and internal surface of the wall respectively at 29.2°C and 25.1°C at PR A-A and D-D, respectively. The internal surface of the wall 30% RHA creates a cooler internal space which is required for Nigeria internal boundary to achieve comfort.

Table 5.8: Temperature of Wall section EP at areas with high relative internal humidity

	Temperature (°C) at Point of Reference (PR)			
Wall section EP	A-A (°C)	B-B (°C)	C-C (°C)	D-D (°C)
0% (S/0 RHA)	28.6	27.0	26.5	25.6
10% (S/0.2 RHA)	28.6	27.0	26.6	25.7
20% (S/0.4 RHA)	29.1	27.3	26.8	25.5
30% (S/0.6 RHA)	29.2	27.4	26.8	25.1

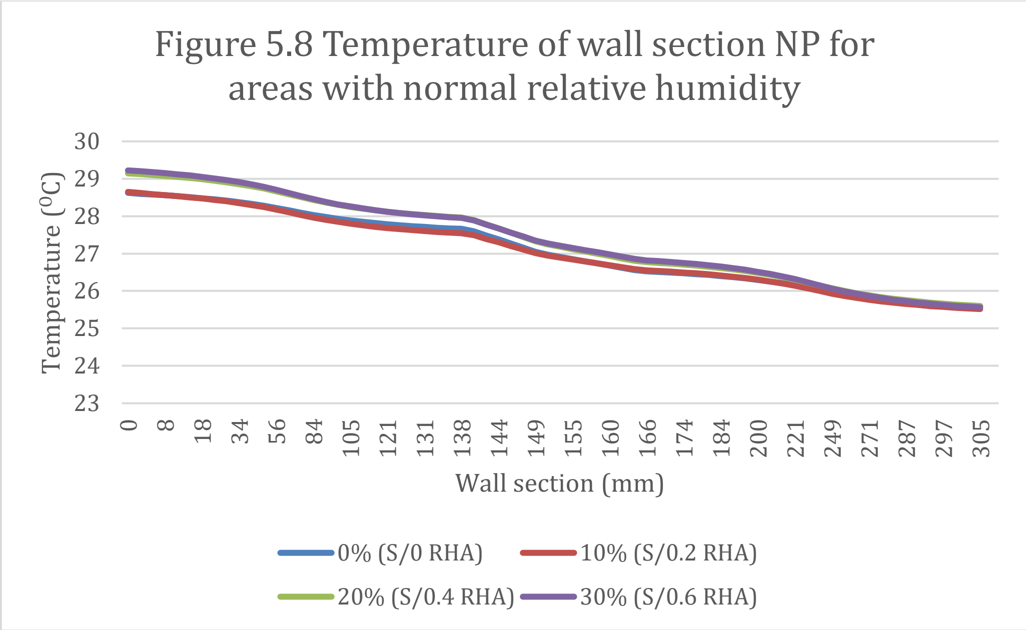


5.1.2.3. Temperature simulation of Wall Section NP – with normal internal relative humidity

The temperature values are presented in Table 5.9 in relation to the NP Wall points of reference (identified in Figure 5.2). PR E-E (exterior) had temperatures which were 2-3.7oC higher than the values at PR H-H (interior). At the PR H-H, the wall section 30%RHA (S/0.6 RHA) had the lowest temperature value (25.2ºC), while wall section 0%RHA (S/0 RHA) had the highest (25.7ºC). The temperature of wall section NP shows a steady decrease from the outer surface layer to the inner surface layer as shown in Figure 5.8.

Table 5.9: Temperature of Wall section NP at areas with normal internal relative humidity

	Temperature (ºC) at Point of Reference (PR)			
Wall section EP	E-E (ºC)	F-F (ºC)	G-G (ºC)	H-H (ºC)
0% (S/0 RHA)	28.7	28.5	26.7	25.7
10% (S/0.2 RHA)	28.8	28.6	26.8	25.6
20% (S/0.4 RHA)	28.8	28.6	26.8	25.6
30% (S/0.6 RHA)	28.9	28.7	26.8	25.2

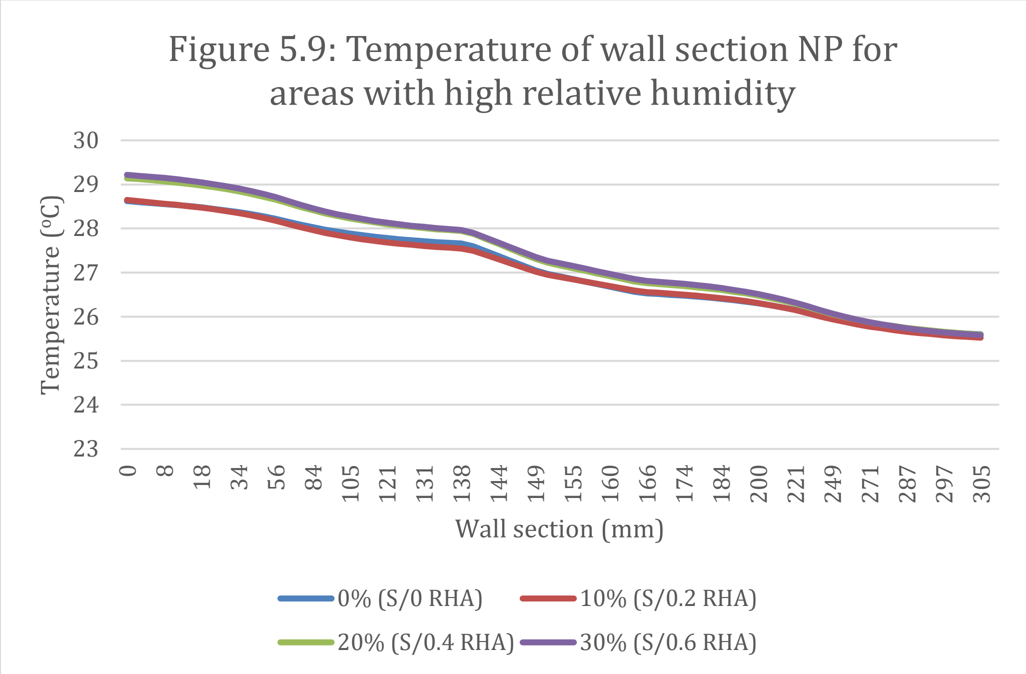


5.1.2.4. Temperature simulation of Wall Section NP – with high internal relative humidity

The temperature values are presented in Table 5.8 in relation to the NP Wall PR (identified in Figure 5.2). PR E-E (exterior) had temperatures which were 2.9-4ºC higher than PR H-H at inner surface of the inner CEB. The wall sections 30%RHA (S/0.6 RHA) and 10%RHA (S/0.2 RHA) had the lowest (25.2ºC) and the highest (25.7ºC) temperature values, respectively at PR H-H. The temperature of wall section NP showed a steady decrease from the outer surface layer to the inner surface layer (Figure 5.9).

Table 5.10, Temperature of Wall section NP at areas with high relative internal humidity

	Temperature (ºC) at Point of Reference (PR)			
Wall section EP	E-E (ºC)	F-F (ºC)	G-G (ºC)	H-H (ºC)
0% (S/0 RHA)	28.6	27.1	26.5	25.7
10% (S/0.2 RHA)	28.6	27.0	26.6	25.6
20% (S/0.4 RHA)	29.1	27.3	26.8	25.6
30% (S/0.6 RHA)	29.2	27.4	26.8	25.2



The temperature of the internal surface of the wall for the two option EP and NP in areas with high internal relative humidity and normal internal relative humidity fall within the range of 25-26ºC for all the varying CEBs wall with varying RHA.

5.1.3. Relative humidity Simulation results

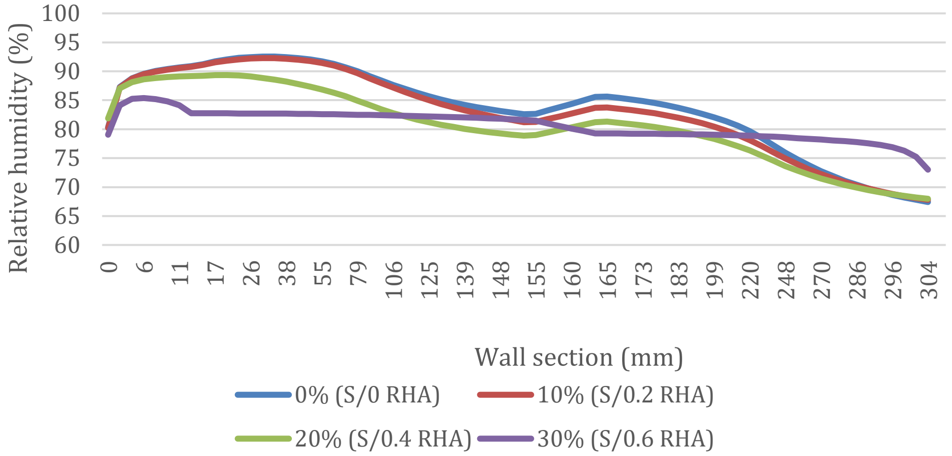
The relative humidity gradient from external to interior surface of the wall structures in normal and high internal relative humidity conditions are presented in Sections 5.1.3.1-5.1.3.4. This is discussed further in Section 6.3.

5.1.3.1. Relative humidity simulation of Wall Section EP – with normal internal relative humidity

The RH results are presented in Table 5.11 in relation to the EP Wall points of reference (identified in figure 5.1). PR A-A (exterior) had relative humidity values which were 2.8-13.4% higher than the values at PR D-D (interior). The highest (76.2%) and lowest (68.2%) relative humidity values occurred in the wall section 30%RHA (S/0.6 RHA) and 0%RHA (S/0 RHA), respectively at PR D-D. The trend shown by relative humidity is depicted in Figure 5.10. It indicated that relative humidity increased from PR A-A (exterior surface) towards PR B-B (external CEB wall section), declined mildly towards PR C-C (surface of the internal CEB after air cavity), and finally dropped sharply towards PR D-D (inner CEB wall section).

Table 5.11, Relative humidity of Wall section EP at areas with normal internal relative humidity				
Wall section EP	**Relative humidity (%) at Point of Reference (PR)**			
	A-A (%)	B-B (%)	C-C (%)	D-D (%)
0% (S/0 RHA)	80.3	91.2	85.4	68.2
10% (S/0.2 RHA)	80.2	91.1	83.8	68.5
20% (S/0.4 RHA)	81.9	89.1	81.1	68.5
30% (S/0.6 RHA)	79.0	84.1	79.2	76.2

Figure 5.10: Relative humdity of wall section EP for areas with normal relative humidity

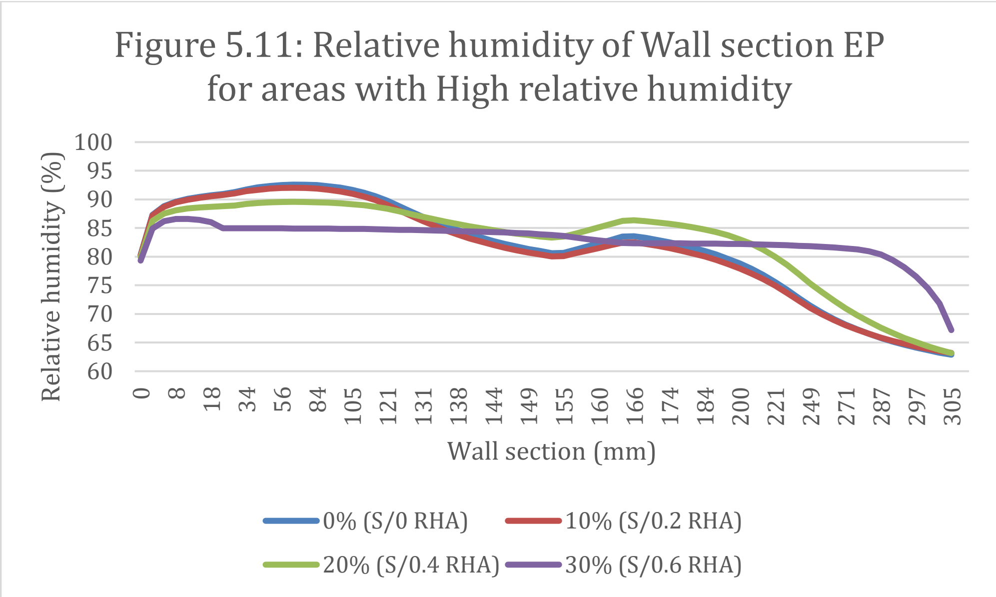


5.1.3.2. Relative humidity simulation of Wall Section EP – with high internal relative humidity

The RH results are presented in Table 5.12 in relation to EP Wall points of reference (identified in Figure 5.1), PR A-A (exterior) had RH values which were 3.5-12.5% higher than the values at PR D-D (the inner CEB). The relative humidity of the wall at the PR D-D records the highest value at 30% RHA (S/0.6 RHA) and lowest value at 0% RHA (S/0RHA) with value of 72.9% and 68.6% respectively.

Table 5.12: Relative humidity of Wall section EP at areas with high internal relative humidity				
	Relative humidity (%) at Point of Reference (PR)			
Wall section EP	A-A (%)	B-B (%)	C-C (%)	D-D (%)
0% (S/0 RHA)	81.1	89.6	88.4	68.6
10% (S/0.2 RHA)	81.1	88.8	86.5	68.8
20% (S/0.4 RHA)	77.7	74.4	75.6	67.9
30% (S/0.6 RHA)	76.4	82.6	77.3	72.9

The results of relative humidity values of the entire PR in the wall section EP at areas with high RH presented in Table 5.10 revealed a similar trend with that shown under normal RH. For all the wall sections, there were initial rises in RH from A-A, and thereafter the values declined to the lowest at D-D. Figure 5.11 illustrates the pattern exhibited in the trend of RH changes at the various PR.



