PERFORMANCE OF COMPRESSED EARTH BLOCKS STABILISED WITH CEMENT AND PALM KERNEL SHELL ASH COMPOSITIONS

BY

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CERTIFICATION

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DEDICATION

This Ph.D. Thesis is dedicated to the Almighty God, the lifter of my head and the source of all wisdom, not limited in scope or in capacity.

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ABSTRACT

Cement is the conventional stabiliser used for Compressed Stabilised Earth Blocks (CSEB), which has been in use as a building material over the ages. However, its production causes environmental pollution. Hence, efforts have been directed at finding partial replacements for it with domestic, industrial and agricultural wastes such as Palm Kernel Shell Ash (PKSA). The PKSA has been used to partially replace cement in concrete blocks but information on its use in CSEB is sparse. Therefore, the potential of using PKSA as a supplementary cementitious material in CSEB was investigated.

The physical properties (specific gravity, moisture content, liquid limit, plastic limit and plasticity index) of lateritic soil used for the production of the CSEB were determined, as well as the chemical composition of PKSA. The CSEB (100x100x100mm) cubes were produced from lateritic soil, cement, PKSA and water at 11.5% water to mixture of soil and binder. The cement-PKSA mixes were stabilised at 8:2, 6:4, 4:6, 2:8, while the control mix was stabilised at 10.0% cement. The mixes were compacted with a pressure of 6 MPa for the production of 66 Control Mix Blocks (CMB) and 528 Cement-PKSA Blocks (CPB). The blocks were cured at 100% humidity followed by 28 days secondary curing. Wet and Dry Compressive Strengths (WCS and DCS), Block Dry Density (BDD) and Total Water Absorption (TWA) of the blocks were determined according to standards. Data were analysed using a t-test at $\alpha_{0.05}$.

Specific gravity, moisture content, liquid limit, plastic limit and plasticity index values were 3.3, 17.7, 53.4, 59.5 and 6.1%, respectively. The average chemical compositions of PKSA were 46.6 SiO_2, 13.5 Al_2O_3, 11.8 Fe_2O_3, 0.5 SO_3, 1.0 MgO, 1.5 K_2O, 1.4 Na_2O and 9.8% CaO, while specific gravity was 2.0. The WCS for CMB was 8.99 MPa, while CPB were 9.84, 7.51, 5.29, 3.21 MPa for 8:2, 6:4, 4:6, 2:8 mix proportions, respectively. The DCS for CMB was 9.84 MPa and at 8:2, 6:4, 4:6, 2:8 mix proportions, CPB were 11.79, 9.66, 7.33, 4.61 MPa, respectively. These values fare better than the 3.00 and 4.12 MPa recommended standards for WCS and DCS, respectively. The BDD for CMB was 2128±0.33 kg/m^3, while CPB ranged from 2102 to 2132 kg/m^3 for 8:2, 6:4, 4:6, and 2:8 mix proportions, respectively, all within the required minimum standard of 2000 kg/m^3. The TWA for CMB was 7.5% and ranged from 6.8 to 9.8% for CPB. These values were lower than the 12% maximum standard. A 44% decrease in TWA with variation in cement content from 2 to 8% was attained; with a 2.3% increase in density. An increase in BDD led to an increase in WCS for both CMB and CPB (100% positive correlation). An increase in BDD led to a 44% decrease in TWA for both CMB and CPB (strong negative correlation).

Palm kernel shell ash is a suitable partial cement replacement in the production of compressed stabilised earth blocks, with the best performance obtained at 4% PKSA and 6% Cement.

Keywords: Compressed stabilised earth blocks, Palm kernel shell ash, Compressive strength, Water absorption, Agricultural waste.

Word count: 491

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVATIONS

BDD	Block Dry Density
CEB	Compressed Earth Blocks
CMB	Control Mix Block
CPB	Cement-Palm Kernel Shell Ash Block`
CRM	Cement Replacement Materials
CSA	Cross-Sectional Area
CSEB	Compressed Stabilised Earth Blocks
DCS	Dry Compressive Strength
ML	Maximum Load
OBS	Ordinary Builders Sand
OPC	Ordinary Portland Cement
PKSA	Palm Kernel Shell Ash
PSD	Particle Size Distribution
SSA	Specific Surface Area
TWA	Total Water Absorption
VFP	Volume Fraction Porosity
WCS	Wet Compressive Strength

CHAPTER ONE
INTRODUCTION

1.1 Background

For low-income groups in developing countries, affordable housing is a fundamental need. Rural workers and people living below minimum wage in urban areas do not have the ability to live in suitable and affordable housing, since land and construction costs are far beyond their means. Steel, cement, and crushed stone aggregates, including energy and importation costs, are becoming prohibitively expensive, making it necessary to develop and use other locally available materials (Owolabi, 2012). To reduce construction costs, therefore, cheap yet durable building materials must be produced and used locally. In so doing, there is the possibility of a reduction in the amount of foreign exchange spent on importation and also a reduction to the damage caused to the environment through ecological imbalance. It is worth noting that so many traditional construction materials that exist in Nigeria have over the years proven suitable for a wide range of buildings. These materials are expected to see increased usage in the future, and one such material is the Compressed Stabilized Earth Block (Owolabi, 2012).

Compressed Stabilized Earth Block (CSEB) is a better version of moulded earth block, also known as adobe block, which is an old building material. It is not a new concept to compact earth and heighten the performance and quality of moulded blocks. Since its emergence, the technology with which Compressed Earth Block is produced and its use in construction keeps gaining ground which proves its technical and empirical value. Soil Stabilization, which is a method used to improve the strength of Compressed Earth Blocks is employed in many countries (Adam and Agib, 2001).

Soil Stabilization entails the upgrading or enhancing the engineering characteristics of soil with a view to making it more stable, firm and having the inability to give way. A connecting material or a chemical is added to a natural soil for the purpose of stabilizing it. The stabilization of soil is utilized to scale back the permeability and the capacity of the soil mass to be reduced in size by pressure in earth structures, and to grow its shear strength. It is needed to extend the bearing capability of foundation soils.

When a soil is successfully stabilised, the evident effects are:

i. An increase in soil strength and cohesion.
ii. A reduction in soil permeability.
iii. Water will be repelled from the soil.
iv. An increase in soil durability.
v. As a result of dry and wet conditions, the soil shrinks and expands less.

Since natural stabilizers such as animal dung, natural oils and plant extracts, and crushed anthills were used centuries ago, soil stabilization is not a new idea. There have also been advances in soil stabilization using scientific rather than adhoc methods, including alkalis, aluminium compounds, ammonium compounds, bitumen, gypsum, lime, calcium chloride, polymers, Portland cement, resins, silicates, sodium chloride, and agricultural and industrial wastes. A major stabilizer in developing countries like Nigeria, is Portland cement, because it is more readily obtained than lime and bitumen, hence the advent of Cement Stabilization in Compressed Earth Blocks (Adam and Agib, 2001).

It is estimated that cement production is growing by approximately 3% per year (Olowe, 2015). When limestone is de-carbonated in the kiln during cement manufacturing and fossil fuel is burned, about one tone of CO_2 is released into the atmosphere (Olowe, 2015). The atmospheric release of about 7% of all greenhouse gases are caused by Portland cement production worldwide (Malhorta, 2002). Materials such as cement are also among the most energy-intensive construction materials. The cost of Portland cement can be reduced, if an alternative cheap cement can be produced locally (Olutoge, 2012).

Compressed Cement-Stabilised Earth Blocks have been studied as partly replacing cement with mineral admixtures to reduce costs and greenhouse emissions. In scientific researches, a variety of materials have been recorded to be used to partially substitute cement. These include fly ash, palm kernel shell ash, rice husk ash, palm oil fibre ash, slag and silica fume. It has been found that the silica in these industrial and agricultural wastes reacts with calcium hydroxide which emanates as a result of cement hydration to form calcium silicate hydrates (Olutoge, 2012), which increases and improves the durability and mechanical properties of pozzolanic materials.

It has also been discovered through many early researches that Palm Kernel Shell Ash (PKSA) can be used as a material for construction. Palm Kernel Shell Ash is produced from the burning of palm oil husk fibres and shells in the boilers of palm oil mills in order to fuel their operations (Olowe and Adebayo, 2015). A high pozzolanic content with a strength activity index of 60% (Opeyemi *et al.,* 2017) has been found in PKSA. As a result, it can be used to replace some of the cement in compressed stabilised earth blocks and increase their durability and strength.

1.2 Aim and Objectives

The aim of this research is to study the performance of compressed earth blocks stabilised with cement and palm kernel shell ash compositions.

The specific objectives are to:

i. Determine the physical properties of the lateritic soil used in the study.

ii. Investigate the properties of palm kernel shell ash.

iii. Produce and test Compressed Stabilized Earth Blocks (CSEB).

iv. Evaluate the effect of varying palm kernel shell ash on the durability, mechanical and physical properties of compressed earth blocks.

v. Compare the performance of regular CSEBs and modified CSEBs when partial cement replacement materials are absent or present in the mix composition, respectively.

1.3 Justification of the Study

Compressed Stabilised Earth Blocks (CSEB) have been found to have a lot of potentials and advantages when used in construction. A lot of academic and technical researches, as well as professional courses have been developed on CSEBs based on scientific research, experimentation, and architectural achievements. Improvement on durability is now the major concern, and this study should help to validate the technique of soil stabilization. (Owolabi, 2012).