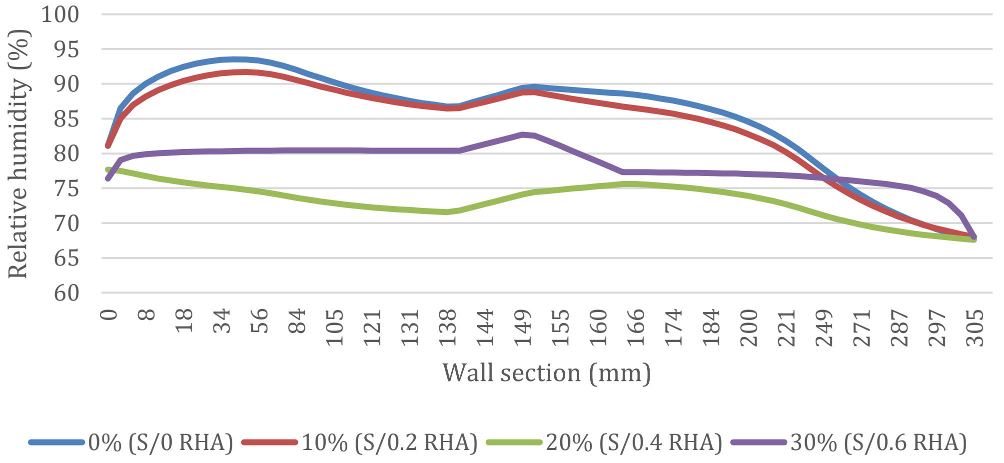
5.1.3.3. Relative humidity simulation of Wall Section NP – with normal internal relative humidity

The RH results are presented in Table 5.13 in relation to the EP Wall points of reference (identified in figure 5.2). PR E-E (exterior) had RH values which were 4.8-16.6% higher than the values at PR H-H (interior). The lowest (63.7%) and highest (74.5%) RH was found in wall sections 0%RHA (S/0 RHA) and 30%RHA (S/0.6 RHA), respectively. The RH trend pattern is illustrated in Figure 5.12. The RH of wall section NP showed an increase from PR E-E (Exterior surface) to F-F (External CEBs wall section), and thereafter decreases towards PR G-G (surface of Internal CEBs after air cavity|) and finally dropping to the lowest level at PR H-H (Inner CEBs wall section).

Table 5.13; Relative humidity of Wall section NP at areas with normal internal relative humidity

	Relative humidity (%) at Point of Reference (PR)			
Wall section EP	E-E (%)	F-F (%)	G-G (%)	H-H (%)
0% (S/0 RHA)	80.3	90.4	83.5	63.7
10% (S/0.2 RHA)	80.2	90.2	82.5	63.9
20% (S/0.4 RHA)	79.8	88.6	86.2	64.5
30% (S/0.6 RHA)	79.3	86.4	82.6	74.5

Figure 5.12: Relative humdity of wall section NP for areas with normal relative humdity

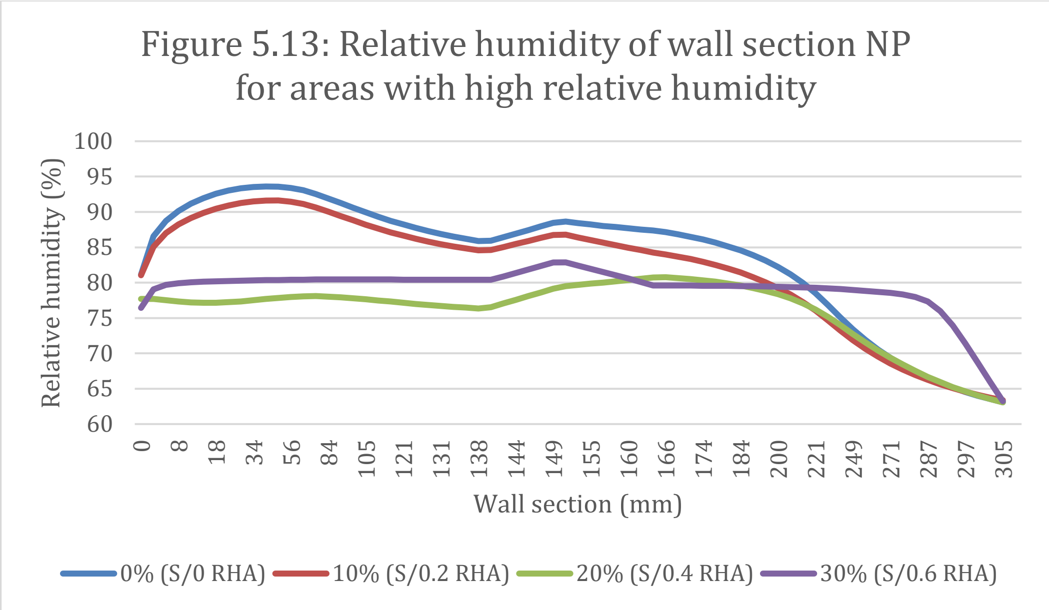


5.1.3.4. Relative humidity simulation of Wall Section NP – with high internal relative humidity

The RH results are presented in Table 5.14 in relation to the EP Wall points of reference (identified in figure 5.2). PR E-E (exterior) had RH values which were 7.7-17.1% higher than the values at PR H-H at the inner CEB. Also, at the PR H-H, the wall section 30%RHA (S/0.6 RHA) had the highest (68.7%) relative humidity value whereas the wall sections 0%RHA (S/0 RHA) and 20%RHA (S/0.4 RHA) had the lowest (64.0-64.1%). The trend pattern of RH shown in Figure 5.13 was like those observed earlier. The RH of the wall section NP regardless of the %RHA increased from PR E-E (External surface of outer CEBs) towards F-F (surface of MDF facing air cavity), and thereafter decreased towards PR G-G (Joints between air cavity and Internal CEBs); and finally dropped to the lowest level at the PR H-H (Inner CEBs wall section).

Table 5.14; Relative humidity of Wall section NP at areas with high internal relative humidity

	Relative humidity (%) at Point of Reference (PR)			
Wall section EP	E-E (%)	F-F (%)	G-G (%)	H-H (%)
0% (S/0 RHA)	81.1	88.5	87.2	64.0
10% (S/0.2 RHA)	81.0	86.8	84.0	64.1
20% (S/0.4 RHA)	77.7	79.1	80.8	64.0
30% (S/0.6 RHA)	76.4	82.9	79.6	68.7



All the wall relative humidity for wall type EP and NP for CEBS with RHA of 0-20% have relative humidity between 68-69%. The CEBs with RHA of 30% records relative humidity 70-75% except for wall NP for areas with high relative humidity.

Based on the figure 2.13 using the relative humidity and temperature of the material, there is no mould growth likely to germinate on the internal wall surface on all walls type EP and NP used in areas with high and normal internal relative humidity for all the varying RHA.

There is likely to be mould growth germination with category highly xerophilic organism for wall type EP in areas with normal and high relative humidity and wall type NP for areas with normal internal relative humidity.

The relative humidity and temperature alone are not enough to adequately predict mould germination, the moisture content generated need to analyse to come to a certain conclusion. The moisture buffering property of the material can also change the effect of mould germination in the wall.

5.1.4. Moisture content Simulation results

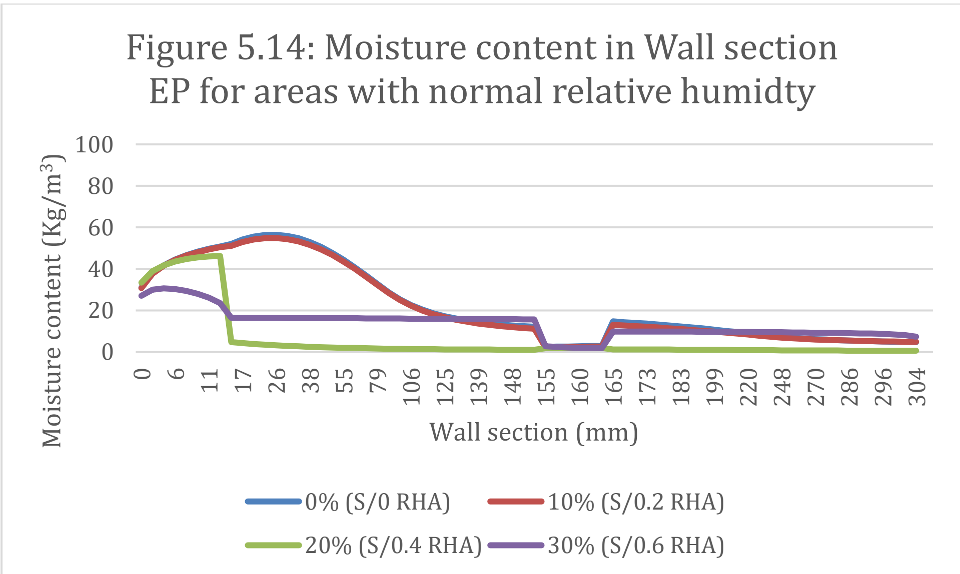
The relative humidity gradient from external to interior surface of the wall structures in normal and high internal relative humidity conditions are presented in Sections 5.1.4.1-5.1.4.4. This is discussed further in Section 6.3.

5.1.4.1. Moisture content at different positions in Wall Section EP – with normal internal relative humidity

The flow of moisture content for the wall section EP as shown in Table 5.15, shows the walls section at PR A-A have similar values at this point. Wall section 0% (S/0 RHA) and 10% (0.2/RHA) show similar moisture content at each point of reference (PR). The moisture content increases from PR A-A (external plaster) to PR B-B (external CEBs), the moisture in the air cavity reduces and continues to reduce to PR D-D (internal CEBs). The moisture content for wall section 20% (S/0.4 RHA) has lowest value of 4.8 kg/m^3 at PR B-B and continues to reduce to PR D-D to have a value of 0.6 kg/m^3, this wall type is the best in areas with normal relative humidity environment. The next most suitable is wall section 30% (S/0.6 RHA), the moisture content from the external surface of the wall at PR A-A to PR D-D also reduces as it gets closer to the interior wall.

Table 5.15; Moisture content of Wall section EP at areas with normal internal relative humidity				
	Moisture content (%) at Point of Reference (PR)			
Wall section EP	A-A (kg/m^3)	B-B (kg/m^3)	C-C (kg/m^3)	D-D (kg/m^3)
0% (S/0 RHA)	30.9	52.0	1.7	5.0
10% (S/0.2 RHA)	30.8	51.0	13.0	5.0
20% (S/0.4 RHA)	33.4	4.8	1.2	0.6
30% (S/0.6 RHA)	27.1	16.5	9.8	8.5

Figure 5.14 shows moisture content at each point within the wall section. The wall section EP shows reduction of moisture content at the air cavity and reduces to the internal CEBs at PR D-D. The highest moisture content through all the wall type for wall section EP at areas with normal relative humidity is less than 60 kg/m^3.



5.1.4.2. Moisture content at different positions in Wall Section EP – with high internal relative humidity

The flow of moisture content for the wall section EP as shown in Table 5.16, shows the walls section at PR A-A have similar values at this point. Wall section 0% (0/ RHA) and 10%

(0.2/RHA) show similar moisture content at each point of reference (PR). The moisture content increases from PR A-A (external plaster) to PR B-B (external CEBs), the air cavity in the wall reduces and continues to reduce to PR D-D (internal CEBs). The moisture content for wall section 20% (S/0.4 RHA) has lowest value of 4.1 kg/m^3 at PR B-B and continues to reduce to PR D-D to have a value of 0.8 kg/m^3, this wall type is the best in areas with high relative humidity environment. The next most suitable is wall section 30% (S/0.6 RHA), the moisture content from the external surface of the wall at PR A-A to PR D-D also reduces as it gets closer to the interior wall.

Table 5.16; Moisture content of Wall section EP at areas with high internal relative humidity				
	Moisture content (%) at Point of Reference (PR)			
Wall section EP	A-A (kg/m^3)	B-B (kg/m^3)	C-C (kg/m^3)	D-D (kg/m^3)
0% (S/0 RHA)	30.6	51.0	13.1	6.3
10% (S/0.2 RHA)	30.5	50.0	13.1	6.5
20% (S/0.4 RHA)	30.8	4.1	4.4	0.8
30% (S/0.6 RHA)	27.5	22.0	13.8	11.6

Figure 5.15 shows moisture content at each point within the wall section. The wall section EP shows reduction of moisture content at the air cavity and reduces to the internal CEBs at PR D-D. The highest moisture content through all the wall type for wall section EP at areas with normal relative humidity is less than 60 kg/m^3.

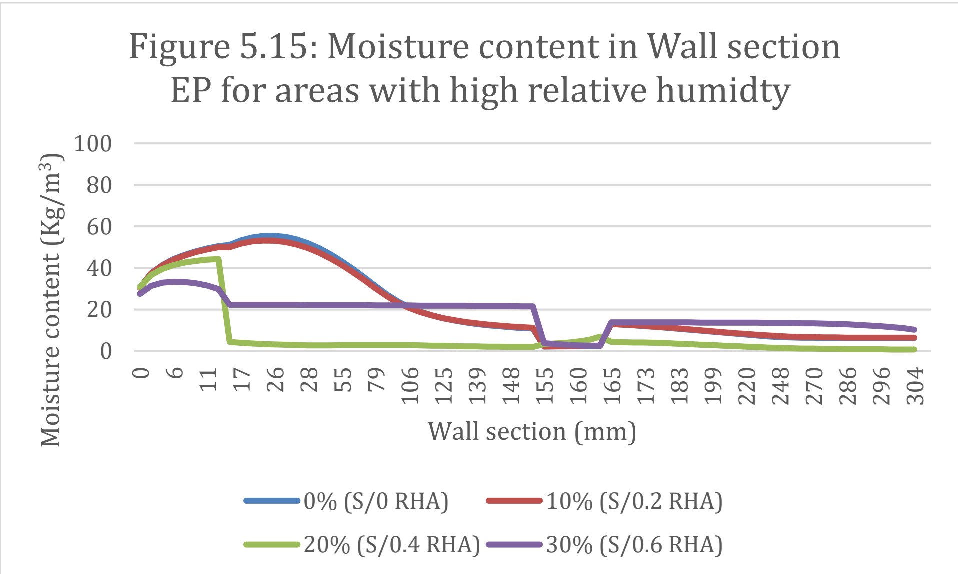


Figure 5.15: Moisture content in Wall section EP for areas with high relative humidty

5.1.4.3. Moisture content at different positions in Wall Section NP – with normal internal relative humidity

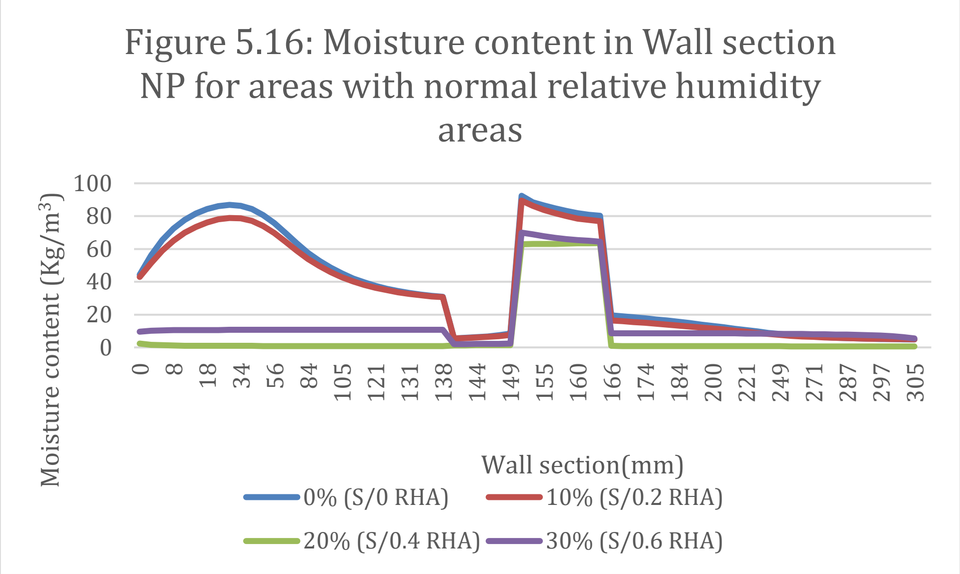
Table 5.17 shows the wall section 0% (0/ RHA) and 10% (0.2/RHA) show similar moisture content at each point of reference (PR) E-E, value of 44.3 kg/m^3 and 42.9 kg/m^3. The PR F-F (external CEBs) increase to value of 92.4 kg/m^3 and 89.5 kg/m^3. The moisture in the blocks starts to decrease towards the partially filled cavity, PR G-G has value of 19.5 kg/m^3 and 19.4 kg/m^3. The point of PR H-H (Internal CEBs) reduces to 5.0 kg/m^3 and 5.1 kg/m^3 respectively.

The moisture content for wall section 20% (S/0.4 RHA) recorded its lowest values at each point of reference (PR). The peak occurs at the PR F-F (point between air cavity and MDF) has value of 62.9 kg/m^3 and continue to reduce until PR H-H (Internal CEBs, though the values are lowest the cavity of the wall shows high moisture absorption increase which makes its unsuitable.

The next most suitable is wall section 30% (S/0.6 RHA), the moisture content for this type is like wall type 20% (S/0.4 RHA) with slightly higher moisture content.

Table 5.17; Moisture content of Wall section NP at areas with normal internal relative humidity				
	Moisture content (%) at Point of Reference (PR)			
Wall section EP	E-E (kg/m^3)	F-F (kg/m^3)	G-G (kg/m^3)	H-H (kg/m^3)
0% (S/0 RHA)	44.3	92.4	19.5	5.0
10% (S/0.2 RHA)	42.9	89.5	16.4	5.1
20% (S/0.4 RHA)	2.4	62.9	0.9	0.6
30% (S/0.6 RHA)	9.6	69.9	8.1	6.8

Figure 5.16 shows moisture content at each point of reference within the wall section. The wall section NP shows the external CEBs wall in the wall section reduction of moisture content within and reduces within the air cavity and rises at the MDF. The highest moisture content through all the wall type for wall section NP at areas with normal relative humidity is less than 100 kg/m^3.



5.1.4.4. Moisture content at different positions in Wall Section NP – with high internal relative humidity

Table 5.18 shows the wall section 0% (0/ RHA) and 10% (0.2/RHA) have similar moisture content at each point of reference (PR) E-E, value of 43.5 kg/m^3 and 42.0 kg/m^3. The PR F-F (external CEBs) increase to value of 88.7 kg/m^3 and 85.4 kg/m^3. The blocks then start to decrease towards the partially filled cavity, PR G-G has value of 17.6 kg/m^3 and 14.8 kg/m^3. The point of PR H-H (Internal CEBs) reduces to 6.4 kg/m^3 and 6.5 kg/m^3 respectively.

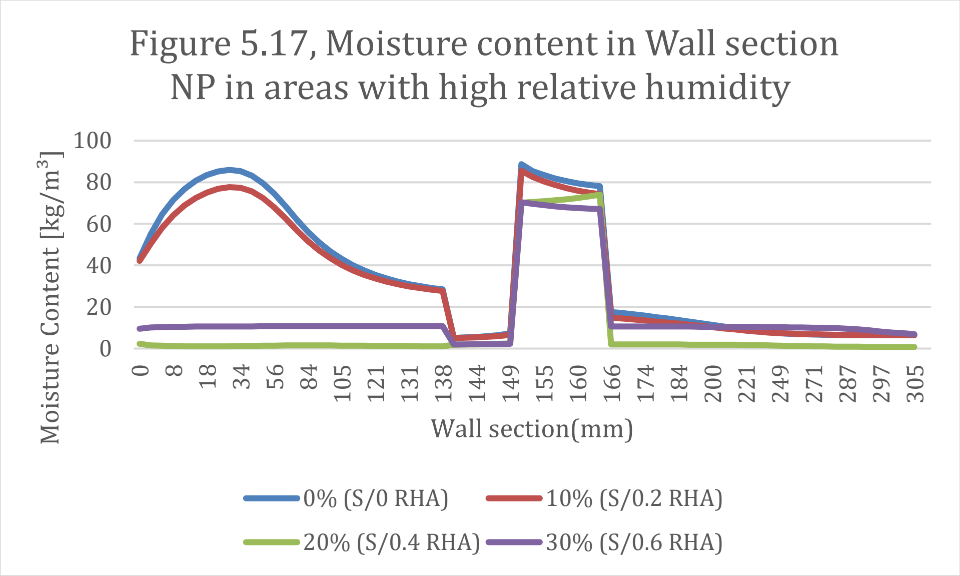
The moisture content for wall section 20% (S/0.4 RHA) has lowest value at each point of reference (PR). The peak occurs at the PR F-F (point between air cavity and MDF) has value of 70.1 Kg/m^3 and continue to reduce until PR H-H (Internal CEBs). Although the internal moisture content is lowest in the internal layer of the wall, the moisture level in the cavity is high which makes it unsuitable.

The next most suitable is wall section 30% (S/0.6 RHA), the moisture content for this type is like wall type 20% (S/0.4 RHA) but is slightly higher.

Table 5.18; Moisture content of Wall section NP at areas with high internal relative humidity

	Moisture content (%) at Point of Reference (PR)			
Wall section EP	E-E (kg/m^3)	F-F (kg/m^3)	G-G (kg/m^3)	H-H (kg/m^3)
0% (S/0 RHA)	43.5	88.7	17.6	6.4
10% (S/0.2 RHA)	42.0	85.4	14.8	6.5
20% (S/0.4 RHA)	2.4	70.1	2.0	0.8
30% (S/0.6 RHA)	9.5	70.3	10.6	7.7

Figure 5.17 shows moisture content at each point within the wall section. The wall section NP shows moisture content reduce in the external CEBs and reduces further within the air cavity and rises at the MDF. The highest moisture content through all the wall type for wall section NP at areas with normal relative humidity is less than 100 kg/m^3.

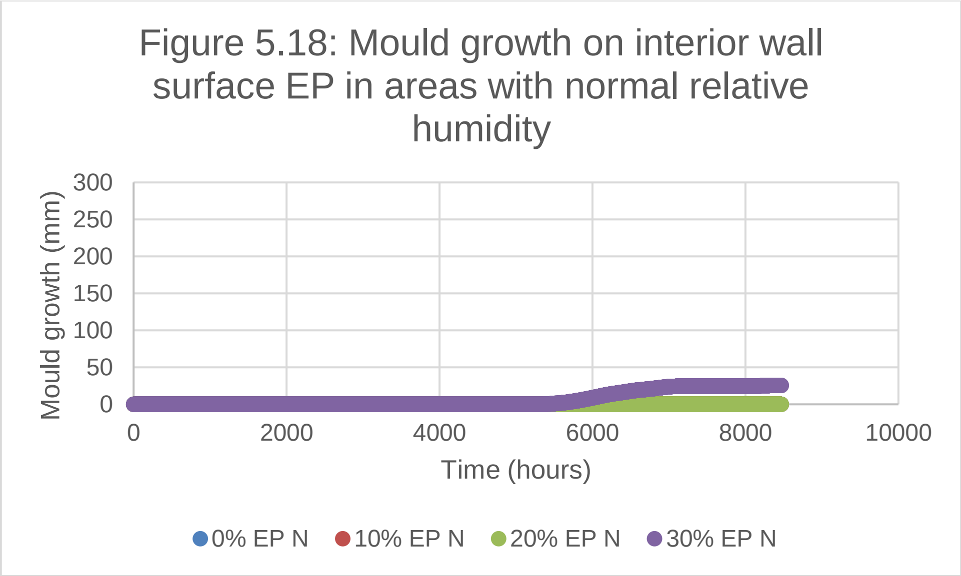


5.1.5. Mould Growth on interior wall - Simulation results

The mould growth results after 8700 hours (1 year) are presented in Sections 5.1.5.1-5.1.5.4. This is discussed further in Section 6.3.

5.1.5.1. Mould Growth on interior wall surface after 1 year: Section EP – with normal internal relative humidity

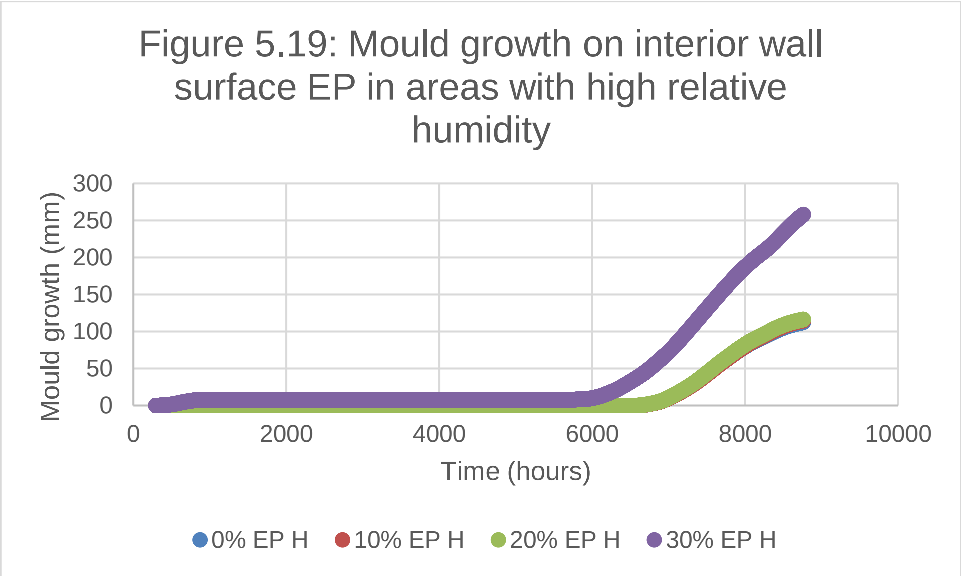
Mould growth results are presented in Figure 5.18 for wall section EP with normal internal relative humidity.



No Mould growth occurred on interior wall surface for CEBs wall section 0%, 10%, 20% for 1 year. The mould growth on wall CEBs 30% for 1 year was zero until, third quarter of the year, and was less than 50mm at the end of the year.

5.1.5.2. Mould Growth on interior wall surface after 1 year: Section EP – with high internal relative humidity

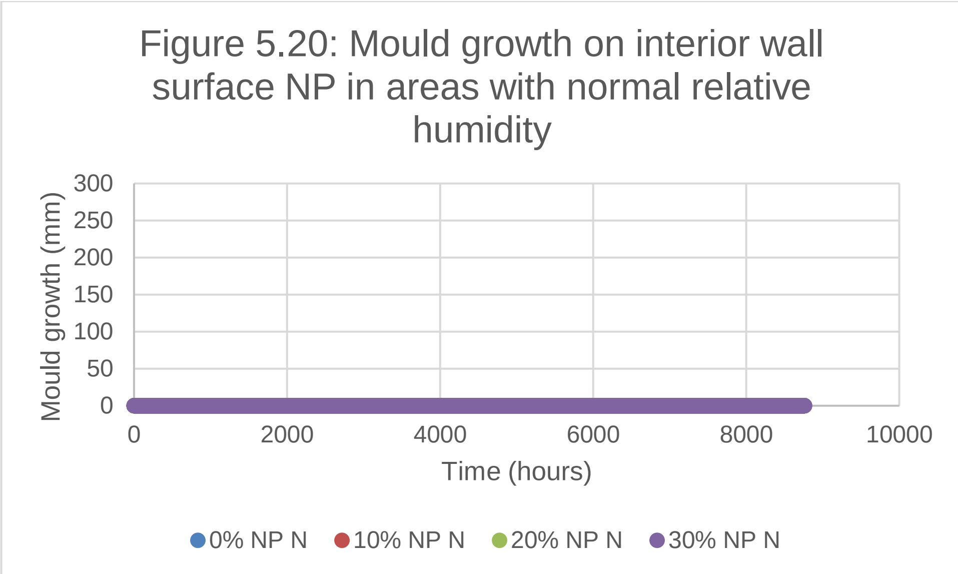
Mould growth results are presented in Figure 5.19 for wall section EP with high internal relative humidity.



There was mould growth in all the EP wall sections in areas with high relative humidity. The mould growth for CEB with 30% RHA was two times more than for CEBs with 0%, 10%, and 20%. The mould growth for CEBs with 30% RHA is 258mm and that of 0%-20% CEBs RHA wall is approximately 116mm.

5.1.5.3. Mould Growth on interior wall surface after 1 year: Section NP – with normal internal relative humidity

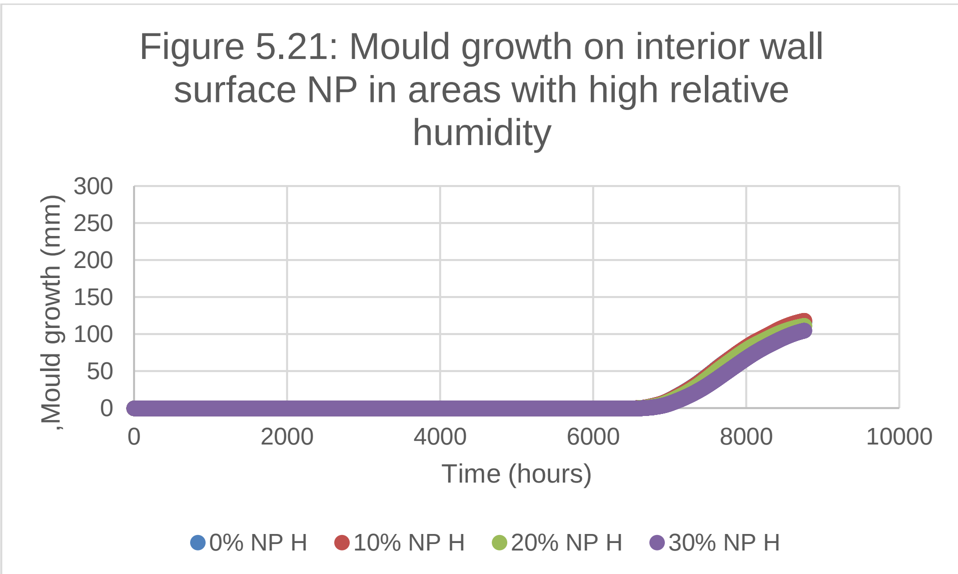
Mould growth results are presented in Figure 5.20 for wall section NP with normal internal relative humidity.