Also, the use of CSEB has been found to have a myriad of advantages. There is a large supply of soil available in most regions and it can be obtained for a low price. The production of CSEB requires little specialized equipment to operate. This means that it is usually easy to produce. Most parts of the building can be constructed from this material. It has also been found to be non-combustible (Owolabi, 2012). The deployment of CSEB also provides an advantageous response to climate in most areas because of its temperature regulation capability, porosity and low thermal conductivity, which allows it to minimize the effect of harsh outdoor temperatures while maintaining a satisfactory balance in the temperature inside the building (Owolabi, 2012). The soil used for its production is processed and handled with low energy input and the use of this resource (which is unlimited) in its natural state is non-polluting and requires minimal energy, thereby saving the environment from pollution or ecological imbalance (Riza *et al.,* 2010).

Another advantage of using CSEB is its technical performance. When soil is compacted with a press, it is improved in terms of its strength. Its higher density increases both its compressive strength and also its rate of resistance to the effects of erosion and damage by water (Riza *et al.,* 2010). Compressed Stabilised Earth Blocks can meet a wide range of needs in both rural and urban environments due to the flexibility in its usage (Riza *et al.,* 2010). The scale of production can range from small to medium and then large, be it semi-industrial or industrial.

Another advantage is having a relief from importation. The CSEB is locally produced and meets the same obligations of modern-day construction materials as well as offering a substitute to imported building materials, which is socially accepted because of standardized requirements (Riza *et al.,* 2010). From luxury homes and prestigious public buildings to social housing, CSEB has a wide range of use.

CHAPTER TWO
LITERATURE REVIEW

2.1 Soil as a Construction Material

Building construction uses soils whose properties can be altered by adding various stabilizers to boost performance. There is a sufficient amount of current compressed soil block literature available which discusses the fundamentals of soil properties and behaviour. Soil consists of particles that have mineral and organic origin, separated mechanically, and including varying quantities of air as well as water, according to BS 1377 (1990). Soil is usually composed of minerals but can also contain organic compositions. As a result of climatic factors as well as other physico-chemical and biological processes, soil is the loose material that is formed as a result of the overtime effect of evolving changes of the parent rock (Craig, 1998; Das, 2000; Houben and Guillaud, 2008). It is important to note that soil within countries, and within regions within the same country, remains a highly variable material. In addition to being able to control the properties of soil such as plasticity, particle or grain size distribution, moisture content, bulk density and so forth, artificial laboratory blended soil has proven to be advantageous. It may be possible to keep these soil properties consistent across all block samples. The properties of soil and the blocks manufactured from it would be affected by any changes in soil properties. It is thus easier to determine how other production variables affect the performance of a block when the soil type remains constant. Moreover, it might be possible to attribute variations in block performance to the method of investigation rather than changes in soil composition (Houben and Guillaud, 2008).

2.2 Soil Composition and Classification

Disintegrated rock, soluble mineral salts and decomposed organic matter, make up all soils. According to the classification system in Table 2.1, soil types are classified according to their particle size distribution based on soil fractions. The various fractions of the soil shown are gravel, sand, silt, and clay.

Table 2.1: Soil Fraction Classification

Name of Fraction		Diameter size ranges of particles (mm)
Gravel	Coarse Gravel	20.00 – 60.00
	Medium Gravel	6.00 – 20.00
	Fine Gravel	2.00 – 6.00
Sand	Coarse Sand	0.60 – 2.00
	Medium Sand	0.20 – 0.60
	Fine Sand	0.06 – 0.20
Silt	Coarse Silt	0.02 – 0.06
	Medium Silt	0.006 – 0.02
	Fine Silt	0.002 – 0.006
Clay	Clay	Less than 0.002

(Source: Craig, 1998)

2.2.1 Gravel

A soil's structure formed by the larger granular particles (coarse aggregates) is known as gravels. In accordance with BS 1377 Part 2: 1990, their sizes range from 2 mm to 20 mm. They are formed when parent rocks and pebbles dissolve directly into a soil, leaving it with no cohesivity (Houben and Guillaud, 2008). In addition to their rough texture, gravel comes in a wide range of shapes, which includes but are not limited to rounded shapes, angular shapes, irregular shapes, and so on (BS 1377 Part 2: 1990). As they are loosely packed and stable, they limit shrinkage and capillarity in soil, which is important for CSB production. Rigassi (1995) recommended avoiding using gravel levels above 10% in CSB production because the presence of excess gravel can create voids and weak points within the blocks making them prone to cracking, deformation, or even failure under load. In CSB production, there is no standard for the maximum size fraction of gravel. In some literature sources, a range of 15 - 20 mm was recommended (Houben and Guillaud, 2008), whereas in some other sources, 6 mm is recommended to enhance workability and cohesiveness in the soil mix (Hall *et al.*, 2012).

2.2.2 Sand

According to BS 1377 Part 2: 1990, the ranges of the size of particles of sand in any soil vary from 0.06 to 2 mm**.** As sandstones and crystalline rocks disintegrate, granular grains of quartz and silica are formed. There is no cohesion in sandy soils and they have a gritty texture and are non-sticky. Furthermore, they are very frictional and do not shrink when they are heated. These properties make them essential for providing soil with mechanical strength. As a result, they limit swelling and shrinkage in soils simultaneously. A sand's specific bulk density is estimated to range between 2500 and 3000 kg/m^3 (Houben and Guillaud, 2008), while its specific surface area and specific heat are estimated to be 23 cm^2/g and 800 J/kgK, respectively. It is recommended that between 70 and 85% of sand be present in a soil mix when producing compressed stabilised blocks (Hall *et al.*, 2012).

2.2.3 Silt

According to BS 1377 Part 2: 1990 silt are particles between 0.002 and 0.06 mm in size. Other than their size, silts and sand have almost identical properties. In contrast to sand, they have significantly less internal friction. Caterpillar (2006); Houben and Guillaud (2008) reported that they have specific surface areas around 454 cm^2/g as well as densities which range from 1600 and 1800 kg/m^3. The texture of these products is smooth, they have a sticky consistency, and they are lightly cohesive but they do not display a significant shrinkage capacity. Compressed Soil Block production should not be done with gravels, sands, and silts alone without the inclusion of clay due to their lack of cohesion. Studies have found that 12-20% silt fractions should be present in soils in order to produce compressed stabilised blocks due to the fact that they enhance the plasticity of the soil mix (Hall *et al.,* 2012).

2.2.4 Clay

The particles of clay are the tiniest fragment of soils having a size that is less than 2 µm (Scot, 1963). They differ from the other three soil fractions in terms of their physical and chemical characteristics. Clay has approximately 800 m^2/g of specific surface area, whereas its specific heat has been found to be approximately 965 J/kgK (Houben and Guillaud, 2008). According to BS 1377 Part 1: 1990 clays are cohesive because they are fine grained and will result in a cohesive mass when wetted with sufficient moisture (Vickers, 1983). Clays play a vital role in contributing to some of the important engineering properties of CSBs. Often hexagonal in shape, these hydrate alumino-silicates have irregular shapes. There are a number of sheets of silica and alumina that are not electrically neutral, making up large clay molecules (Van, 1977). Based on the type of clay, sheets have varying chemical compositions. Houben and Guillaud (2008), Hall *et al.,* (2012) described three types of clay as kaolinite, iolites and montmorillonite. Within these three major types, clay is divided into about 20 subgroups (Scot, 1963). Clay is important for soil stabilization because it provides cohesion within soils.

Compressed stabilized earth blocks need to be made from the quality soil containing sand and fine gravel, along with clay and silt in order to gel the sand particles to each other. It was recommended to add a form of stabilizer to reduce the rate of linear expansion that occurs once water is added to soil (Adam and Agib, 2001). There are some soils that are not suitable for earth construction, and especially for CSEB. The manufacture of CSEB can, however, be carried out using several soils based on available data and knowledge. The use of surface soils and organic soils is not recommended due to the fact that these soils are typically rich in organic matter and may contain high concentrations of organic material such as decaying plant matter, roots and organic debris, which can significantly affect the stability and structural integrity of the compressed earth blocks (Adam and Agib, 2001). When it comes to producing smart, quality goods, it is crucial to identify the soil's properties. There should be more sandy soil than clayey soil for compressed earth blocks, and its proportions should be as follows: 20% Clay, 15% Silt, 50% Sand and 15% Gravel (Houben and Guillaud, 2008).

There are three main components of soil namely: disintegrated rocks, water soluble mineral salts and, decomposed organic matter. The descriptions provide evidence of soil's variability and complexity. It is not all soils that can be stabilized despite their ability to be modified to improve their performance (Caterpillar, 2006). Identification of the main soil constituents likely to influence the soil's properties and behaviour is essential to the decision on suitability (Caterpillar, 2006).

2.3 Criteria for Selection of Soil for Block Production

It is important to note that the requirements for suitability are varied, and they are set forth in CSB literature in a variety of ways. The particle size distribution of a soil, its plasticity, and its compressibility should be favourable for stabilization. A soil has to meet the following criteria to be considered suitable:

i. It must be continuously graded or densely graded. Neither gap grading nor uniform grading should be used. Hall *et al.*, (2012) recommended that soil particles should be smaller than 6 mm in diameter. The poor bonding of particle sizes larger than this may make it easy for them to come loose from the block fabric. Adding gravel and sand to the block gives it a skeletal structure that bears loads on top of it, but it also provides the block with its skeletal structure. Clay and silt proportions in a soil should be sufficient in order to maintain sufficient cohesion and for easy demoulding and transporting of blocks at the time of wet curing.