All the wall section with various degree of partial stabilization of RHA for wall section NP had no mould growth on the interior wall surface after 1 year.

5.1.5.4. Mould Growth on interior wall surface after 1 year: Section NP – with high internal relative humidity

Mould growth results are presented in Figure 5.21 for wall section NP with high internal relative humidity.



All the wall section NP in areas with high relative humidity had mould growth of 107mm at the end of the year.

5.1.5.5. Mould Growth – Summary

The wall sections with normal relative humidity showed little to no mould growth after a year on all wall sections. These do not need further investigation. However, the wall sections under high relative humidity showed mould growth which warrants further investigation – these results are presented in section 5.1.6.

Table 5.19 Building use, proportion of OPC replacement with RHA, mould growth and WUFI code

Building use	Proportion of OPC replaced with RHA	Mould growth depth (mm)	WUFI Bio code
Option EP High relative humidity	0%	112.5	[yellow]
	10%	114.8	[yellow]
	20%	116.3	[yellow]
	30%	257.9	[red]
Option NP High relative humidity	0%	116	[yellow]
	10%	118	[yellow]
	20%	111	[yellow]
	30%	105	[yellow]
Option EP Normal relative humidity	0%	0	[green]
	10%	0	[green]
	20%	0	[green]
	30%	25.2	[green]
Option NP Normal relative humidity	0%	0	[green]
	10%	0	[green]
	20%	0	[green]
	30%	0	[green]

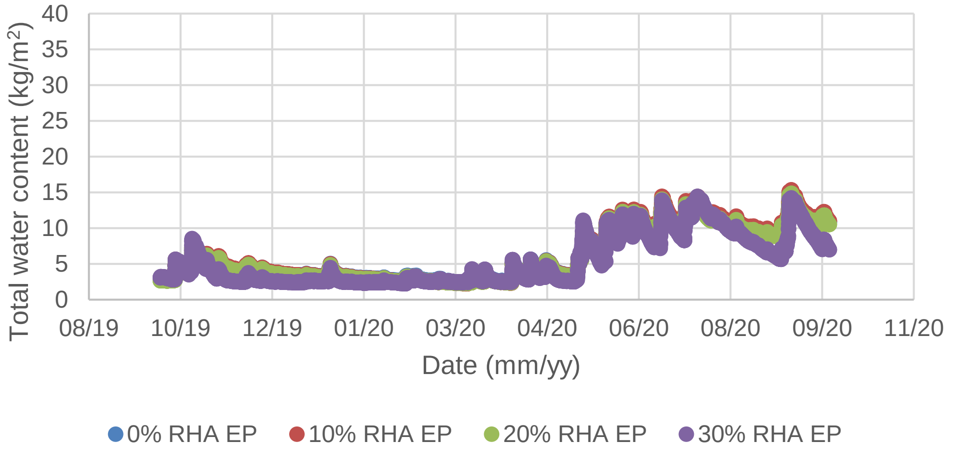
5.1.6. Total water content Simulation results

The wall sections which showed significant mould growth in Section 5.1.5 are initially investigated for total water content after one year (Sections 5.1.6.1-5.1.6.2), then for 3 years (Sections 5.1.6.3-5.1.6.4). This is discussed further in Section 6.3.

5.1.6.1. Total water content after 1 year: Section EP – with high internal relative humidity

Total water content results after 1 year are presented in Figure 5.22 for wall section EP with high internal relative humidity.

Figure 5.22: Total water content in wall section EP in areas with high relative humidity for 1 year

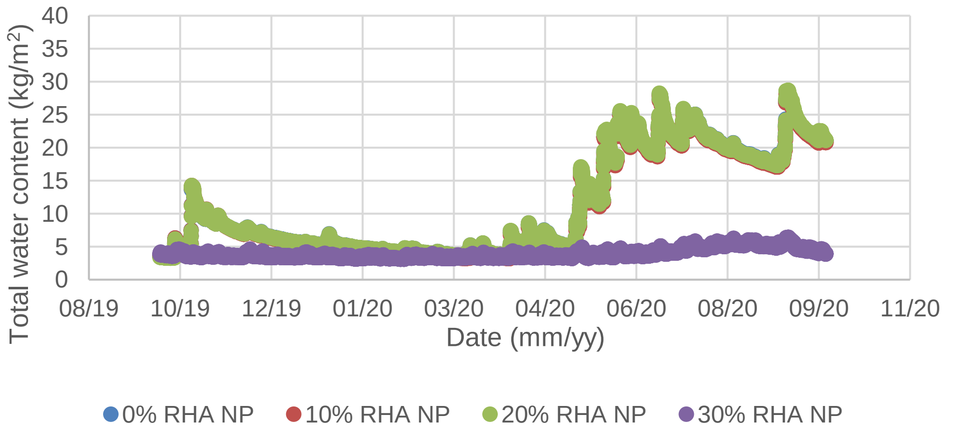


Total water content for all wall types at end of 1 year shows that water content doubles at the third quarter of the year in wall section EP. The total water content is always less than 20 kg/m^2.

5.1.6.2. Total water content after 1 year: Section NP – with high internal relative humidity

Total water content results after 1 year are presented in Figure 5.23 for wall section NP with high internal relative humidity.

Figure 5.23: Total water content in wall section NP for areas with high relative humidity for 1 year



Total water content for wall types at end of 1 year shows that the water content raises to 15-30 kg/m^2 in the third quarter of the year for RHA contents of 0%, 10%, and 20%. The total water content for wall type 30% RHA is stable throughout the year at less than 10 kg/m^2.

5.1.6.3. Total water content after 3 years: Section EP – with high internal relative humidity

Total water content results after 3 years are presented in Figure 5.24 for wall section EP with high internal relative humidity.

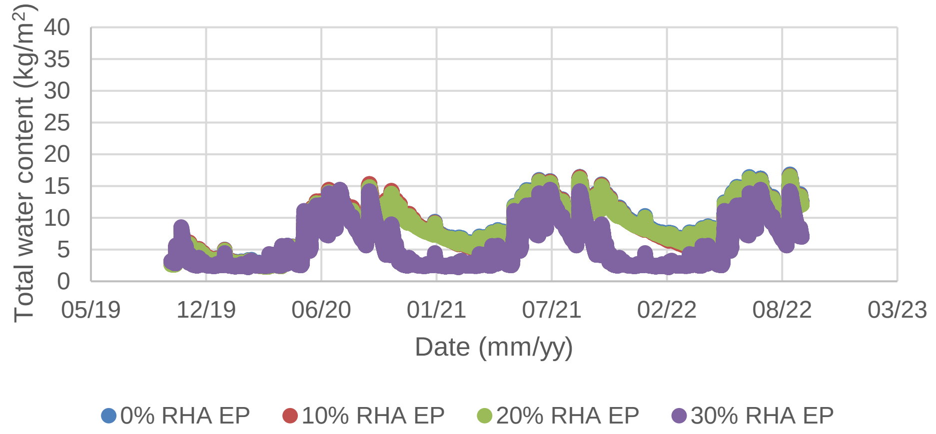


Figure 5.24: Total water content in wall section EP for areas with high relative humidity for 3 years

Total water content for the wall section EP rises and drops as the total water content is studied for 3 years. This shows that the wall absorbs and desorbs over time.

5.1.6.4. Total water content after 3 years: Section NP – with high internal relative humidity

Total water content results after 3 years are presented in Figure 5.25 for wall section NP with high internal relative humidity.

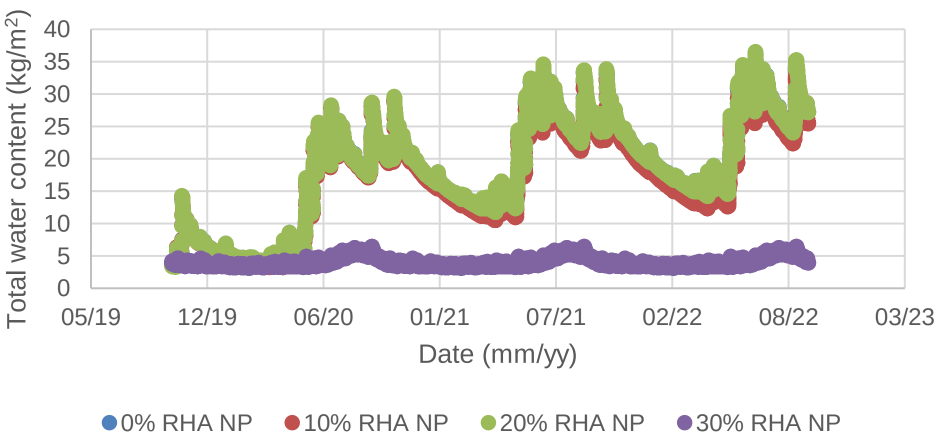


Figure 5.25: Total water content in wall section NP in areas with high relative humidity for 3 years

Total water content for wall type 0%, 10%, and 20% for wall section absorbs and desorbs from less than 5 to 40 kg/m^2. The total water content for wall type 30% RHA is stable for 3 years at a value of less than 10kg/m^2.

5.1.7. Summary of Hygrothermal behaviour of wall system

All the varying RHA content in wall type EP and NP are all suitable for use in areas with normal internal relative humidity (living room, bedroom). In areas exposed to high relative humidity (Kitchen) because of the use of the space, the material surface need to further treated to prevent mould growth. The most suitable wall system design for the tropical savanna climate, Lagos Nigeria is the wall system type EP, 20% RHA, it was selected as it's the least likely to allow germination of mould growth. For it to be provide adequate air quality in the space in areas like bathroom or kitchen, the internal surface layer needs to be treated to prevent mould growth (i.e. Moisture retarding material).

5.2. Simulation of Thermal Comfort Performance

The process for comparing the thermal comfort performance of CEB walls in comparison to concrete walls was described in Section 3.4.2. In summary: the tropical savannah climate (Aw) represented by the climate data from Lagos (described in Section 3.4.2.1) which indicates high temperatures and high relative humidity – monthly data is presented in Table 5.20 and visual representation of climate shown Figure 5.26, 5.27,5.28.

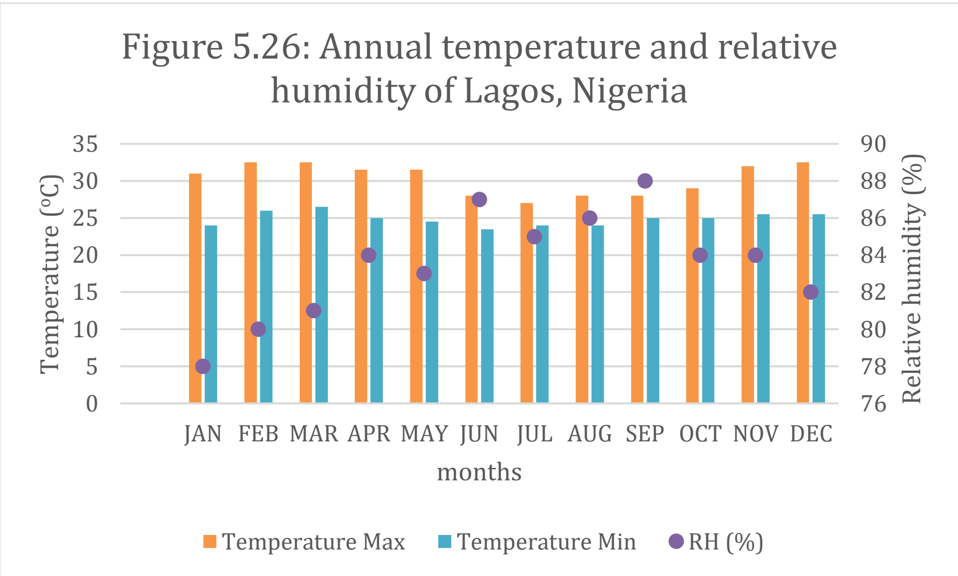


Table 5.20: Average Climatic data of Lagos, Nigeria (2000-2009)						
Month	Temperature		RH (%)	Wind		Rainfall (mm)
	Max	Min		Speed (m/s)	Direction (dominant)	
JAN	31	24	78	2.19	SW	14.3
FEB	32.5	26	80	3.09	SW	42
MAR	32.5	26.5	81	3.49	SW	77.1
APR	31.5	25	84	3.4	SW	142.4
MAY	31.5	24.5	83	2.5	SW	204.8
JUN	28	23.5	87	2.6	SW	312.2
JUL	27	24	85	3.8	SW	256.9
AUG	28	24	86	3.9	SW	112.4
SEP	28	25	88	3.4	SW	167.1
OCT	29	25	84	2.6	SW	135.8
NOV	32	25.5	84	2.4	SW	54
DEC	32.5	25.5	82	2.3	SW	19

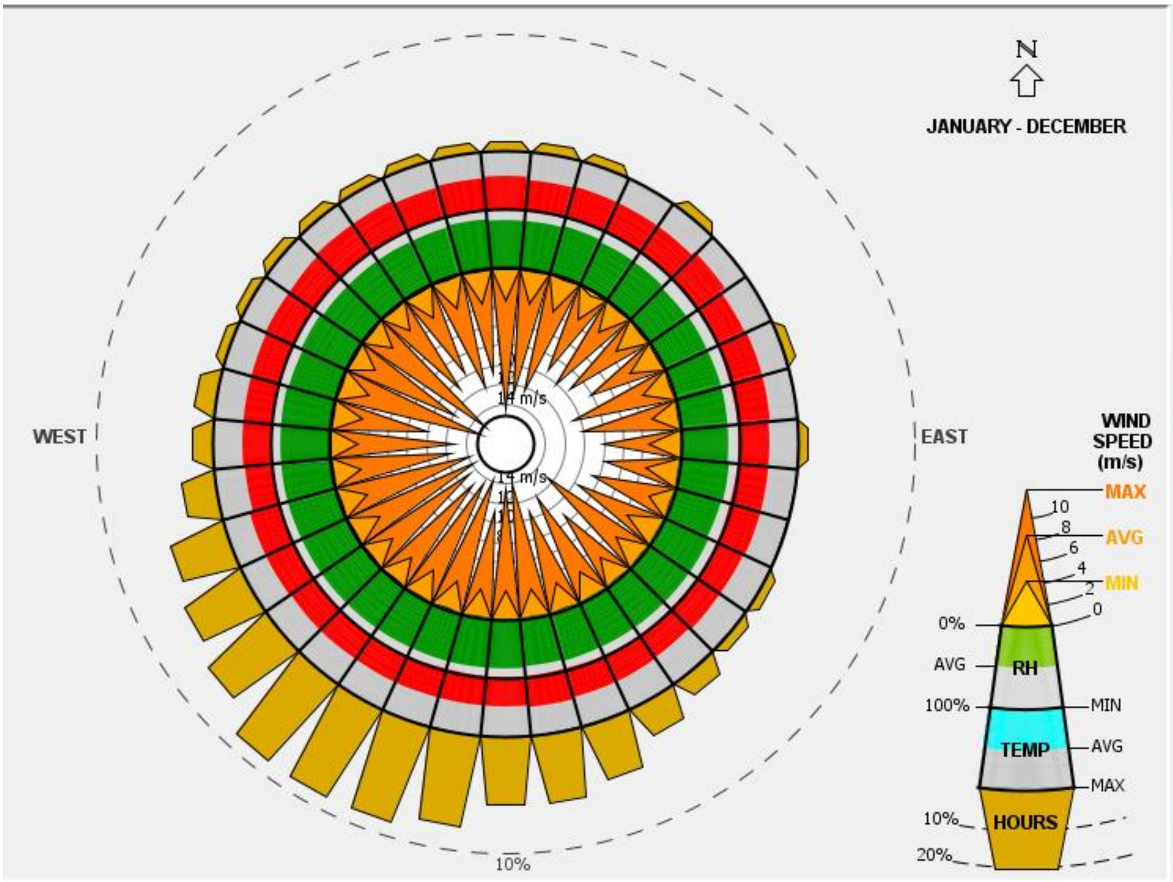


Figure 5.27: Wind direction and wind speed using wind rose.

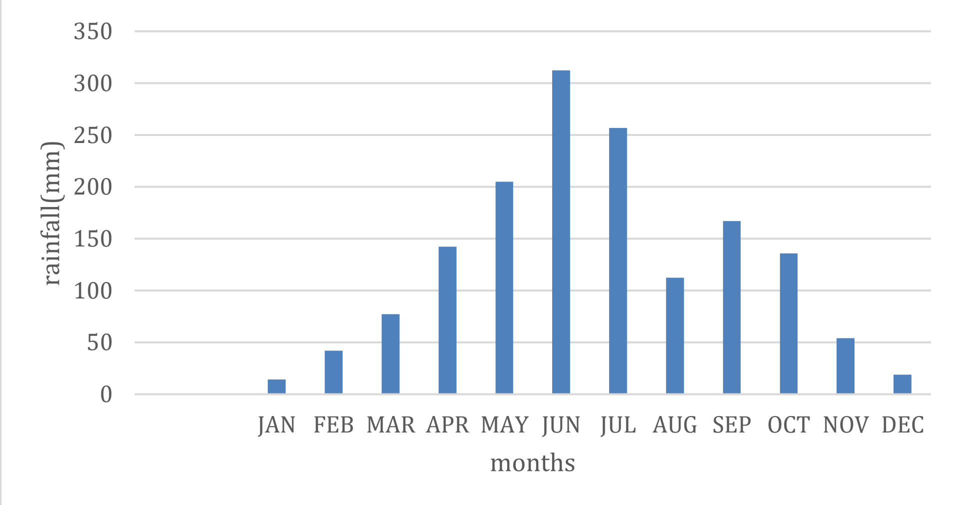


Figure 5.28: Annual Rainfall of Lagos, Nigeria

Natural ventilation is a recommended passive designs strategy (Section 2.2.1) which is facilitated by large openings (window wall ratios of 40-80% recommended). The thermal comfort was assessed base on the adaptive Comfort model in ASHRAE Standard 55-2010.

Thermal comfort is a condition that is gained by the individual as a result of thermal environment. Factors that affect thermal comfort include the: Metabolic rate; Clothing insulation; Air temperature; Radiant temperature; Air speed; Humidity.

5.2.1. Adaptive comfort for a tropical savanna climate (ASHRAE 55-2010)

Table 5.18 describes the temperature limits for 80% and 90% acceptance calculated using ASHRAE 55-2010 Adaptive comfort model.

Table 5.21 Adaptive Comfort using natural ventilation

90%	Acceptable RH limits (80-90%)
23.1	Comfort low- min operative temperature in this climate (^oC)
29.4	Comfort high- max operative temperature in this climate (^oC)
80%	Acceptable RH limits (80-90%)
25.1	Comfort low- min operative temperature in this climate (^oC)
31.4	Comfort high- max operative temperature in this climate (^oC)

5.2.2. Comparison of hours in thermal comfort

A simplified structure was simulated for one year using climate data for Lagos (Aw climate). The numbers of hours which did not achieve 80% and 90% comfort as indicated by ASHRAE 55-2010 adaptive comfort model are indicated in Table 5.22. In addition to the wall material, two structure shapes and two window wall ratios were tested.

Table 5.22: Time not achieving thermal comfort over 1 year - using Adaptive comfort model at 90% and 80%

Wall material	WWR	Length (m) x breadth (m)	"Not comfortable" 90% satisfaction		"Not comfortable" 80% satisfaction	
			hrs	%	Hrs	%
CEB (20% RHA)	60%	24 x 15	2270	25.9	1682.5	19.2
Concrete wall	60%	24 x 15	2243	25.6	1659	18.9
CEB (20% RHA)	60%	36 x10	2432.5	27.8	1420	16.2
Concrete wall	60%	36 x10	2432.5	27.8	1962	22.4
CEB (20% RHA)	40%	36 x10	2221.5	25.4	1639.4	18.7
Concrete wall	40%	36 x10	2222	25.4	1633.5	16.6

In relation to achieving 90% thermal satisfaction, there was little difference between CEB (20% RHA) and concrete wall materials. In relation to achieving 80% thermal satisfaction, the results were more variable. The two wall materials had similar performance for 24x15m shape structure. CEB (20% RHA) had a better performance for 36x10m shape structure with 60% WWR, while the opposite result held true for 40% WWR.

6. Discussion

6.1. Raw materials for CEBs

6.1.1. Laterite soil

The results of tests conducted on the laterite used in the current research presented in Table 4.1 showed that the soil had higher liquid limit (43.3%) and plastic index (27.24%) values but lower plastic limit value (16.06%) than those reported by Bodian et al., 2018 for laterite soil (Liquid limit, 38%; Plastic index, 16.1%; Plastic limit, 21.9%). However, charting the readings in the Unified Soil Classification Chart (Figure 6.1) showed that both soil samples fell in the CL soil category. The results for laterite sample used in the current research indicate that it had more clay content. Hence, the soil is susceptible to shrinkage, cracks easily when it dries, and is more vulnerable to exposure. Also, the characteristics shown by the laterite soil used in the current study showed that the soil met the standards recommended for use in compressed earth block (Uzoegbo, 2020). The author recommended liquid limit (25 – 50%), plastic limit (10 – 25%), plastic index (3 – 30%), linear shrinkage (<4%), and soil of CL category. The relationship of the laterite used in this research to the conditions indicated by (Uzoegbo, 2020) is shown in Figure 6.1.

A preliminary test was conducted on using the laterite soil and ordinary Portland cement to make some samples of compressed earth block and cured for between 14 and 28 days. The blocks during the curing period developed visible cracks and when lifted began to crumble. Consequently, sand particles were introduced in the mix to reduce the proportion of clay in the mix and to neutralize the effect of shrinkage and cracking.

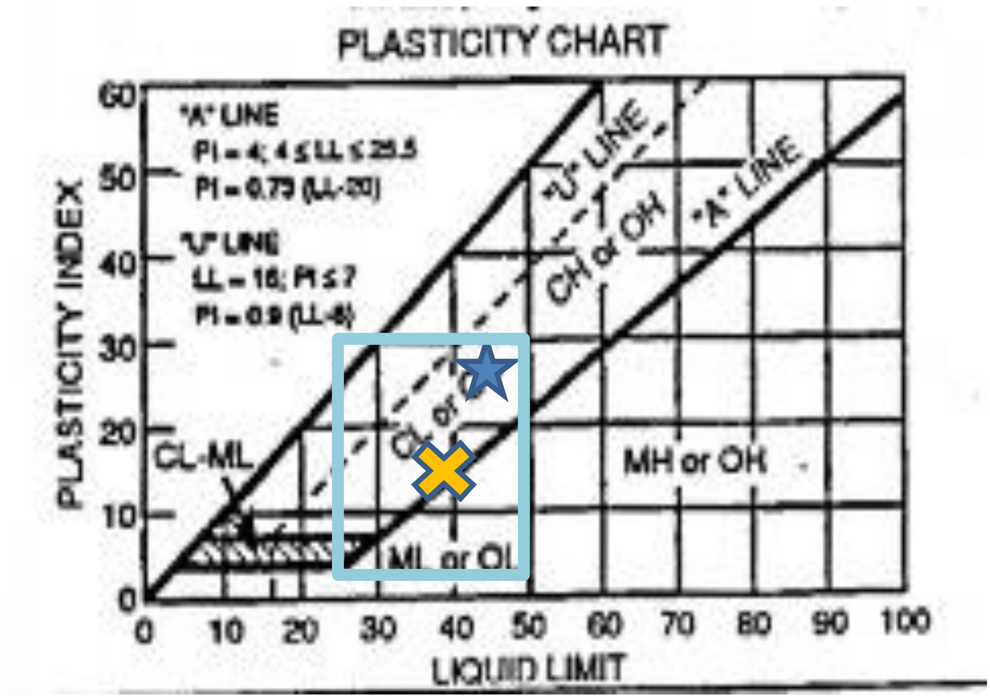


Figure 6.1 Chart for the unified soil classification showing data points for laterite soil used for this research (blue star) and soil analysed by Bodian et al (2018) (orange cross). Acceptable properties for use in CEBs (Uzoegbo, 2020) indicated with rectangle. (Bodian et al, 2018; Hind K.J, 2007; Uzoegbo, 2020)

The plastic index, plastic limit and liquid limit for laterite are similar with other findings from literature (Anifowose, 2000; Bodian et al, 2018; Uzoegbo, 2020). These sources state that it responds to stabilisation to improve compressive strength. Laterite soil (even when adequately stabilized) may disintegrate over time when it's not properly protected. The soil property improves when compaction pressure increases to reduce the water absorption rate in the soil.

6.1.2. Amorphous Silica in RHA

Malhotra and Mehta (1996) defined pozzolan as siliceous or siliceous and aluminous material, which when in a finely divided form and in the presence of moisture chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Rice husk, an agricultural waste from the paddy rice processing, was burnt and ignited in furnace under controlled temperature and time to produced Rice Husk Ash used in current study. The x-ray analysis of the RHA using x-ray diffraction machine revealed the ash samples contained between 80 and 96% SiO_2 (Figures 4.2 and 4.3, and Table 4.3). The results of the x-ray diffraction analysis indicated that the RHA could have pozzolanic properties in the presence of moisture and calcium hydroxide. Also, that it could be used as stabilizing agent in CEB or as partial replacement for Ordinary Portland cement.

Optimisation of the amorphous silica in the RHA was necessary for the economics of production, and this could be ensured through the control of the combustion process. The production process had a controlled time and temperature for combustion to ensure the phase change of the ash does not reach crystalline state when burnt for too long and higher temperature than required.

In the current research two methods of producing ash from the rice husk were tried. In the first method, the rice husk was subjected to charring before igniting in the furnace for 2 – 3h. The charring process could be done by the indigent users who would use the rice husk first as source of fuel for their local cooking, then the charred rice husk would be sent to the furnace. The disadvantage of using this method is that the process to seek out the waste might take a longer process before it goes to the furnace.

The second method for producing high amorphous silica rice husk ash can be achieved ensuring a standard procedure for collecting the rice husk and combusting by the waste management body converting the agricultural waste to rice husk ash. The waste from the agricultural rice farm can be sourced directly by commercial industry and taken to the furnace for combustion process and be bagged into to standard sizes for the end user (construction industry).

To ensure that there is a form of standardization the second method that allows the commercial industry to process or produce the rice husk ash is the most suitable method. The combustion furnace is not easily available as mentioned is section 3.2.1.4 by a layman.

The management of RHA waste helps provide another income revenue to the farmers and ensures that every part of the rice is made useful. The use of agricultural waste means there can be a positive improvement of the urban metabolism of the country.

6.2. CEBs for residential buildings

It was established that the soil (type and proportion), stabilizer (type and content), mix, compaction pressure, and curing condition affected the quality of compressed earth blocks (Uzoegbo, 2020). Consequently, a mechanical press (shown in Figure 3.5) was used to ensure application of adequate pressure for compaction of compressed earth blocks. Two types of compressed earth blocks (solid and hollow types) were prepared for experiments in the current research. The rationale for using different mix for solid (11:7:2) and hollow blocks (13:5:2) was the requirement for improved workability of the hollow blocks. Otherwise, the hollow blocks tended to break apart as soon as the mould was removed; hence more laterite was added to the mix for hollow blocks in order to increase the clay content in the mix.

The volumes of solid and hollow blocks were $0.00386m^3$ and $0.00371m^3$, respectively. The production of the hollow blocks required 3.9% less of materials than the solid blocks and resulted in 0.39% of OPC less in hollow blocks than solid. This implied that hollow CEB would save production cost and may be particularly economical in construction areas requiring less compressive strength and hygrothermal property as in the internal partition walls.

The curing process in an open environment is a common and affordable practice in the Nigerian construction industry. The blocks were laid (as shown in Figures 3.6 and 3.7) in an open environment where they remained covered with water-proof plastic film as covering the blocks with waterproof plastic film to allow for curing. The blocks were prevented from direct exposure to high solar radiation and rainfall but were sprayed with water intermittently. Curing reduced the rate of moisture loss, thus preventing cracking of the blocks (Serbah et al, 2018). Curing periods were 14, 21 and 28 days. The production and construction of the compressed earth blocks in this research was intended for sustainable and affordable wall material in Nigeria. Also, it was to incorporate simple and current method used by the semi-skilled workers (laborers). Apart from combusting the RHA in the furnace and transporting it and the laterite were transported to site, the remaining processes of block production and curing were manual, so CEB production required low energy.

In the current research, ordinary Portland cement was replaced gradually with RHA at the rates of 0% to 50% in the mix used to produce experimental compressed earth blocks. The blocks were tested for mechanical and hygrothermal properties to ascertain the effects of RHA on the properties of the blocks and or whether RHA replacing a proportion of the cement would be acceptable as a stabilizing agent in CEB.

6.2.1. Mechanical Properties

6.2.1.1. Bulk Density

Bulk density, a function of the weight of material in a unit volume of space, depends on the extent to which the material is compressed per unit of space during block moulding. Results obtained in the current research showed that bulk density values of CEB ranged from 1738.0 ± 34 to 1935.9 ± 51 kg/m^3 in solid CEBs, and from 1753.9 ± 66 to 1977.9 ± 29 kg/m^3 in hollow CEBs (Tables 4.4 and 4.5). The results affirmed earlier findings by Mansour et al. (2016), Taallah and Guettala (2016), and Nshimiyimana et al. (2020). These authors reported that bulk density of CEB ranged from 1700 to 2000 kg/m^3.