Furthermore, the clay type present within a soil should be determined because shrinkage and swelling do not occur equally in all clays. The future performance of a block may be disrupted by the clay property. A predominantly sandy soil is usually the best substrate to use as the stabilizer when using OPC. For best results, lime is best used with clayey soils. Nevertheless, if the grading of the fractions of a soil is poor before stabilization, it can still be improved. Soil fractions present in inadequate quantity can either be added or subtracted. Normally, the coarse fraction of the soil is removed by sieving, whereas the fines from the coarse fraction are removed by washing.

ii. Due to its low plasticity index, it has the ability to exhibit very low cohesion. It is not possible to detect an appreciable plastic limit in sandy soils with little clay content (less than 10% clay). It is again the clay content that makes a difference and Houben and Guillaud (2008) found that soils with a high plasticity have liquid limits above 50%. This may result in clay content exceeding 40% in such cases. By altering the particle size distribution of a soil, the plasticity index can be changed. Addition of sand lowers the plasticity index, while addition of clay raises it (Rigassi, 1995). In order to mould and handle soils effectively, adequate plasticity is vital because it enhances the ability of the soil mix to stay in close cohesion.

iii. For maximum dry density to be achieved, the material must be compacted at its optimal moisture content (Guillaud *et al*, 1995). Also, each value of a soil's porosity is considered low when it has reached its peak dry density which causes the strength of the material to increase in shear and compression under load. There are several factors that contribute to the reduction in porosity of a soil at maximum dry density (Hall *et al.*, 2012). Every soil's gradation, optimum moisture content, and amount of compaction energy will influence the reduction in porosity.

iv. Soil should contain no organic matter or soluble salts. In addition to affecting OPC during hydration, impurities can also affect the stability of blocks after hardening. Houben and Guillaud (2008) indicate that organic matter above about 1% is a potential hazard. As a result of the presence of nucleic acids, tartaric acid, and sometimes glucose, organic matter is harmful. They can weaken the hardened cement paste by interfering with the proper setting of the OPC (Neville, 1995). The reaction between soluble salts and sulphates in soil and hardened cement can form expanded products in blocks. Soils with over 3% of soluble salts and sulphates should not be used to make CSB (Rigassi, 1996).

2.4 Soil Tests

Block production should not begin without soil tests. A substantial amount of time and money could be wasted if the testing is not done at the beginning. In manufacturing compressed stabilised earth blocks on a large scale, laboratory analysis of the material is often required. To determine the appropriateness of a soil for production in small quantities, however, it is not important to use subtle tests. A soil sample is sometimes tested in the field to get an idea of its composition. Tests like these include:

2.4.1 Smell test

While conducting this test, a musty smell indicates organic matter is present. When the soil is heated or wet, the smell becomes more potent. The production of compressed stabilised earth blocks requires soils that do not contain organic matter due to the fact that organic matter in the soil can decompose over time, leading to settling, changes in volume and instability of blocks (Houben and Guillaud, 2008).

2.4.2 Nibble test

Putting samples in the mouth should only be done under strict supervision. Snibble a tiny amount of soil gently between the teeth. Sandy soil grinds between the teeth, having an unpleasant sensation. Silty soil can be ground between the teeth without giving an unpleasant sensation. Houben and Guillaud (2008) state that clayey soil has a floury or smooth texture, sticking to the tongue when a small amount is licked.

2.4.3 Touch test

Rub the soil in-between the palm of the hand and fingers to remove the largest grains and crumble the soil. In wet conditions, sand has no cohesive properties and feels rough. Silty soil has a slight rough texture and a moderate degree of cohesiveness when moistened. Houben and Guillaud (2008) determined clayey soil as being one that contains lumps or concretions that are resistant to crushing when dry and becomes plastic and sticky when damp.

2.4.4 Sedimentation/Composition test

Tests such as those mentioned earlier can provide an indication of the consistency or feel of the soil and, therefore, the particle sizes among the various fractions. Field sedimentation tests can provide a better understanding of soil fractions. To perform the test, a transparent cylindrical glass bottle, of about a litre in capacity, with a neck circumference large enough to insert a hand into and also a lid that can be shaken, is needed. Approximately one-third of the bottle should be filled with clean water. To equal volumes of dry soil, add a teaspoon of common salt and a 6mm sieved layer of soil. Ensure that the water and soil are thoroughly mixed by closing the lid of the bottle and shaking. After the bottle has been left on a flat surface for at least 30 minutes, remove it from the surface. Continue shaking the glass bottle for about two minutes and standing on a flat surface for 45 minutes until the water clears. Consequently, finer particles will settle on top of the larger particles because they fall slower. A two- to three-layer structure will emerge, with fine gravel at the bottom, sand at the centre, and clay and silt at the top. A measured depth of each layer can determine the relative proportions, as well as the percentages, of each fraction (Houben and Guillaud, 2008). Figure 2.1 shows the sedimentation test described above.

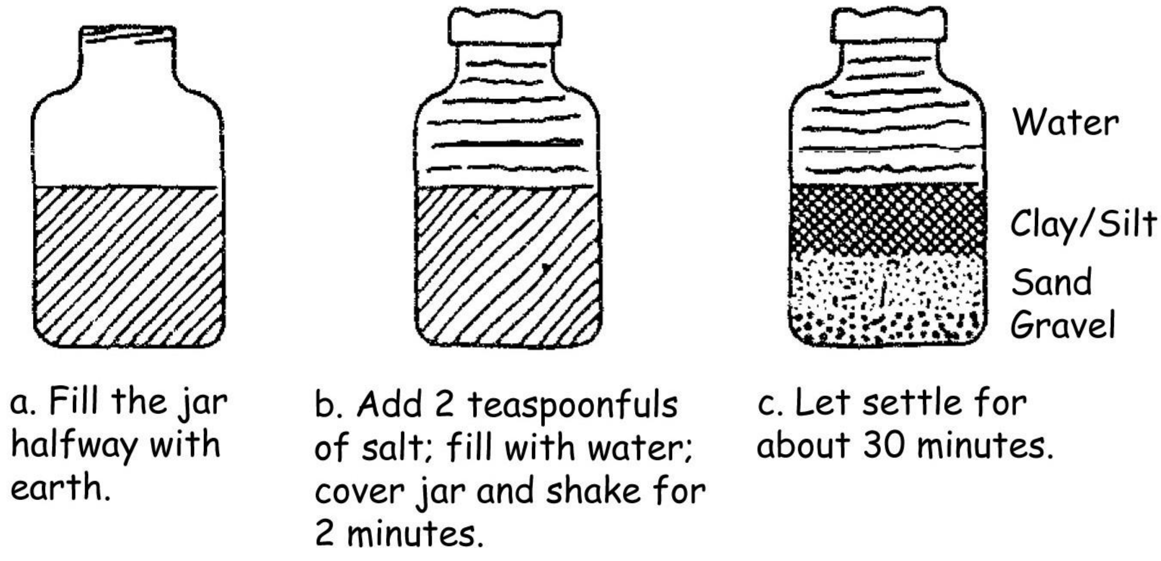

Fig. 2.1: Sedimentation Test

(Source: Houben and Guillaud, 2008)

2.4.5 Adhesion/Compaction test

The procedure suggests placing a spatula or knife in the middle of a ball of damp soil to prevent it from sticking to one's fingers. According to the guidelines, if the soil is highly clayey, the spatula cannot penetrate it without sticking, and soil adheres to it upon withdrawal. However, in the case of an averagely clayey soil, it is reported that the spatula can be easily inserted into the soil without any soil residue on the blade upon withdrawal. It has been demonstrated by Houben and Guillaud (2008) that soil contains only a small amount of clay when pushed into it without any resistance at all.

2.4.6 Washing test

In the procedure for conducting a washing test, it is recommended to moisten the hands slightly before applying a small amount of soil and rubbing it. If the soil has a sandy texture, rinsing the hands becomes effortless. On the other hand, when dealing with silt soil, the hands can be cleaned easily, and the sampled soil appears powdery in consistency. A clayey soil would not be easily rinsed and would have a soapy feeling (Houben and Guillaud, 2008).

2.4.7 Linear shrinkage mould test

A box of 4 cm wide, 60 cm long, and 4 cm deep is used for the linear shrink test, or Alcock's test. Spritz the internal surfaces of the box with oil, then fill it with moist soil having an optimum moisture content. Use a small wooden spatula to smooth out the surface of the box while compressing the soil into all corners. Allow the packed box to stay in the sun either for three days or under the shade for a total of seven days after it has been filled. Determine the shrinkage length of the soil by comparing the span of the dried, hardened soil to the box's length (Houben and Guillaud, 2008).

2.4.8 Dry strength test

Soft oil should be formed into two or three pats. Once the pats have completely dried in the sun or oven, remove them from the oven. To pulverize soil, break it and apply thumb and index finger pressure. Pulverize the pat and observe how easily it crumbles.

Implications: Typically, soils with low clay content and silty or fine sand will pulverize easily. It means that the soil is either silty or sandy clay, if it can be squeezed to powder form with a little effort. If it is difficult to break or cannot be pulverized, then the percentage of clay content in it is high. (Houben and Guillaud, 2008).

2.4.9 Water retention test

Water retention test is conducted by moulding a ball of soil with fine particles of diameter of 2 or 3 cm. it is recommended that the ball stays together without sticking to the fingers by moistening it. With the extended hand, spread the ball slightly flat, and hold the sample in the hands. Make sure all water content is brought to the surface by vigorously tapping the moulded ball with the other hand. A greasy, shiny and smooth appearance would be observed on the ball. Press down the ball, flattening it between index finger and the thumb. Check the soil consistency and the amount of the taps needed to get a reaction.

Implications: In the event that a fast reaction occurs (between 5 and 10 taps) making the ball to crumble, then the soil is extremely fine or at most, a rough silt. Those soils which do not crumble after 20-30 taps and do not flatten are plastic silts or silty clays. If there is no change in appearance after pressing for a very long time (more than 30 taps), the soil contains a high concentration of clay.

2.4.10 Consistency test

Make a ball of soil with some fine particles of about 3 cm diameter and set it aside. The ball should be moistened before modelling so that it will not stick to the fingers while being modelled. Form a thread by rolling a ball on a flat, clean surface. There is too much dry soil if the thread breaks over 3 mm thick, so add water. As soon as the thread reaches a thickness of about 3 mm, it should break. Make a small ball out of the thread when it breaks and flatten it between your index finger and thumb. Take note of the effects of crushing the ball.

Implications: It is highly silty or sandy if soil breaks apart before forming a ball. There is low clay content in a ball if it cracks and crumbles. An increased clay content is evident by the inability of the ball to crumble or crack. Balls containing organic matter will feel spongy. (Houben and Guillaud, 2008).

2.4.11 Cohesion test

Shape soil into a sausage that is approximately 12 mm in diameter. Rolling the soil into a continuous thread, 3 mm wide, would be ideal, as it does not need to adhere to the surface. Take the thread in your hand and place it in the palm. Create a ribbon of about 3 mm to 6 mm wide by flattening one end between index finger and thumb. Check how long the ribbon will last before it breaks.

Implications: When ribbons are not present, clay content is minimal. Ribbon with a diameter of about 5 cm to10 cm which indicates a very low clay content. A ribbon with a diameter of 25-30 cm contains a high percentage of clay.

2.5 Principles of Soil Stabilization

Essentially, stabilizing soil is a way to enhance the structural characteristics and properties of soil. In order to it more stable, this is done by adding a linking material or a chemical. The soil supplied for construction needs stabilization when it does not meet the expectations of the intended purpose. A wide range of processes are involved in stabilization, including compaction, pre-consolidation, drainage, among others.

Adding other stabilizers to soil will increase the innate strength as well as tensile strength of a soil, according to BS 1377 Part 2:1990. According to Rigassi, 1995 stabilizing soils is the process of transferring irreversible properties to them when they are subjected to physical strain. The stabilizing soil involves the adaptation of the properties of soil in a bid to achieve enduring properties that are suitable for various applications, according to (Houben and Guillaud, 2008).

It has been observed that silt and clay in soil samples expand when moist, and shrink when they dry out. It is possible for such expansion movements to cause a cracking on wall surfaces and subsequently speed up erosion, which then results in structural dysfunction. This expansion movement is one of the main reasons for the disintegration of surface coatings. As part of soil stabilization, changes in temperature, humidity and rainwater will cause soil to be more resistant to the impact of corrosive wind blowbacks. If specific stabilization techniques (i.e. compaction, stabilization using agents like cement, lime, etc.) are used correctly, the compressive strength of soils can be enhanced by 400 to 500% and the soil's resistance to erosion and mechanical degradation is increased. One or more of the following methods can be utilized to create excellent resistance to erosion: There should be an increase in soil density, stabilizing agents should react with, or bond with, soil grains and there should be a stabilizing agent that acts as a waterproofing material.

As a natural material, soil cannot be used for long-term construction in its natural state, so it requires stabilization. By so doing, the long-term capacity of the site can be increased by modifying the properties of the soil accordingly. An important part of soil stabilization is changing the interphase from soil to water to air. Interstitial voids should be reduced, bare voids should be filled, and soil grains' bonding should be enhanced. The result is an improvement in mechanical properties, a reduced permeability, a limited amount of dimensional changes, and improved resistance to typical conditions and harsh exposures. A literature review (Riza, 2010) reveals that stabilizers are quite prevalent and considered a very successful way to improve soil strength when it comes to solving soil-instability problems or enhancing the durability and strength properties of compressed earth blocks (Riza, 2010).

Although researches regarding stabilizing agents is sparse, the most common ones include cement, bitumen, gypsum and lime (mineral products), manufactured products, animal products and natural fibres or plant fibres. In choosing a stabilizer, soil quality and project requirements must be considered. Sandy soil can be strengthened quickly with cement, making it an ideal material for sandy soils. A clayey soil is better suited to lime. The only disadvantage to this material is that it takes longer to harden.

Clay proportions (materials smaller than 0.002 mm) in unstabilised CEB cause the soil to expand with the addition of water and shrink with drying (Hall *et al.,* 2012). Thus, it multiplies the potential for cracking and results in problems adhering renderings to the walls, eventually leading to disintegration (Hall *et al.,* 2012). By stabilizing soil, the intention is to increase its resistance to weathering as well as increased strength and rigidity, thereby facilitating blocks to carry greater loads (Adam, 2001). As a result of the bylaws and housing standards that are in place in African countries, the stabilised or enhanced form of soil is more acceptable for the African context (Zami and Lee, 2011).

Houben and Guillaud (2008) explained that stabilizing soil involves altering its soil-water-air system properties so that they will be compatible with a specific application for the long term; stabilization is nevertheless an intricate issue, as a great deal of factors have to be considered. Compressed Stabilised Earth Blocks use a wide range of binders such as emulsions, lime, asphalt, fly ash, and others, but Portland cement appears to be the strongest of the binder materials.

Based on their interaction with clay plates, various clusters of stabilizers can be classified. While there are different types of stabilization, it is important to note that none of them are exclusive; the strongest earth block is a result of a combination of different methods of stabilization.

2.6 Compressed Stabilised Earth Blocks (CSEB)

Compressed earth blocks (CEBs) consist of small brick elements with regular verified characteristics, which are derived from the compaction of soil in a mould in a wet state which is followed immediately by demoulding (Riza, 2010). The proportion of clay within the soil contributes to the cohesion of compressed earth blocks. Furthermore, Compressed Stabilised Earth Blocks (also known as CSEBs) are CEBs which are improved or enhanced by the addition of additives. CEB is sensitive to water, and additives are meant to neutralize the effect (Rigassi, 1995). In addition to modifying colour and shrinkage cracks, additives may also modify other characteristics. Alternatively, compressed stabilised earth blocks may also be called stabilized soil blocks (SSBs), Stabiblocs, Terracretes, Soilcretes, or Pressed Soil Blocks (PSBs) (Rigassi, 1995).

Modern compressed earth blocks are the improved version of moulded soil blocks, also known as adobe blocks. The earliest compressed earth blocks were made with wooden tamps, which enhanced the overall quality of moulded earth blocks. The concept of compressing the soil to improve strength is not new, however. There is no doubt that the first machines for pressing earth appeared during the eighteenth century (Riza, 2010).The precision tool was designed by Francois Cointeraux, a fervent advocate of rammed earth (new tread). The first mechanical presses, which used heavy lids, were not invented until the early twentieth century. These types of presses can even be motorized. Static compression presses were used in the brick manufacturing industry to compress the earth between two plates. However, in 1952, the widely known CINVA-RAM press was designed by an engineer known as Raul Ramirez, in Bogota, ClNVA centre, Columbia and a significant change occurred in the use of compactors and compressing earth blocks for building, aesthetics, and architectural design. As a result, it became widely used around the world (Riza, 2010).

As a result of the discovery of motor-driven, mechanical, and manual compactors in the 1970s and 1980s, the compressed earth block industry became a genuine market. In terms of building materials, earth is without a doubt the oldest. As modern building methods and materials were being developed, earth-based construction became unpopular until the energy crisis prompted its revival (Riza, 2010). Soil has also become more popular as a building material globally due to growing concerns about environmental issues. A number of benefits were associated with CSEB as compared with other building materials. Due to its in situ production, it allows local material to be used and reduces transportation costs, making quality housing more accessible to more people, and generating local economic activity instead of importing materials (Riza, 2010). As a result of faster and easier construction techniques, fewer skilled labourers and less proficient labour are needed, the materials are stronger, more insulated, and more thermally efficient, the production phase has less carbon emissions and embodied energy, the waste level is low and easily disposed of, and the product causes no direct environmental pollution.

Most developing countries use earth as a primary method for building houses, as it is the oldest and most common method. Due to its accessibility, it is the most widely used and the material is readily available and low in cost. This material is workable and does not depend on a great depth of skills, so it is an effective means of facilitating the participation of unskilled individuals and groups in the construction of houses on an independent basis (Arumala, 2007). Its high heat insulation and thermal value, it offers excellent fire resistance offering a high degree of thermal comfort. Moreover, it emphasizes alternative and important solutions, which have a strong bearing on the development of good house plans, house designs, and construction. Buildings have been constructed using soil for centuries using three traditional methods:

1. Adobe block: a combination of straw, sun-dried soil and sometimes some rice pods used to enhance the strength of blocks;

2. The wattle and daub: a construction produced from woven timber, bamboo or reeds, as well as soil.

3. An earth mixture with stabilizers is called compressed earth. It is a mixture of soil and stabilizers that has been compressed under high pressure. Based on its physical characteristics, laboratory properties of soil has shown that it is heavy and weak. Although it cannot yield high compressive strength by itself, an attempt can be made to stabilize it to achieve high performance and strength.

There are durability problems associated with earthen houses. There have been several possible solutions suggested by past researchers as to how to make earth raw material stronger and more durable, even under less arid conditions:

i. Improve soil properties by using stabilizers.

ii. Designing earth buildings in an appropriate manner, i.e. using suitable architecture.

iii. Enhancing the structure with bonding mortar.

iv. The building surface is plastered and rendered.

A compressed earth block or housing wall can be protected from external attack by rendering, paint or plaster, but these materials are expensive, making them inappropriate for a CEB or housing wall. Furthermore, the expansion rates between renders/plasters mortars and soil blocks differ, resulting in peeling. In addition to factors such as cost and skills, appropriate architecture is impeded (Montgomery, 2002).