6.2.1.2. Compressive Strength

Compressive strength, defined as the maximum load a material can bear before fracturing, is a key index used to ascertain the quality of building construction materials. Consequently, compressive strength value as high as 3-4N/mm^2 and as low as 0.35N/mm^2 depending on the bulk density of stabilized CEB had been reported (Mansour et al., 2016; Mostafa and Uddin, 2016). Also, researchers (Kolawole et al, 2020; Mansour et al, 2016; Mkaouar et al, 2019; Nshimiyimana et al, 2020) reported a range of between 0.4 and 12 N/mm^2 (compressive strength) for CEB. (Nshimiyimana et al, 2020) recommended compressive strength requirements for CEB use in the construction of wall structure for affordable and sustainable building in the tropical climate including Nigeria – these are indicated in Table 6.1.

Table 6.1 Required CEB compressive strength for wall structures ((Nshimiyimana et al, 2020)

CEB use (Structure type)	Required Compressive Strength (N/mm^2)
Non-load bearing	2
Load bearing – 2 storeys	2-4
Load bearing – 3 storeys	3-6

In the present study, compressive stength for solid CEB ranged from 2.39 ± 0.3 to 6.39 ± 0.5 N/mm^2 (Table 4.8). While compressive strength for hollow CEB ranged from 0.61 ± 0.1 to 2.68 ±0.1 N/mm^2 (Tables 4.9). The results indicate that the solid CEBs were significantly stronger than the hollow type. This may be due to the perforations in the hollow blocks, or to the higher laterite mix composition.

Mansour et al. (2016) noted that the variation in the compressive strength values reported for the CEB was due to the differences in the bulk densities (1800-2100 kg/m^3) of the blocks. The ranges of bulk density values obtained in the present study (1738.0 ± 34 to 1935.9 ± 51 kg/m^3 in solid CEBs, and from 1753.9 ± 66 to 1977.9 ± 29 kg/m^3 in hollow CEBs) as presented in Tables 4.6 and 4.7 were lower than the range reported by Mansour et al. (2016). The difference might be attributed to the differences in mixes used for the various CEB in the earlier and current studies. However, positive correlation between compressive strength and bulk density of the CEB was observed (Table 4.16), and the correlation coefficient, r being 0.740422. The results, therefore, affirmed earlier findings reported by Mansour et al. (2016).

Results shown in Table 4.10 indicated that compressive strength for solid blocks increased with increased duration of curing up to 21 days but declined thereafter. The highest compressive strength (4.27 ± 0.803 N/mm^2) was attained at 21 days of curing. Also, inclusion of RHA in the mix affected the compressive strength of the CEB where the group having 10%RHA inclusion recorded the highest value (5.61±0.910 N/mm^2) whereas the group with 50%RHA inclusion had the least value (3.15±0.732 N/mm^2). The results suggest that inclusion of RHA in the mix beyond 10% resulted in the lowering of the compressive strength. Indeed, the results of correlation analysis presented in Table 4.16 showed that the correlation coefficient, r of the relationship between RHA inclusion in the aggregate mix and compressive strength of CEB was -0.87885.

In both types of CEBs, substitution of OPC with 10% RHA raised the compressive strength by about 4.2% and 16.9% beyond control CEBs which OPC alone.

All the solid CEBs would be considered acceptable for non-load bearing or load bearing use in 2 storey buildings. All solid CEBs (excepting those with 40% RHA cured for 28 days and 50% RHA cured for 14 days) would be considered acceptable for load bearing use in 3 storey buildings. Hollow CEBs with 10% RHA would be considered acceptable for non-load bearing or load bearing use in 2 storey buildings according to (Nshimiyimana et al, 2020).

6.2.1.3. Water absorption capacity

In the current study, the mean values of water absorption capacity ranged from 6.76% to 8.20% in solid CEB, and from 0.39% to 0.55% in hollow CEB (Tables 4.12 and 4.13). The mean values observed in the experimental CEB were within the range (6 - 9%) reported in earlier studies (Kolawole et al, 2020; Narayanaswamy et al, 2020).

It was observed also that duration of curing affected water absorption capacity of the CEB. The lowest (5.85±1.11%) and the highest (9.01±0.85%) values were obtained at 14 and 21 days of curing, respectively (Table 4.14). Water absorption capacity declined slightly beyond 21 days of curing. The group having 10% RHA inclusion has a lower water absorption capacity than the groups with 20% or higher RHA inclusions. However, there was no clear difference in water absorption capacity between different curing periods. Both the water absorption capacity and RHA inclusion were positively correlated. The correlation coefficient, r was 0.67619. Also, the least value (6.76±1.59%) and the highest value (8.20±0.91%) were recorded in blocks that had 10% and 50%, respectively. All the blocks have acceptable water absorption capacity.

6.2.1.4. Relationship among the mechanical properties of CEB and the effect of RHA inclusion

In order to examine any possible correlation among the RHA inclusion in the compressed earth solid and hollow blocks and the mechanical properties of the latter, data obtained in the study were subjected to correlation analysis. Results of the analysis are presented for solid blocks in Table 6.2.

Bulk density is a function of the weight of material in a unit volume of space, whereas water absorption capacity is a function of voids in the block. Therefore, an inverse relationship is expected to exist between bulk density and water absorption capacity. Indeed, the results of correlation analysis presented in Table 4.16 for solid blocks shows the negative correlation between the two parameters (r = -0.86766). Also, water absorption capacity was negatively correlated with compressive strength (r = -0.84013). On the other hand, bulk density was positively correlated with the compressive strength (r = 0.740422). These results indicate that greater force should be applied in the block-pressing machine in order to increase the bulk density and compressive strength of the CEBs. All of the correlational relationships as obtained in the current study agree with the relationships between these properties reported in literature (Kolawole et al, 2020; Mansour et al, 2016).

The results (Table 4.16) indicated also that %RHA was negatively bulk density (r = -0.43637) has a weak relationship and compressive strength (r = -0.87885) but was positively correlated with water absorption capacity (r = 0.67619) of the CEB.

Table 6.2 Correlation coefficient (r) matrix for Solid CEBs

	%RHA	Bulk density (kg/m^3)	Compressive strength (N/mm)	Water absorption capacity (%)
%RHA	1			
Bulk density (kg/m^3)	-0.4367	1		
Compressive strength (N/mm)	-0.87885	0.740422	1	
Water absorption capacity (%)	0.67619	-0.86766	-0.84013	1

Results of the analysis are presented for solid blocks in Table 4.17 and it revealed that whereas %RHA inclusion was negatively correlated with bulk density (r = -0.8048) and compressive strength (r = -0.95452), it was positively correlated with water absorption coefficient (r = 0.67619). Also, compressive strength was positively correlated with bulk density (r = 0.775174) but negatively correlated with water absorption capacity (r = -0.46535). Bulk density and water absorption capacity were negatively correlated (r = -0.66708).

Table 6.3 Correlation coefficient (r) matrix for Hollow CEBs

	%RHA	Bulk density (Kg/m^3)	Compressive strength (N/mm)	Water absorption capacity (%)
%RHA	1			
Bulk density (kg/m^3)	-0.8048	1		
Compressive strength (N/mm)	-0.95452	0.775174	1	
Water absorption capacity (%)	0.678098	-0.46535	-0.66708	1

6.2.2. Hygrothermal Properties

Based on the result of compressive strength required for medium rise structure ((Nshimiyimana et al, 2020) the hollow CEBs would not be test further on its hygrothermal property as it doesn't meet the requirement for load bearing wall minimum strength. For this reason, they would not be applied on an external wall, but may be of use in partition walls.

6.2.2.1. Water absorption coefficient

In the current research, compressed earth blocks with varying RHA content had values ranging from 0.089 - 0.12 $kg/m^2\ s^{1/2}$ (Table 4.24). Water absorption coefficients of building materials based on the tangent method of calculation reported include traditional handmade clay brick, typical clay brick, and quarry stones, was recorded as 0.205 $kg/m^2\ s^{1/2}$, 0.27 $kg/m^2\ s^{1/2}$ and 0.085-0.10 $kg/m^2\ s^{1/2}$ respectively (Karagiannis et al, 2016). Also, (Mukhopadhyaya, 2002) reported water absorption coefficients to be temperature dependent and had average for red clay brick 0.084 $kg/m^2\ s^{1/2}$ and 0.065 $kg/m^2\ s^{1/2}$ when temperature was 21^oC and 35^oC respectively. The water absorption coefficient value for light earth building material ranged from 0.027-0.135 $kg/m^2\ s^{1/2}$ (Colinart et al, 2020). CEBs analysed by (Lavie Arsène et al, 2020) had water absorption coefficients ranging from 0.09-0.3 $kg/m^2\ s^{1/2}$. The CEBs in this research have similar water absorption coefficients to those reported for red clay bricks and earth materials.

6.2.2.2. Water vapour transmission

Water vapour test is about movement of moisture from a point of higher relative humidity to a point of lower relative humidity. While conducting water vapour test, Liuzzi et al. (2017) noted that water resistance factor was dependent on the bulk density of materials. Also, BS EN 12524-2000 affirmed that materials varied in their water vapour resistance factor according to their bulk densities. That is, fired clay bricks with bulk density 1000-2400 kg/m^3 has water vapour resistance factor of 16 and 10 (dry and wet respectively), calcium silicate brick with bulk density of 900-1200 kg/m^3 had a resistance of 20 and 5 (dry and wet respectively), concrete masonry with bulk density of 500-1300 kg/m^3 had a water vapour resistance of 50 and 40 (dry and wet conditions respectively) (BS, EN 12524:2000). The implication is that the higher the water resistance factor is the more resistant the building material is to water vapour passing through its structure. Therefore, a larger water vapour resistant factor is more beneficial in a material to use in places that have high moisture or high relative humidity such as Nigeria.

Similarly, documentation in the WUFI library on some building materials revealed that the water vapour resistance factors were: concrete blocks with pumice aggregate has a vapour resistance factor of 4 (664 kg/m^3 bulk density); fired clay blocks has a vapour resistance factor of 15 (800 kg/m^3 bulk density), solid brick extruded has a vapour resistance factor of 9.5 (1650 kg/m^3 bulk density); solid brick hand formed has a vapour resistance factor of 17 (1725 kg/m^3 bulk density) and solid bricks historically has a vapour resistance factor of 15 (1800 kg/m^3 bulk density).

In the current research, compressed earth blocks with varying RHA content had water vapour resistance factor values ranging from 11.65-44.91 (Table 4.26), the highest values relating to RHA content of 20% and 50%, which had comparable water vapour resistance factor values to concrete masonry

6.2.2.3. Moisture absorption

Moisture absorption of test material is a function of the quantity of water vapour absorbed from the climatically controlled environment. Consequently, the relative humidity and temperature of the environment affect the moisture absorption of the test material. The experimental CEB were subjected to the test and the moisture absorption equilibrium curves were plotted (Figures 4.21 – 4.25). The water absorption patterns shown by the various CEB indicated that regardless of the level of inclusion of RHA (and its non-inclusion) water absorption increased progressively, though at different rates, as the relative humidity increased. The results thus suggested that inclusion of RHA in the CEB affected water absorption properties of the latter (Table 4.27). Indeed, moisture absorption rate increase when relative humidity increases from 33%- 85%; For the inclusion of RHA, CEBs material 0% RHA,10% RHA, 20% RHA and 40% RHA has an increase of 3.6%,4.8%, 2.2% and

3.5% respectively. The result obtained in this study agrees with the findings of Wang et al. (2020) who reported that the addition of fibre increased moisture absorption in geopolymer concrete reinforced by polypropylene fibres but the results obtained in this study agree with the findings of Ouedraogo et al. (2020), who reported that stabilization of earth with 4-8% cement reduces moisture adsorption rate by 20%. Replacement of ordinary Portland cement by up to 40% with RHA in the CEB aggregate mix resulted in 33.985% reduction in the moisture absorption (Table 4.28). However, 10% replacement caused an increase of 19.535% in moisture absorption. The results tended to suggest that up to 10% replacement of ordinary Portland cement with RHA was not enough to serve as a stabilizing agent in the CEB and hence could not cause a reduction in the moisture absorption in the earth block.

For practical application, Hola et al (2017) classified masonry wall into five categories according to the moisture absorption or content as: I, permissible moisture content (0.3%); II, masonry with elevated moisture content (>3-5%); III, medium damp masonry (>5-8); IV, very damp masonry (>8-12%); and V, wet masonry wall (>12%). Nigeria's climate being tropical – hot and humid, surface walls are exposed to a range of relative humidity would remain medium damp unless the wall has adequate buffering property. The continuous exposure to moisture could cause chipping of wall and mortar, and crystallization of salts on the wall material. This would lead to continuous degradation of the material's strength, cross section area and load bearing capacity of the wall. Furthermore, it would affect the wall surface finishing – mould growth, deterioration and peeling of the paint, etc. The CEBs with 20% RHA is the most suitable material for external use (Hola, 2017).

6.2.2.4. Moisture buffering

The incidence of mould and indeed biological growth on the wall surface is a function of the wall material's ability to absorb or release moisture from its structure. Also, the ability of the material to mitigate the effect of wetness or high moisture absorption of the masonry wall is dependent on the moisture buffering characteristic of the material (Hola et al., 2017). The moisture buffering values (MBV) of the experimental CEB in the current research are shown in Table 4.28. The range of MBV obtained in this study (i.e. 1.2 – 2.1 g/m^2 %RH) agrees with literature values of 1.2-3.9 g/m^2 %RH (Rode et al. 2005; Zhang et al. 2017; Bruno et al 2017). In addition, application of the NORDTEST classification (Rode et al. 2005; Zhang et al. 2017) indicated that RHA inclusion in the CEB's aggregate mix remarkably affected the moisture buffering value of the CEB where RHA inclusion of 0%,10%, 20%, 40% boosted the moisture buffering characteristic. Indeed, the CEB with RHA up to 40% made them good. The excellent moisture buffering characteristic of the CEB would be of pactical importance in the provision of affordable low-cost housing in Nigeria. The excellent moisture buffering ability of the CEB to which RHA has been included would ameliorate the effect of high moisture absorption encountered in the humid and hot tropical climate of Nigeria in areas where earth compressed blocks are used for building construction.

6.2.2.5. Thermal Conductivity

The thermal conductivity of compressed earth bricks/blocks has been studied by several workers, and values reported include 0.52 – 0.72 W/m.K (Doubi et al, 2017) and 0.79 – 1.10 W/m.K (Saidi, 2018). The results of thermal conductivity of the experimental blocks in the current study are shown in Table 4.29. The thermal conductivity values ranged from 0.55 to 0.87 W/m. K and they were within the ranges reported in the literature. The results record that thermal conductivity of the CEB was affected remarkably by the inclusion of RHA in the aggregate mix. There was a decrease in thermal conductivity when RHA was included in the mix from 0.87 W/m. K for blocks with no RHA to 0.55-0.61 W/m.K.