2.7 Advantages of Compressed Stabilised Earth Blocks

i. A local material: Manufacturers prefer making their products on-site or nearby. This will result in a reduction in transportation costs, fuel costs, time and money.

ii. It is possible to build a house made with CSEB materials that can withstand harsh weather conditions without it being destroyed, as long as it is designed and built properly. It has proven to be durable and strong for more than half a century.

iii. Limiting deforestation: The production of CSEB does not require the use of firewood. A short-sighted approach and mismanagement of resources will stop forest depletion around the world.

iv. An adapted material: The fact that it is manufactured locally makes it easy to adjust to a variety of needs, whether they be technical or aesthetic, cultural and social.

v. A transferable technology: Its technology is easy to learn and requires semi-skills. Within a few weeks, even a simple labourer will be able to do it. The technology will be transferred in a week by an efficient training centre.

vi. A job creation opportunity: The CSEB provides employment opportunities to less skilled and unemployed people while allowing them to discover a talent and rise within the social structure.

vii. Market opportunity: In most cases, it will be cheaper than firing bricks, but the cost will vary based on the local context (for example, equipment, labour, materials, labour, etc.).

viii. Reducing imports: Because CSEB is manufactured locally by less skilled workers, no expensive and possibly heavy building materials need to be imported or transported over long distances.

ix. Flexible production scale: From local to semi-industrial scale, CSEB tools range from manual to motorized. As long as the appropriate equipment is used for each case, using it will become quite easy.

x. Energy efficiency and eco friendliness: As with fired bricks, there is a reduction in the rate of energy use of a m^3 of this product by up to 15 times, than one m^3 of stabilizer. Furthermore, this will cause pollution emissions to be reduced by 2.4 - 7.8 times when compared with fired bricks.

xi. Cost efficiency: Due to its local production, its natural resource, and the fact that it requires little or no transport, CSEB is certainly a cost-effective product, depending on the context and the knowledge of the individual.

xii. Social acceptance: In addition to being able to adjust itself to a wide range of needs, CSEB has shown itself to be adaptable to a wide range of income levels and government levels. Various products can be made from it thanks to its strength characteristics, regular shape, and style.

2.8 Limitations of Compressed Stabilised Earth Blocks

i. Identification of soils must be done properly.
ii. Resource management is not understood.
iii. A lack of knowledge of the fundamentals of manufacturing and using.
iv. In terms of height, length, and width, there are limitations to the kinds of buildings that can be built with CSEB.
v. Contrary to concrete, this material has low industrial performance.
vi. Product quality is poor due to untrained personnel.
vii. Excessive stabilization caused by panic or ignorance.
viii. Under-stabilized products result in low quality.
ix. Unsuitable production equipment or low quality.
x. Social disapproval due to amateurish people or bad equipment or soil.

2.9 Soil Stabilization Techniques

2.9.1 Chemical Stabilization

Soil is modified by adding other materials or chemicals, by virtue of a physical/chemical interaction between the fragments and the additional materials, or by generation of a matrix that secure or coats the grains. The reaction between clay and lime can produce a pozzolana, which is a new material created by a physico-chemical reaction.

2.9.2 Mechanical Stabilization

The soil is compacted by tamping or weighing down with a heavy weight, resulting in an increase in the soil's thickness as the volume of the voids decreases. In addition to increasing the soil's strength, compressing the soil also decreases its permeability. There are a number of considerations that impact the extent of compaction possible, however, including soil type, moisture during compaction, and compression effort.

Sand and clay should be mixed correctly in a soil for best results. Using vibrating rollers and tampers to compact soil has become a common practice for road and embankment construction. Construction of one-storey buildings can also be accomplished using tampers and block-making presses. In places with moderate to high rainfall, mechanically compressed stabilized earth blocks are less durable than solid earth blocks. Foot treading or hand tamping are manual compaction methods, with compacting pressures ranging from 0.05 to approximately 4 MPa. Compressive pressures of several thousand MPa may be achieved with mechanical equipment.

The term granular stabilization can also be used to describe mechanical stabilization. There are two types of soils for mechanical stabilization:

i. **Aggregates**: consist of soils with granular skeletons and particles larger than 75 μm.
ii. **Binders:** soils containing a size of 75 μm or smaller. They do not process a bearing skeleton.

Angular sand and gravel particles are incorporated into aggregates to supply soil with friction and incompressibility. In addition to providing immunity, the binders maintain soil cohesion. Clay and silt make up these materials. It is important to apply enough binder to aid the plasticity of the soil, and in the process, not cause swelling. To ensure that the mixed soil has the proper gradation, aggregates and binders are blended precisely. Internal friction and cohesion are both necessary for a blended soil. As well as being workable, the material needs to be able to be placed easily. Mechanical security is achieved when the blended material is positioned and compacted properly. It gains more load-carrying capacity and improves its resistance against temperature and moisture variations when this is achieved. In order for mixed soils to have mechanical strength stability, the following must be considered:

i. The aggregate's mechanical strength
ii. A description of mineral composition

iii. Level of Gradation
iv. Differentiation based on plasticity
v. The compacting process

In terms of soil stabilization, this method is considered to be the simplest. Subgrades with low bearing capability are usually improved with it. A substantial amount is used in constructing the base of roads, the sub-bases of roads as well as the surfacing. Soil stabilization techniques refer to a range of methods used to improve the engineering properties of soil, making it more suitable for construction and other applications.

2.9.3 Physical Stabilization

It is possible to alter the characteristics of a soil by modifying its appearance. An instance would be to regulate the mixing of various fractions. There are more procedures that can be performed to enhance the drainage characteristics of a soil and give it fresh engineering characteristics, including drying and freezing, heat treatment, electrical conduct, and electrical osmosis.

2.10 Soil Stabilizing Agents

A total of 130 stabilizing agents were identified including cement, lime and bitumen, however no perfect or ideal stabilizer was discovered that could be applied arbitrarily (Houben and Guillaud, 2008).

2.10.1 Cement Stabilization

Cement is a substance with binding properties, useful for putting in place, solidifying, and making different materials adhere to one another. Mortar, a component in masonry, and concrete is created by mixing cement with aggregate for a stronger binding material. Cement is used in a variety of forms and classes. The reaction between Ordinary Portland Cement and water produces an ordinary cement-shaped gel, which is devoid of soil. The gel is composed of hydrated lime, calcium aluminate hydrates and calcium silicate hydrates. Cementitious gel is composed of the first two compounds, while lime is deposited in crystalline solid form. An insoluble binder is deposited between soil particles during the cementation process, in the form of cementitious gel, which ingrains soil elements. A specific cement type, temperature, and time determine the saturation of gel during soil hydration. In the process of hydrating, lime is released and cementitious bonds are formed due to further reaction between the clay and cement fraction. In order to prevent breakdown of the newly formed gel, soil-cement mixes should be packed down or compacted as soon as they are mixed, in order to prevent a reduction in strength. In addition to making soil more water-resistant, cementation also boosts its compressive strength and reduces swelling. Table 2.2 shows other various stabilisation techniques in the production of compressed stabilised earth blocks.

Table 2.2: Soil Stabilization Methods

STABILIZATION METHODS					
Stabilizer		**Nature**	**Process**	**Means**	**Principle**
Without Stabilizer			Mechanical and Hydraulic	Compaction, synthetic reinforcement, soil nailing, embankment piling, displacement	Creation of a dense material, blocking pores and capillarity
With Stabilizer	Inert Stabilizer	Minerals			
		Fibers	Physical	Reinforcing	Creation of isotropic matrix, opposing any movement
				Cementation	Formation of an inert matrix, opposing any movement
	Physico-Chemical Stabilizer	Bonding and Water Repellent	Chemical (deep, medium or surface soil layer mixing with chemical reactions)		Formation of stable chemical bonds between clay crystals
				Water Proofing	Coating of soil particles with an impermeable film and filling pores and ducts
				Water Repelling	Maximum elimination of water absorption and adsorption
			Electric and Thermal	Electrokinetic vitrification, heating	Complete changes in soil physical properties

(Source: (Vincevica-Gaile *et al*., 2021)

Several dynamics are involved in the overall procedures of cementation, saturation, as well as binding discussed in the previous paragraph. There may also be differences in procedures primarily based on which type of soil is being considered. Granular soils are stabilized effectively with cement, but clay soils cannot. Generally, the application of cement is suitable for any type of soil except clay, which requires more cement to be effective. A good stabilization can be achieved by varying the cement content between 3% and 18% by the weight, as with the soil type used (Adam and Agib, 2001).
Ordinary Portland cement used in most construction projects moistens upon addition of water. Also, a cementitious clot is formed as a result of this reaction, which is not dependent on the soil (Adam and Agib, 2001). By cementing the block, particles of soil are inside the cementitious clot, thus serving as a layer or coating around the particles of the soil (Adam and Agib, 2001). As soon as the soil-cement mix is finished, it needs to be compressed to preserve the stability and bond of the newly created gel. CSEB's are stoked by cementation because it provides the soil with water resistance and supports the structure's compressive strength (Montgomery, 1998).

Adam and Agib (2001) state that cement is suitable for any soil type; however, it may not be wise to mix cement and clay (cohesive soil) since clay demands a larger quantity than would normally be needed. Likewise, Hall and Allinson (2008) claim that many particles in clay-like soils are smoother than cement grains and cannot be coated by cement. A better coating of clay particles requires more cement to overcome this problem.

In OPC, the constituent materials (soil particles) are strongly combined and built into a thick, resilient unit that remains dimensionally stable and resilient. Other binders used today include pozzolans, lime, bitumen, resins, and gypsum (Luigi *et al*, 2018; Stulz and Minke, 2009). Two unique features have made Ordinary Portland Cement (OPC) an excellent choice; firstly, it has a better binding capacity. As a second advantage, most countries across the globe have access to it.

Its uniqueness is its capacity to gather tremendous strength in a short amount of time (basically about 28 days), which sets it apart from other binders. In comparison to similar unstabilised blocks fashioned in a similar way, OPC stabilized blocks have been found to remain stable along the lines of its edges even in the presence of water. Increasing OPC greatly reduces uninhibited swelling and shrinkage.

The differences in OPC quantity and value for stabilized blocks can have a profound effect on their properties and actions (Gooding, 1994). As it stands, CSB literature currently covers OPC in a way that leaves much to be desired. Minke, G. 2009 describes the extent to which coverage is inadequate, sparse and habitual such that widespread and error-prone use of the binder has replaced its proper use.

In cement chemistry, phenomena with grave importance like the necessity for ample quantities of water to guarantee absolute moisture, and precise settings to see to it that moisture remains in the sample to help complete of the action of hydration, are quite overlooked because of pitiable coverage.

2.10.1.1 Properties of OPC

Essential properties of cement to look out for are: an estimate of the surface area as well as an analysis of particle or grain size distributions.

The particle size distributions and specific surface area of cement are essential to CSEB production, this is due to the fact that they oversee the approach and way in which the binder stabilizes soils. Binder manufacturers directly influence these physical properties. Based on Rajasekaran's 2005 paper, OPC is a mixture of 75 percent limestone ($CaCO_2$) and 25 percent clay.Mixing and grinding are done thoroughly. Modern OPC is created by heating a ground mixture to about 1450 – 1800 K in a kiln against a counter spread of hot air (Neville, 1995; Taylor, 1998). It is estimated that the resulting melts form clinker of dimensions between 5 and 10 mm. It takes about three to five percent gypsum to cool clinker (Taylor, 1998; Young, 1998) before it can be mixed with gypsum ($CaSO_4$). Introducing gypsum directs impulsive initial setting. Lastly, the powdery form of OPC is produced by finely grinding the mix. Following the grinding process, OPC particles can weigh up to 1.1×10^{12} per kilogram (Neville & Brookes, 1994). OPC's SSA and PSD are determined by its grinding process.

2.10.1.2 Chemical Components of OPC

An assessment of the major components of OPC and its contribution to the stabilization of CSBs has never been addressed in CSB literature. OPC is a mixture of reactive minerals that exist as solid solutions composed of more than one component (Weidemann *et al*., 1990; Taylor, 1998). These ingredients are expected to undergo complex reactions after being incorporated into soil particles after being added to water. Not only will each component react singly with water, they also have an impact on the style or way that the others (which includes raw soil minerals), react with one another. So, there is a lack in the knowledge of the precise process of stabilizing soil with cement and this is expected to be a subject of active and continuous research in future years. Table 2.3 shows the chemical components of cement and their shorthand denotation.

2.10.1.3 Properties of Cement

The major properties of cement which are of utmost importance to engineers include:

i. Rate of hardening
ii. Compressive strength
iii. Setting time
iv. Heat evolution

The setting process refers to the transformation of cement paste into a solid, but in a weak state, in the process of time while hardening is the process by which the weak set mortar or concrete gains strength. Table 2.4 shows the properties of different types of cement.

2.10.2 Lime Stabilization

A lime injection can produce four basic reactions, according to Adam and Agib (2001): pozzolanic reactions, agglomeration, cation exchange, carbonation, and flocculation. According to Adam and Agib, 2001), lime bonds with the minerals in clay forming cementitious compounds that brings about cohesiveness in soil particles through pozzolanic reactions (Adam and Agib, 2001). Lime can also, cut back the quantity of water that clay soaks up; consequently, causing a reduction in the sensitivity of soil to humidity and advance its reliability. It has the benefit of stabilizing clay soils, as well as being relatively easy to construct, which makes it an ideal stabilizer for small scale production (Adam and Agib, 2001). In kilns, limestone is burned to create lime. Production techniques and procedures determine the grade of lime produced. Principally, the various types of limes are:

i. Dolomitic lime ($CaO + MgO$)
ii. High calcium, quick lime (CaO)
iii. Normal, hydrated dolomitic lime [$Ca(OH)_2 + MgO$]
iv. Hydrated, high calcium lime [$Ca(OH)_2$]
v. Pressure, hydrated dolomitic lime [$Ca(OH)_2 + MgO_2$]

Table 2.3: Chemical shorthand for cement

Compound	Formula	Shorthand Form
Calcium oxide (lime)	CaO	C
Silicon dioxide (silica)	SiO_2	S
Aluminium oxide (alumina)	Al_2O_3	A
Iron oxide	Fe_2O_3	F
Water	H_2O	H
Sulfate	SO_3	S
Magnesium oxide	MgO	M
Potassium oxide	K_2O	K
Sulfur trioxide	SO_3	s

(Source: Mindes *et al*, 2002)

Table 2.4: Properties of different types of cement

Table	**Unit Ordinary**	**Rapid Blast Portland**	**Low Hardening**	**High Furnace**	**Heat**	**Alumina**
Tensile strength						
After 1 day	kg/cm	-	20	-	-	-
After 3 days	kg/cm	20	30	20		
After 7 days	kg/cm	25	-	25		
Compressive strength						
After 1 day	kg/cm	-	115	-	-	400
After 3 days	kg/cm	115	210	115	70	490
After 7 days	kg/cm	175	-	175	115	-
Setting time						
Initial	Minutes	30	30	30	60	120-360
Final	hours	10	10	10	10	8
Soundness	mm	10	10	10	10	10
Residue less than (I.S. sieve no 9)	%	10	5	10	-	8
Heat evolution in 7 days	Cal/gm	85	100	-	65	90

(Source: BS 5224, 1995)

In terms of stability, high calcium quick lime proves efficient than ordinary hydrated lime; however, hydrated lime is easier to manage and more secure. Lime that is hydrated or slaked is generally used. Increase in the magnesium content of the lime, causes a reduction in the affinity for water and also a reduction in the heat created during the process of mixing. Sandy soils do not respond well to lime stabilization. The soils can, however, be stabilised with the help of other pozzolanic materials, fly ash or clay, which react upon application of pressure.

2.10.3 Bituminous Stabilization

Bitumen is a non-liquid system of hydrocarbons which is easily dissolved in carbon disulphide. Bituminous tars are acquired by the disparaging decontamination of organic matters like coal. Also, asphalts are substances which have their chief components as refined or natural petroleum bitumen. The use of bitumen for stabilization is done making use of asphalt as a form of binder. Though asphalts are usually thick or too gelatinous to be applied directly, they are used as a form of restrain with the addition of some solvent like gasoline. They also serve as emulsions, though in this context, they need an extended time to dry.

Inorganic soils that can be blend well with asphalt is considered good enough and satisfactory for bituminous stabilization. In cohesion-less soils, the work of asphalt is to safeguard soil by capping the voids and even waterproofing it. Also, it assists the bonded soil to retain low humidity content as well as to accelerate the bearing capability.
The core drawbacks of using bitumen materials as stabilizers are:

i. They are regarded as an old building material in third world countries,
ii. Bitumen is costly to import,
iii. Production expenses to heat, mix and store are really expensive,
iv. Heat can affect their cohesive properties, especially in tropical areas.

2.10.3.1Types of soil-bitumen

There are four kinds of soil bitumen and they consist of:

1. **Soil-bitumen:** This is often a waterproof, unified soil type. The most effective results are acquired if the soil meets the criteria listed below:

a. 50% Passing No. 4 (4.76 mm) Sieve
b. 35% - 100% Passing No. 40 (0.435 mm) Sieve
c. 10% - 50% Passing No. 200 (0.074 mm) Sieve

d. Plastic limit of less than 18%
e. Liquid limit of less than 40%
f. The utmost size need not be larger than a third of the thickness of the compacted soil-bitumen. The measure of bitumen ranges from 4% to 7% of the dry weight.

2. **Sand-Bitumen:** This is a soil type without cohesion, stabilised with bitumen. The sand should be devoid of vegetative particles or chunks of clay. Also, the sand may need some sort of filler of about 25% less No. 200 sieve material, in order to achieve mechanical constancy for sand dune. Also, it should not exceed 12% for other different forms of sand.

3. **Water-Proofed Clay Concrete:** This is a soil with excellent gradation, waterproofed by a standardized allocation of about 1% - 3% bitumen.

4. **Oil Earth:** Here, a soil's surface containing clay/silt material is engineered to be waterproof by sprinkling bitumen two or three times. Average or slow curing bitumen or better still, emulsions, are applied. Bitumen here infiltrates a little deep into the soil. For this soil type, the amount of bitumen needed amounts to 5 litres per square meter of the entire surface of the soil.

2.10.4 Other Stabilizers

In the past stabilizers such as bird droppings, plant extracts, animal dung, animal blood and ant-hill materials, have been included in the manufacturing of compressed stabilised earth blocks, it is believed that the waste materials typically encompass nitrogenous organic compounds which facilitates the binding of soil grains (Adam and Agib, 2001).