Doubi et al. (2017) observed that in cement-stabilized compressed earth bricks addition of shea butter wastes improved porosity that explained the improvement of the thermal insulation properties of the bricks. Furthermore, addition of the agricultural wastes caused reduction of the bulk density of the bricks. Finally, the authors were able to establish a positive correlation between bulk density and thermal conductivity. The results indicate that RHA has improved the thermal insulating property of the CEBs.

Thermal conductivity is a key parameter in the calculation of the U-value which is commonly used to compare the thermal performance of wall systems. The U-value of wall section EP without inclusion of RHA was 1.299 W/m^2K. More RHA inclusion further reduced the U-value to 1.136 W/m^2K and 1.146 W/m^2K at 10% and 30% RHA inclusions, respectively. The U-value of wall section NP was 1.22 W/m^2K for CEBs without RHA inclusion. Similarly, the U-value reduced with inclusion of RHA to 1.076 and 1.086 for 10%RHA and 30% RHA, respectively. In earlier study, (Olaniyan, 2012) noted that the U-value of external walls in building construction using hollow sandcrete blocks in Nigeria was 1.035 W/m^2K. Therefore, the findings of the current research indicated that without and with inclusion of the RHA up to 30% in the aggregate mix of the experimental CEB the latter was suitable for the construction of external wall of buildings in Nigeria.

6.2.2.6. Choice of material for simulation

A summary of the mechanical properties of the CEBs is presented in Table 6.4 and 6.5. This focuses on the suitability of the CEBs for application, where prime considerations were given to ensuring that the material would be safe and structurally sound for the intended use. From the mechanical properties, it is found that hollow blocks are generally not suitable for load-bearing applications and are eliminated from the hygrothermal analysis. The common practice of curing masonry unit in Nigeria is a maximum of 28 days, the CEBs cured for 28 days were therefore ideal for simulation of hygrothermal properties.

Table 6.4 Suitability of solid CEBs for application based on mechanical properties

RHA (%)	Curing time (Day)	Compressive strength for wall structures ((Nshimiyimana et al, 2020)	Water absorption capacity
0	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
10	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
20	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
30	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
40	14	3 storey	No issue
	21	3 storey	No issue
	28	2 storey	No issue
50	14	2 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue

Table 6.5 Suitability of hollow CEBs for application based on mechanical properties			
RHA (%)	Curing time (Day)	Compressive strength for wall structures ((Nshimiyimana et al, 2020)	Water absorption capacity
0	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
10	14	3 storey	No issue
	21	3 storey	No issue
	28	3 storey	No issue
20	14	N/A (not acceptable)	No issue
	21	N/A	No issue
	28	N/A	No issue
30	14	N/A	No issue
	21	N/A	No issue
	28	N/A	No issue
40	14	N/A	No issue
	21	N/A	No issue
	28	N/A	No issue
50	14	N/A	No issue
	21	N/A	No issue
	28	N/A	No issue

Hygrothermal performance is important for several factors including, durability of the material, acceptable indoor air quality, thermal comfort, and prevention of mould growth. A summary of the hygrothermal performance focussing on suitability for application is presented in Table 6.6 for solid CEBs which had been cured for 28 days.

Table 6.6 Suitability of solid CEBs for application based on hygrothermal properties					
RHA (%)	Water absorption coefficient	Water vapour resistance factor	Moisture absorption	Moisture buffering value	Thermal conductivity
0	No issue	No data	Masonry with elevated moisture content	Good	0.87 W/m.K
10	No issue	Fired clay brick equivalent	Masonry with elevated moisture content	Excellent	Better than 0% RHA
20	No issue	Calcium silicate brick equivalent	Masonry wall with permissible moisture content	Good	Better than 0% RHA
30	No issue	Concrete masonry equivalent	No result	No result	No result
40	No issue	Fired clay brick equivalent	Masonry with elevated moisture content	No result	No result
50	No issue	Concrete masonry equivalent	No result	Good	Better than 0% RHA

From a combination of mechanical and hygrothermal properties (Tables 6.2 and 6.4), it was decided to eliminate CEBs with 40% or 50% RHA from the simulation studies. Although these had similar hygrothermal performance to the CEBs with lower RHA content, their compressive strength performance was poorer.

6.3. Mould growth and interstitial condensation simulation

Indoor air quality affects the health of the occupants of the building. The quality of air in the building depends on the air temperature, relative humidity and the use of the space. These factors can affect the mould growth, and condensation within the space, which in turn affect occupant health. Consequently, the WUFI simulation was used to check the hygrothermal property of the wall under the tropical savanna climate (Aw). Two wall section types (full cavity - EP and partially insulated cavity - NP) were chosen to study changes in temperature, relative humidity, and mould growth on the interior wall surface.

Mould growth occurs within a space when the environment is moist and warm. Mould grows on wall surfaces within the temperature range of 10 - 50^{0}C and relative humidity of 80% and above. The use of the space determines the relative humidity and temperature, so the activities such as cooking, and bathing generate more moisture in the air than spaces used for resting. Also, the type of surface material and its porosity also determines its susceptibility to mould growth.

The results in the current research showed that the temperature of the wall sections in areas with normal and high relative humidity values shows that temperature reduced progressively from the external to the internal space (Figure 5.6-5.9). The results inferred that heat transfer into the internal wall was retarded. This could be considered a good property to have in this climate.

The results of relative humidity of all the wall sections are shown in Figures 5.10 – 5.13. Throughout the year, the relative humidity of the wall surfaces was less than 100%, a condition required for condensation to occur. So, there was no occurrence of condensation on the external or inner wall surfaces.

The highest relative humidity on internal surface of the wall section EP were 76.2% and 72.9% for areas with normal and high relative humidity. The highest RH values were obtained in wall having 30% RHA inclusion. The wall section NP relative humidity also reduces at the internal surface to 74.5 and 68.7%, again for 30% RHA inclusion. The moisture value for areas with high and normal relative in the interior surface reduces in wall section NP compared to EP.

The wall should be studied to understand the moisture content on the whole wall section. The areas where normal and high relative humidity prevails, the wall section EP had moisture content of less than 30 kg/m^3. The wall section also showed that the cavity in the wall retarded movement of moisture from the external layer to the internal layer. In the cases of all wall types in NP, moisture movement reduced from external to the cavity but increased towards internal surface. This phenomenon might promote mould growth inside the wall section where the MDF insulation is placed where normal and high relative humidity are prevalent.

A key consideration in this investigation is mould growth. Figures 5.18-5.21 show the simulated mould growth on each wall type and humidity condition over a period of a year. In regions where normal relative humidity is prevalent, the inclusion of RHA beyond 20% might result in potential mould growth in the wall section EP. Inclusion of 30% RHA resulted in the wall section having less than 50mm mould growth. Testing on WUF bio, resulted in a green traffic signal indicated that it is acceptable. However, in the case of regions where high relative humidity is common, the highest mould growth on the wall section EP occurred at 30% RHA inclusion and reached approximately 200mm. Testing on WUF bio showed a red traffic signal, indicating that the material is not suitable in the region. The wall types having 0%, 10% and 20% RHA inclusion had mould growth of less than 200mm, showed yellow signal on the WUFI bio, suggesting further investigation was required.

The results of the present study showed further that no mould growth occurred on the interior surface of wall section NP that had been partially stabilized with varying percentages of RHA in regions where normal relative humidity is prevalent. On the other hand, under the condition of high relative humidity, mould growth on the interior wall surface was more than 50mm but less than 200mm. In addition, yellow traffic signal was observed.

Consequent upon the results of total water contents and mould growth on all the wall types in the regions where high relative humidity is prevalent, further investigation was required. This was carried out as a study on the changes in total water content for wall section types EP and NP in high humidity and is illustrated over 1 year in Figures 5.22-5.23 and over 3 years in Figures 5.24-5.25. The water content in wall section absorbs for a quarter of the year and desorbs for the three quarter of the year for wall type EP. This pattern shows that the wall structure can desorb satisfactorily after absorbing. The study revealed that wall type NP absorbed water for a quarter of the year, and it desorbed for three quarter of the year. The wall type NP showed a higher water content than the wall section EP as shown in Figures 5.24 and 5.25.

The simulation results are visualised in Table 6.7.

Table 6.7 Suitability of solid CEBs for application based on results from mould growth and interstitial condensation simulation

RHA (%)	Wall Structure	RH	Temp interior (°C)	RH interior (%)	Moisture (%)	Mould growth (mm)	WUFI BIO traffic light	Water content (Kg/m^2)	
								1 yr	3 yr
0	EP	Normal	similar	64-68	5	0	Green	-	
0	EP	High	similar	64-68	6.3	112.5	Yellow	<20	<20
0	NP	Normal	similar	64-68	5	0	Green	-	
0	NP	High	similar	64-68	6.4	116	Yellow	<40	<40
10	EP	Normal	similar	64-68	5	0	Green	-	
10	EP	High	similar	64-68	6.5	114.8	Yellow	<20	<20
10	NP	Normal	similar	64-68	5.1	0	Green	-	
10	NP	High	similar	64-68	6.5	118	Yellow	<40	<40
20	EP	Normal	similar	64-68	0.6	0	Green	-	
20	EP	High	similar	64-68	0.8	116.3	Yellow	<20	<20
20	NP	Normal	similar	64-68	0.6	0	Green	-	
20	NP	High	similar	64-68	0.8	111	Yellow	<40	<40
30	EP	Normal	similar	68-76	8.5	25.2	Green	-	
30	EP	High	similar	68-76	11.6	257.9	Red	<20	<20
30	NP	Normal	similar	68-76	6.8	0	Green	-	
30	NP	High	similar	68-76	7.7	105	Yellow	<20	<20

From the findings so far, CEB with 20%RHA inclusion was considered the most suitable material using the wall type EP. This was because it combined the highest possible RHA content (displacing expensive OPC) with suitable properties for use in the region where normal and high relative humidity conditions are prevalent. This material and wall type were analysed further for thermal comfort performance (Section 6.4).

6.4. Thermal comfort simulation

Prior to undertaking thermal comfort simulation, key passive design strategies for cooling were considered in relation to the building. Key factors to be included in the design of the simplified structure are:

- appropriate building orientation and form to minimise solar gains and facilitate natural ventilation for cooling (long axis running North South) with large openings to receive cooling breezes.
- Thermal mass to reduce heat absorption and to use in conjunction with night cooling in appropriate climates.
- Cross ventilation to allow easy natural flow of air into the building to improve thermal comfort.
- Pitch insulated roof to allow the flow of rainwater easily and reduce the solar heat gain from the roof.
- Shading of the windows and walls using the roof overhang (Ogunsote et al, 2010).

Consequent upon the above, the performance of the simplified structure incorporating 20% RHA CEBs in the wall section was compared to the wall section with concrete.

According to ASHRAE 55-2010 Adaptive comfort standard, the 80% and 90% thermal comfort satisfaction temperature and relative humidity for tropical savanna climate where natural ventilation only is prevalent are 25.1 - 31.4ºC and 80 - 90% and 23.1 - 29.4ºC and 80 - 90%, respectively (Table 5.18). Banerjee et al. (2020) noted 19.5 - 31ºC as the thermal comfort temperature of people inhabiting in the tropical climate, which shows a reasonable agreement with the 90% thermal comfort satisfaction conditions. The relative humidity ranged from 70% to 100%.

The climate data presented in Table 5.17, indicated that the outside air temperatures were higher than acceptable comfort levels in February to May. Also, for Lagos, Nigeria the wind was from the south western direction. The wind brings moist air with high relative humidity from the Atlantic Ocean.

For 90% satisfaction in the base building design (24x15m) there was little difference in the number of hours where thermal comfort was achieved (Table 5.19). The use of CEB provided thermal comfort for the user for 74% of the hours at a 90% thermal satisfaction level. At an 80% thermal satisfaction level, this increased to 80% of hours. These results were like those using concrete with same U value in the Aw climate in Nigeria.

An initial investigation was able to increase the hours in comfort by elongating the building (keeping the same floor area) and reducing the window wall ratio. A more detailed investigation could potentially further increase the hours in comfort.

7 Conclusion and contribution to knowledge

7.1 Introduction

The concept of this research was based on the need to provide a possible solution for deficit of residential houses for the low-income earner in Nigeria. The deficit of residential houses in Nigeria is because of growing urbanisation and inadequate planning to meet expansion. Nigeria is a developing country that has a large population of people living below the poverty level as discussed in Section 2.1, there is a need for low-cost building that minimises harm to the present and future environment. The present generation of low-income earners have created an organic response to the income inequality faced to provide housing for themselves through slums, dilapidated houses, squatter housing, unauthorised land development, room, or flats in uncompleted or dilapidated houses. One in 7 people live in informal settlement (Gan et al. 2017). The people are then faced with problems such as overcrowding, inadequate waste management, poor health, poor sanitary systems, insecure residential status, and poor structural buildings. The government have tried to create more houses from the period when the country gained her independence. The reason for the deficit was because of the high cost for providing residential buildings, inadequate policies, poor planning, and mismanagement as indicated in Section 2.2.4. Based on this research, the government needs inclusion of the people that require the houses, agricultural industry, and construction industry to work as a team to ensure the system works. The methods for construction of the buildings for the low-income earners require minimum energy as the country experiences interrupted power supply daily. It also requires simple method of construction, so the people can build their houses themselves and reduce the cost of the construction by eliminating expensive devices and reducing labour. The construction of medium rise building to reduce the land use caused by low rise building is the most suitable. The construction industry can have positive impact by improving by encouraging low energy and low emission products, introducing low carbon material and technology (i.e earth) and embracing circular economy (IEA, 2019). The construction industry uses about 36% of related emission globally (Cao et al, 2016) and 70 of energy consumption in residential buildings in 2018. By aiming to a more sustainable material, design, and principles; the cost of building can also be reduced as indicated in Section 2.1.

This research concentrated on the sourcing, processing of a sustainable, earth-based masonry unit to achieve optimized mechanical and hygrothermal property. The material showed adequate property for indoor air quality on the health of the users.

7.1.1 Aim and objectives

The aim of this research was to investigate the provision of a possible low cost, sustainable building material for wall construction in Nigeria. To provide this solution the research concentrated on using locally sourced material (earth) partially stabilized with pozzolanic agricultural waste to reduce the amount of ordinary Portland cement (OPC) that was used in the construction of houses. The reduction of OPC means an improvement on the environment caused by reducing the pollution caused by the cement industry in the country over time and the preservation of the raw material for the future generation. The use of local material (laterite soil) and reduction of OPC for wall material has significant potential to reduce the cost of the material (Section 2.1).

The objectives set to facilitate this research were.

1. To investigate the raw materials, particularly proportions of laterite, RHA, OPC and sharp sand needed to produce RHA CEBs for walls in the tropical savanna climate of Nigeria.
2. Evaluate the mechanical and hygrothermal properties of the resulting CEBs and analyse them against wall construction requirements.
3. Simulate the hygrothermal and thermal performance to evaluate indoor air quality and thermal comfort.