2.11 Waste to Wealth Opportunity

From history, wastes from farming and manufacturing sources have produced waste management and contamination issues. Construction can however take advantage of the realistic and cost-effective benefits of agricultural and industrial wastes. As wastes are locally available and generally of no commercial value, transportation costs are low (Chandra and Berntsson, 2002). Low-cost construction can benefit from agricultural wastes over conventional materials (Abdul-Rhaman, 1997). Construction using waste materials contributes to the preservation of natural resources and environmental protection. (Ramezanalianpour, Mahdikhani and Ahmadibeni, 2009). The disposal and management of industrial and agricultural wastes has posed major challenges to efforts to preserve the environment, but their use protects supplies, protects the environment, and reduces construction costs. (Ramezanianpour *et al*, 2009), because it is possible to access waste materials at little or no cost while contributing significantly to the conservation of natural resources as well as the maintenance of ecological balance.

Due to the bountiful waste products in the world today, and their significant volume, there are environmental dangers and problems of disposal. Nigeria's "Waste to Wealth policy" allows waste materials to be treated and then used for enhancing or adding stability to soil with below standard geotechnical properties, particularly expansive soils. A lot of these were locally and traditionally available materials from industrial and agriculture wastes, for example, Palm Kernel Shell Ash (PKSA), maize cobs, Saw Dust Ash (SDA), coconut shell ash, rice husk, Locust beans ash, Cocoa Pod ash etc. Usually, they came from milling stations, thermal power plants, or waste management facilities. (Ikeagwuani, 2019, Bheel *et al*, 2021, Zaid *et al*, 2021).

Scientists have looked into the feasibility of utilizing agricultural wastes in building construction as well as civil engineering projects. (Bheel *et al*, 2021) examined the performance of concrete made with coconut shells compared to concrete made using palm kernel shells as alternatives for crude aggregates. He concluded that coconut shells had a better performance than palm kernel shells. According to Olutoge (2010), palm kernel shell and sawdust replacement of 25% decreased the asking price of producing concrete by 7.45%. The study evaluated the suitability of these materials to replace coarse and fine aggregate in reinforced concrete slabs. It has been reported that in volume batched concrete of 8% and weight batched concrete of 13% crushed granite can be replaced by palm kernel shells, according to (Osei *et al*, 2012). As long as the prerequisites are met (BS 8110-Part I: 1997).

Among the agro-waste generated in manufacturing palm oil is Palm Oil Fuel Ash (POFA), according to Rani *et al*, 2015. Palm fruit residues from oil palm trees are used to make it. Palm oil industry provides fresh fruit bunches as raw materials, but it creates a lot of waste materials such as empty fruit bunches, shells and fibres as a result of its processing. After the oil is withdrawn from palm fruit bunches, about 70% of the raw waste is generated. The waste is categorized into three types; fruit-kernel shells, fibre-husks, and gels. Kernel Shells and fibre husk waste are burned as fuel in palm oil mills to generate energy at temperatures between 450 and 6000 degrees Celsius. About 15% of solid wastes are produced after combustion as palm oil fuel ash and palm kernel shell ash. Based on the carbon content of the ash, the colour of the ash varies from light grey to dark grey shades after burning, but after pulverization the colour becomes uniform. There have been attempts to replace fine aggregate with palm-kernel shell ash, using palm-oil fuel ash as an admixture as palm-kernel shell ash has pozzolanic properties when mixed with cement.

2.12 Palm Kernel

In about 30 years, the production of oil palm has almost tripled worldwide, according to Muntohar *et al*., 2014. As of 2009-2010, the global palm oil production was expected to reach 45.1 million tons, with Malaysia and Indonesia producing 85% overall and each producing more than 18 million tons. A UN ESCAP report found Indonesia and Malaysia were the most responsible for South East Asian countries having large amounts of oil palm residues. In order to process the fresh fruit bunches for oil, liquid wastes and solid residues are generated from the processing, and these by-products include fibre, shell, and seepage. Consequently, there have been increasing problems with air, river, ocean, and groundwater pollution as a result of waste production.

The management and supervision of agriculture by-products are therefore necessary for sustainable development. For oil-palm manufacturing to avoid environmental pollution, the "zero waste policy" must apply to the by-products as well, i.e. empty fruit fibre can be used as fuel, and also, the ash can be used as fertilizer.

Over time, the waste from palm kernel shell (PKS) has been dumped near the mills because it has not been adequately managed. Previous studies found that PKS aggregates had an abrasion value of about 4.8%. When compared to traditional crushed stone aggregates, PKS aggregates had a much lower impact value and crushing value. Consequently, PKS is most likely to be used as a by-product in construction. From research, palm kernel shells have recently been used in the construction of the oil palm mill's access road, but no reports have been published concerning their performance.

A research by Olutoge (1995) explained that Palm Kernel Shells (PKS) are obtained by crushing or threshing palm fruit to extract the palm seeds as soon as palm kernel oil is extracted. Ondo State and Edo State both produce large amounts of palm kernel shells, and they are also available in average quantities in some other villages and towns in Nigeria, particularly in the South (Alagbon, 1994). Due to their hardness, PKS do not degrade easily once bound in concrete, so they do not sully or produce toxic materials

(Basri *et al.*, 1999). Also, PKS doesn't require the processing of artificial aggregates or industrial by-products before application or use, unlike some aggregates and industrial by-products that are artificially produced.

At the mill industry, Olutoge (1995) added that liquid wastes and solid residues are generated during the process of extracting the oil. As the endocarps of PKS are stony and hard, they serve as protective coverings for the palm kernels, which are generally diverse in size and shape. Natural and lightweight, they can be used to replace coarse aggregates in lightweight construction. They are hard and of organic origin, making them suitable for use in concrete production, and they rarely contaminate or leak to form damaging substances due to their matrix-like structure. Since permeability is low and carbonation is less likely with PKS than with aerated concrete, lightweight concrete is an advantage over aerated concrete. Based on Okafor's (2009) description of palm kernel shells, they have an uneven shape and form after cracking and cannot be defined. Cracks on a shell are typically shaped in various ways ranging from semi-circular to parabolic to uneven and flaking. While the overall shape of the shell is convex and concave, the edges of the shell are rough and spiky after cracking. It is estimated that shell thickness varies depending on which species it comes from, and is usually between 2 and 3 millimetres. Okafor (2009) suggests that there is no set thickness for shells; the thickness varies based on species.

Concrete has been made using PKS as aggregate in several studies. As a result of these studies, lightweight concrete (LWC) structures have undergone extensive changes. In addition to being defiant, the shell doesn't depreciate easily. A 24 hour submersion of the shell results in an increased water absorption capacity of 21% to 33%. Compared to gravel aggregates, PKS absorbs more water. If the material is mixed in an accurate mix design, the PKS can be used to expand concrete that has an average strength of 20 to 30 MPa. In contrast, little to no study has been done examine the application of PKS as bricks for masonry.

Over the years, sustainable housing development is commonly accomplished using clay mud in many developing countries. Most people with a medium or low income prefer this type of housing. It is a massive challenge to develop housing today due to the capital expenditures involved. Furthermore, when environmental factors are considered, it is confirmed that industrial waste is economically feasible in infrastructure development because standards and specifications applicable to these materials have been met. It is being attempted to find additional uses for the by-products instead of letting them rot away. The study of environmental-friendly material recycling and energy conservation has become increasingly important over the past few decades. In contrast, environmental directives are increasing the demand for eco-materials in construction. It is necessary to conduct continuous surveys in order to study whether the PKS could be used to manufacture masonry blocks. Sand-concrete blocks can be partially made with PKS in place of aggregate.

Wastes generated in the palm oil industry are often thrown away in the open, negatively affecting the environment without providing any profitable benefit. According to Alengaram, Mahmud, Jumaat & Shiraz (2010), PKS consists of particles with sizes that range from 0-5 mm, 5-10 mm, and 10-15 mm. In addition to generating disposal and waste management issues, the shells have no commercial value. It is not common for palm kernel shells to be used in construction in Ghana. Local blacksmiths burn them as fuel, and they can also be used as filler or palliatives.

As fractional representations of coarse aggregates in asphaltic concrete, palm kernel shell was investigated by Ndoke (2006). In producing of reinforced concrete slabs, Olutoge (2010) studied the impact of replacing fine and coarse aggregate with sawdust and palm kernel shells. By substituting sawdust and palm kernels for 25% of cement, he estimated a reduction of 7.45% in production costs. While producing lightweight concrete slabs, he suggested the possibility of replacing granite and sand with palm kernel shell and sawdust in partial compositions. The coconut shells were compared with palm kernel shells as replacements for coarse aggregates by Olanipekun *et al.* (2006), and coconut shells were found to be better than palm kernel shells in terms of substituting conventional aggregates. PKSA is a construction material with potential, according to Olowe and Adebayo (2015). By burning palm oil husk and shell, PKSA is converted into energy that is used in palm oil mills to get palm oil. The ash from palm kernel shell is found to contain high pozzolanic materials and can be used to partially substitute cement and enhance concrete's compressive strength and resilience.

2.12.1 Sources and uses of palm kernel shell

There are several types of palms, including Dura, Pisifere, and Tenera, and their shells, fibrous oily parts, and fruits differentiate them mainly by their thickness. The Dura species possess only a thin fibrous part and a very thick shell. The Pisifera variety typically lacks or has a very tiny shell, primarily producing little or no kernel due to its fibrous nature. The Tenera species is a blend of the dura and pisifera species. It has a medium thickness and a medium sized fibre part (Nwokolo, 1994).

Palm kernel shells are used for the following:

i. It is one of the most important fuel sources used for domestic cooking in most places.
ii. They are usually discarded as unwanted materials of the oil industry.
iii. Their shells are used by blacksmiths and goldsmiths to produce bellow for melting iron/gold.
iv. It is also possible to produce terrazzo out of palm kernel shells.
v. They are used in some regions to fill potholes in muddy areas.
vi. It is possible to make pre-stressed concrete from lightweight aggregate obtained from shells, which is useful for thermal insulation (Anthony, 2000).