7.2 Conclusions

The first objective was to investigate the raw materials, particularly the proportions required to produce RHA stabilised CEBs for walls. The selection of RHA as the most suitable pozzolanic material for this research, was based on the following factors.

i.) **the availability of RHA**: the selection of rice husk ash (RHA) as the most suitable pozzolan to be used for the tropical savanna climate is because of the proximity of the raw rice husk and the amount of waste produced from the agricultural industry to meet the needs of the users. Laterite and sand are also readily available to the potential site of construction. This means there would be reduction in the cost of transportation, emission of greenhouse gas (GHG) to the environment from the trucks commonly used in the country. It also means a potential reduction on the damage to the roads infrastructure which uses a large amount of the country's available funds for maintenance. It is the most accessible pozzolan compare to SBA, POFA to tropical savanna climate urban areas in the country.

ii.) **the ease of processing RHA to get high silica content required for the pozzolanic reaction to occur** processing the rice husk ash (RHA) will be a challenging initially, as experienced during the research. Furnaces are required which burn at a controlled temperature (550-700ºC). Such a furnace was found at a private sculptor. To provide energy for the combustion of the furnace the purchase of hydrocarbon gas from a fuelling station is needed regularly. The device is not connected to the electrical grid of the country. The reason for not connecting the grid was the large amount of power the furnace required and the electricity supply in the country is unstable and inadequate. The controlled combustion of rice husk to rice husk ash ensures that there is high amorphous silica content of about 80-96%. Amorphous silica ensures that there is pozzolanic reaction in the particles when water is added to the mix. Although there are challenges involved for production of RHA; OPC required higher combustion temperature of 1450^{0}C and expensive equipment to manufacture.

The most appropriate proportions of laterite, RHA, OPC and sharp sand required to produce RHA stabilised CEBs was based on the results of mechanical and hygrothermal properties (objective 2). The conclusions based on mechanical properties are presented in section 7.2.1, while the conclusions based on hygrothermal properties are presented in section 7.2.2.

The final objective was to simulate the hygrothermal and thermal performance to evaluate indoor air quality and thermal comfort. The conclusions based on indoor air quality are presented in Section 7.2.3, while the conclusions based on thermal comfort are presented in Section 7.2.4.

7.2.1 Mechanical property of compressed earth blocks

The methods used for testing the mechanical and hygrothermal properties were described in Chapter 3 (Methodology). The British standard used for masonry units (BS, EN 772-1:2011+A1:2015) was referred to as Nigeria does not have a particular standard for testing earth blocks. This was particularly important in relation to minimum bulk density and compressive strength allowed for use in residential building construction. There were two shape of blocks made, the solid and the hollow blocks. The results (Tables 4.8 and 4.9) show that solid compressed earth blocks were about two times stronger than the hollow compressed earth blocks with similar rice husk ash content. The compressive strength requirement for different wall structures and the corresponding experimental CEB types are presented in Table 7.1.

Table 7.1 %RHA compositions which meet required CEB compressive strength for wall structures

Structure type	Required compressive strength (N/mm^2) ((Nshimiyimana et al, 2020)	Appropriate CEB type and RHA composition
Non-load bearing	2	Hollow 0%, 10% RHA
Load bearing – 2 storey	2-4	Solid 20%, 30%, 40%, 50% RHA Hollow 0%, 10% RHA
Load bearing – 3 storey	3-6	Solid 0%, 10%, 20%, 30%, 40% RHA

The curing process of the blocks is very important to achieve the required strength of the masonry unit. The blocks need to be cured for a minimum of 21 days to get optimum strength.

Hollow CEBs with RHA of 30% or greater lack enough compressive strength to be used in wall construction. Further hygrothermal testing of hollow blocks was not carried out, as the material did not meet the required mechanical property for load-bearing wall material.

7.2.2 Hygrothermal properties of compressed earth blocks

Tests were carried out on the CEB samples to evaluate the required hygrothermal properties such as water absorption coefficient, water vapour transmission, moisture absorption rate, moisture buffering and thermal conductivity.

The **water absorption coefficient** of samples tested in the laboratory (Table 4.12) shows that RHA stabilised samples have similar characteristics to fired clay bricks (Mukhopadhyaya, 2002) and earth material (Colinart et al, 2020). The water absorption coefficient for sample with RHA inclusion 10%, 20%, 30%, and 50% have lower values compared to control sample with only OPC stabilisation.

The **water vapour transmission** reflects the change in mass of a wall sample due to relative humidity changes (related to seasonal and diurnal changes). The water vapour resistance factor for samples with 10% RHA (11.65) has similar resistance compared to fired clay bricks (16) and concrete with expanded clay as main aggregate with (8) (BS, EN ISO 10456:2007) which are common masonry materials used in Nigeria. The inclusion of 20-50% increase the water resistance factor compared to other masonry materials.

The **moisture absorption** for in CEB samples with 20% RHA was lower than the control sample (0% RHA). All other RHA inclusions caused an increase in moisture absorption compared to the control sample.

The **moisture buffering** value property of the building materials has a significant effect on the amount of energy required to cool building in Nigeria. The higher the buffering value of building material the lower the energy required to cool the building. All the tested compressed earth blocks show values that can be categorised as good or excellent. The CEBs with RHA inclusion of 10% had better performance than control CEBs which were only stabilised with OPC.

The **thermal conductivity** property of CEBs with inclusion of RHA were all significantly lower than the control (0% RHA). CEBs with 10% RHA had the lowest thermal conductivity. The CEBs exhibited favourable thermal conductivity performance to common building bricks (0.6-1.0 W/m. K) and was comparable with concrete (0.4-0.7 W/m. K) (Engineering Toolbox A, No Date).

Based on the mechanical and hygrothermal property analysis of the CEBs, inclusion of RHA from 10-30% have properties which are similar or better than conventional wall materials in Nigeria.

7.2.3 Indoor air quality

It is essential that the hygrothermal properties of the materials should be considered in relation the climate of the country. This is mainly to determine potential issues such as condensation and mould growth which can adversely affect air quality and the health and comfort of the occupants. It can also indicate potential issues which would adversely affect wall durability. In this case, the tropical savanna climate part of Nigeria ensures that the building structure is exposed to high rainfall, high relative humidity and high temperature from the high sun radiation of the climate. The building wall material is required to ensure that the internal temperature and relative humidity is reduced to retard mould growth and condensation on the wall of the building.

Full year simulation of two wall types (full cavity and partial cavity) in high relative humidity spaces (e.g., bathroom or kitchen) and normal relative humidity spaces, utilising solid CEBs with 0%, 10%, 20% and 30% RHA assessed temperature, relative humidity, moisture content, mould growth and total water content for a full year. From this, the most suitable wall design for Nigeria could be identified.

The masonry wall design with cavity partially filled with thermal insulation material (MDF) (NP) does not have mould growth on internal side of the wall in spaces with high and normal internal relative humidity. However, this wall design wasn’t chosen because of high relative humidity within the internal cavity which could cause mould growth in the wall cavity. This would adversely affect the wall durability.

For a full cavity masonry wall (EP) RHA inclusions up to 20% were suitable for both high and normal relative humidity spaces. The inclusion of RHA beyond 20% was found to have potential to allow mould growth on the wall.

7.2.4 Thermal Comfort

A full cavity masonry wall utilising 20% RHA solid CEBs was considered for thermal comfort analysis. This was selected based on the previous research which showed it to combine:

- the highest possible RHA substitution for OPC
- mechanical properties suitable for 3 storey loads bearing walls
- hygrothermal properties which minimise mould growth even in high humidity bathroom/kitchen spaces in the tropical savannah climate.

This wall construction was compared to a "typical" concrete wall structure for a 360m^2 dwelling. The comparison was based on the hours "not comfortable" at 90% satisfaction levels. The number of hours "not comfortable" achieved for CEBs partial stabilised with 20% RHA were like concrete walls using the same design strategy and building area.

7.3 Contribution to knowledge

The following points summarise the contribution to knowledge from this research:

1) A comprehensive literature review outlining the challenges of providing dwellings for low-income earners in Nigeria and discussing the potential material options for construction of such dwellings.
2) With existing materials and facilities in Nigeria, there is capability of:
    a. producing rice husk ash with suitable pozzolanic qualities
    b. producing solid CEBs partially stabilised using RHA with suitable mechanical properties for use in load bearing walls for 2 and 3 storey buildings
    c. producing hollow CEBs with reduced material content and lower OPC & RHA content with suitable mechanical properties for use in non-load bearing walls
3) Data from a comprehensive study of mechanical properties of hollow and solid CEBs which considered 3 curing periods and OPC replaced by 0%, 10%, 20%, 30%, 40%, 50% RHA. This meets a research gap identified after the literature review and concludes that:
    a. at least 21 days curing time is required to achieve full comprehensive strength.

    b. solid CEBs have approximately double the compressive strength of hollow CEBs.

4) Data from a comprehensive study of hygrothermal properties for solid CEBs with OPC replaced by 0%, 10%, 20%, 30%, 40%, 50% RHA. This meets a research gap identified after the literature review and concludes that up to 30% of OPC can be replaced with RHA in solid CEBs while meeting the required mechanical and hygrothermal properties for load-bearing walls up to 3 storeys.
5) Data from hygrothermal simulation of full cavity and partially insulated cavity wall structures over a full year for the tropical savannah climate of Nigeria. This considered the impact of high humidity internal spaces (eg kitchen, bathroom) as well as normal humidity internal spaces on the hygrothermal performance of the wall structures utilising solid CEBs with 0%, 10%, 20% and 30% for temperature, relative humidity, moisture content, mould growth and total water content (also evaluated over 3 years). This data indicates structures which could cause potential indoor air quality issues with mould growth which could affect occupant health and comfort as well as potential impact on the durability of the structure. This meets a research gap identified after the literature review and concludes that the full cavity wall type is less liable to excessive humidity in the cavity which could reduce the wall durability. This is achieved while minimising the environmental / economic impact.
6) Data from thermal simulation over a full year for the tropical savannah climate of Nigeria. This considered a dwelling with 360m^2 floor area. 90% satisfaction "not comfortable" hours are very similar for the CEB and concrete structures, which is considered acceptable, particularly since CEB is a more cost-effective structure material. "Not comfortable" hours at 80% satisfaction could be reduced to 16.2% of the year using CEB full cavity wall with 20% RHA CEBs without introducing any mechanical ventilation or cooling. This is an important finding as Nigeria's electricity supply is not stable and some houses only receive supply for 3 hours a day, energy supply in Nigeria is costly when available.
7) As the use of local materials has been found to reduce the total cost of housing to approximately 50% (Olotuah, 2002), proving the capability of CEBs for use in wall construction, gives an opportunity for residential dwellings to be made more affordable to Nigeria's low-income earners.
8) As a typical concrete mixture (1 part cement, 2 parts sand, 4 parts aggregate) contains 14% cement (discounting water and entrained air), while CEB stabilised with 20% RHA contains 8% cement, a structure has been proposed which significantly reduces the amount of OPC required with corresponding drop in environmental impacts. Particularly since the remaining CEB production is labour intensive with little fossil fuel requirement.

7.3.1 Limitation of research

Simulations were only analysed for the tropic savannah climate in Nigeria. This climate was chosen because it covers a larger area and population than each of the other three climates. It cannot be assumed that simulation findings for tropic savannah climate apply to the other climates, particularly the arid climates. Besides, simulation cannot include every situation and that the computer software are unable to create real-life situations. However, computer simulation offers the advantage of providing guidance towards a possible solution or model creation. Furthermore, it serves as a stopgap where it is impossible to have real-life experience. Because of limitations of time and resources, therefore, the application of computer simulation for the tropical climate was chosen to understand the model of mould growth and thermal comfort of the CEB/RHA wall.

7.3.2 Further research

Further research could be carried out in the further topics:

i.) The condensation and interstitial condensation of the building material to ensure that adequate indoor air quality is meant needs to be analysed on the material.

ii.) The full environmental impact of RHA stabilised CEBs. This would include greenhouse gas (GHG) emissions, embodied energy, operating energy (assuming uninterrupted power supply available for mechanical services), treatment at end of life.

iii.) The financial cost of raw materials, labour required for construction of the CEBs.

iv.) To obtain the hygrothermal property (mould growth) and thermal performance of CEBs partially stabilized with RHA in this research, the numerical simulation was applied. Further test to achieve a more realistic result could apply the in-situ measurement research approach in future studies.

7.4 Summary

The stated aim of this research was to investigate the provision of a possible low cost, sustainable building material for wall construction in Nigeria. This has been achieved.

Solid CEB with RHA at 20% replacement of OPC has been selected as having the best combination of maximum OPC replacement while attaining appropriate mechanical and hygrothermal properties. In some cases, properties such as moisture buffering, water absorption coefficient, water absorption capacity, water vapor transmission, the inclusion of RHA provides improved characteristics of the CEB masonry unit.

The 20% RHA CEB has also been found suitable in relation to the impact on occupant's health and thermal comfort. Hygrothermal simulation under the local climate conditions indicates there is unlikely to be a risk of internal condensation and mould generation. Thermal simulation was undertaken for a free-running building as the local electricity supply is expensive and erratic. The thermal simulation showed similar thermal comfort hours for CEB with 20% RHA and for concrete walls. Although there was no improved comfort for CEB with 20% RHA, this replacement does not cause a detrimental effect on the user.

The major environmental impacts from concrete arise from cement, which is approximately 14% of concrete (excluding water and entrained air). CEBs with 20% of the cement substituted from RHA reduces the cement content to 8%. The remaining material was sourced locally and utilised waste material as a pozzolan. The use of local materials has been indicated as delivering a 50% saving in the construction cost (Olotuah, 2002) while the labour-intensive nature of CEB production also minimises energy used in the process.

The introduction of the proposed compressed earth blocks partially stabilized with 20% RHA would affect the economy, environment, and social aspect of the country. The lack of adequate funds to reduce the housing deficit can be combated by using locally available material, cheaper labour, and low-cost equipment to provide wall material which will also improve the economy of the country. The constant build-up of the slums and informal settlement in the urban city can be reduced when the CEBs masonry is used which will improve the environment over time.

8 Reference

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SOFTWARE TOOLS

Meteonorm 7v7.3.3

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Publication

Ojerinde,A., Adekunle,A., Fatai, O., Stevenson, V. & Latif, E. The partial replacement of Ordinary Portland Cement with Rice Husk Ash to stabilize Compressed Earth Blocks for Affordable Building materials. PLEA 2018: Smart and healthy within the two-degree limit, Hong Kong, China, 10-12 Dec 2018. PLEA 2018-34th International Conference on Passive and Low Energy Architecture. The Chinese University of Hong Kong, pp. 321-325.