2.12.2 Physical properties of palm kernel shell as aggregate

The properties of concrete produced with palm kernel shell (PKSC) is dependent on the properties of PKS. The ascertained physical properties put side by side with crushed normal weight granite aggregate (NWA) are density, size and thickness of the aggregate, surface texture, air, moisture, and water absorption. Table 2.5 shows the physical properties of PKS aggregate.

Table 2.5: Physical properties of PKS aggregate

Name of the author (year)	Specific Gravity	Loose Bulk Density (kg/m³)	Compacted bulk Density (kg/m³)	Moisture content (%)	Water absorption (%)	Porosity (%)
Abdullah (1984)	-	-	620	-	-	-
Okafor (2009)	1.37	512	589	-	27.3	
Okpala (1990)	1.14	545	595	-	21.3	37
Basri *et al.* (1999)	1.17	-	592	-	23.32	-
Mannan and Ganapathy (2002)	1.17	-	592	-	23.32	-
Teo *et al.* (2006)	1.17	500-600	-	-	33	-
Ndoke (2006)	1.62	-	740	9	14	28
Jumaat *et al.* (2008)	1.37	566	620	8-15	23.8	-
Mahmud et al. (2009)	1.27	-	620	-	24.5	(10-12)
Alengaram et al (2010)	1.27	-	620	-	25	-
Gunasekaran et al. (2011)	1.17	-	590	-	23.32	

(Source: Alengaram *et al.*, 2013).

2.12.2.1 Specific gravity

A material's specific gravity is calculated by dividing its density by that of water (Schetz and Fohs, 1999). PKS has a specific gravity between 1.17 and 1.62. According to Ndoke (2006), who attempted to stabilize soil using PKS, the maximum specific gravity was 1.62. According to Okpala (1990), the minimum specific gravity was 1.14, while in their studies, Teo *et al*. (2006), Mannan and Ganapathy (2001), and Basri *et al.* (1999) reported identical value of 1.17. For comparison, Mannan and Ganapathy reported 2.6 specific gravity NWA (2002). The specific gravity of some other artificial and natural lightweight aggregates, is 0.8–0.9 and 1.30–1.7, respectively (Hemmings *et al.*, 2009).

2.12.3 Shape, thickness and texture

Depending on the method used for extraction or the method used to break the nut, PKS aggregate has irregular or flaky shapes, or it can be circular, angular, or polygonal. PKS is available in a variety of thicknesses ranging from 0.15 to 8 mm depending on the kind of species. Convex and concave parts of the shell are generally smooth to some extent. Broken edges reveal rough, spiky attire (Basri *et al*., 1999).

2.12.4 Bulk density

It has been reported that the bulk densities of palm kernel shell aggregates vary from 500–600 kg/m^3 and 600–740 kg/m^3, in that order (Gunasekaran *et al*., 2011). There is also a correlation between bulk densities and sizes of palm kernel shell (Alengaram *et al.*, 2010). Because PKS has a low density, concrete made from PKS has a density varying from 1600 to 1900 kg/m^3 (Clarke, 1993). Table 2.6 shows the chemical composition of PKS aggregate.

2.12.5 Water absorption and moisture content

Since PKS is regarded as an organic aggregate, it is pore-rich and therefore absorbs a great deal of water. The water absorption of PKS is high, but pumice aggregate has an even higher rate of absorption of 37% (Hossain and Khandaker, 2004). Alengaram *et al.* (2010) showed that a variation in PKS sizes, leads to a variation in water absorption ranging from 8–15% for 1 hour and 21–25% for 24 hours, respectively. In general, NWA absorbs between 0.5 and 1% of water. Because PKS is more water absorbing than NWA, the mix design is also different from the usual mix design for LWC or NWC. As Gunasekaran *et al*. (2011) found, PKS aggregate absorbs water the same way coconut shell aggregate does which absorbs about 24%.

Table 2.6: Chemical composition of PKS aggregate

Elements	**Results (%)**
Ash	1.53
Nitrogen (as N)	0.41
Sulphur (as S)	0.000783
Calcium (as CaO)	0.0765
Magnesium (as MgO)	0.0352
Sodium (as Na_2O)	0.00156
Potassium (as K_2O)	0.00042
Aluminum (as Al_2O_3)	0.130
Iron (as Fe_2O_3)	0.0333
Silica (as SiO_2)	0.0146
Chloride (as Cl^-)	0.00072

(Source: Teo *et al.*, 2007).

2.13 Bulk Properties and Performance of CSEB

CSEB bulk properties are determined using the ratios of the components and the methods of processing used to manufacture blocks (moulding pressure, the curing conditions, etc.). This chapter has two objectives, one being to identify the main bulk properties that can influence block durability, the other being to experiment the performance of blocks produced with contradictory variables. (Stabilizer content and moulding pressure). According to Baker *et al* (1991); Rigassi, (1995); Hall *et al., (*2012) and Illston (1994), these bulk properties were known to likely have influenced durability of the blocks: Wet compressive strength (WCS) of the block samples, the block dry density (BDD) of the block samples and the total water absorption (TWA) of the samples. Each of these properties is being examined in relation to some of the input variables described above. CPBs and CMBs are compared based on their performance results obtained from the tests.

2.13.1 The Compressive Strength of Blocks

It is probably one of the most principal and fundamental properties of a block to have a high compressive strength. As Houben and Guillaud (2008) and Minke, G. 2009 state, "the strength of CSEBs increases with increasing durability. As a result, a well-cured block is typically stronger and more resistant to environmental agents. According to Rigassi (1995); Young (1998), a block's mechanical quality and other valuable qualities are based on its strength. Therefore, knowing the strength assessment of a block is useful for checking the consistency of the quality of the block, comparing the block to specific requirements, and determining the rate or extent of hydration achieved by the cement caused by how strong the bonds are.

CSEBs, like concrete, are materials that are made up of two or more component materials with considerably different chemical or physical properties). These materials are known for their brittleness (breaking without significant deformation when stress is applied) and so, are more tolerant of compressive stresses rather than tensile stresses. As a result, a block's tensile strength amounts to 90% less than compressive strength of the block (Fitzmaurice, 1958). Due to this, this segment will focus exclusively on the block's compression behaviour, which is detailed below:

i. Internal bonding of particles in CSEBs
ii. Strength determinants in CSEBs
iii. Procedure for investigating the compressive strength in blocks

2.13.1.1 Internal bonding of particles in Compressed Stabilised Earth Blocks

Compressed Stabilised Earth Blocks are different mixtures of sand, fine gravel, clay, silt, clay and stabilizer, (Hall *et al.*, 2012) "believe that there is a complex bonding between the different particles within a CSEB". “The bond's nature plays a significant role in ascertaining its compressive strength. The cementitious matrix and coarse soil fraction of the block are said to be responsible for most of the block's strength (Houben and Guillaud, 2008). Bond strength varies from point to point among cement hydrates and particularly the sand fraction in the soil. The strength of the bond changes based on the type of coarse soil aggregates and its texture. Young (1998), however, is of the opinion that the characteristics of sand that prevent a hardened cement paste from penetrating its surface cannot contribute to an excellent bonding. Hence, mineralogical variations of sand particles will result in good bonding with cement paste.

Due to their internal bonds that preserve their integrity, sand particles are the strongest component within a block. The lines indicating failure in a block (also known as cracks) can be influenced by the high internal strength, lacking good contact strength. It is therefore unlikely that a block's compressive strength will exceed that of its constituent sand particles. In a study by Weidemann *et al*., 1990; Young, 1998, van der Waal bonds were reported between OPC hydrates. In comparison to their body forces, these gels can produce large forces at their surfaces. In spite of this, the ionic and covalent bonds in the fibres of cement hydrate are naturally chemical (Taylor, 1998). Unlike physical bonds, the bonds in cement are stronger than physical ones, so they can resist unlimited expansion due to thixotropy. Cement hydrates and clay particles in soils have been found to be linked chemically (Awoyera and Akinwumi, 2014). Lime and clay minerals from the cement's hydration form a chemical bond through links caused by the presence of water. Ultimately, how strong a block is, results from how strong the cement mix is, as well as the process of bonding within the cement, sand particles, and also the inert strength available within the sand grains (Hall *et al.*, 2012).

2.13.1.2 Strength Determinants in Compressed Stabilised Earth Blocks

According to BRE (1980) some determinants have been found to influence the strength of CSEBs, namely:

i. A measure of the degree of hydration of the cement and the water-to-cement ratio

ii. Effort required to compact
iii. An analysis of the moisture content
iv. The block’s temperature
v. The block’s age
vi. Presence of coarse fractions

A cement matrix's strength is determined by the rate of water compared to cement and the degree of hydration, according to Neville (1995). Water cement ratio affects hydration, capillary porosity, and strength of the block equally, so the lower the ratio, the higher hydration and capillary porosity. The only way to achieve this is by determining the correct consistency and proportioning of water cement ratio and by properly curing (in order to maximize the extent of hydration). In a nutshell, the extent of hydration would increase as far as the availability of moisture for hydration is guaranteed. As such, wet curing of freshly produced blocks immediately it is de-moulded, is an important step. This study examines this phenomenon experimentally.

Block strength can also be affected by the degree of compaction. An important function of compression is to reduce the number of voids within a block and to increase the amount of interparticle contact within it. A relationship always exists between higher density and greater strength (Minke, 2009; Gooding, 1993).

A block's moisture level can also affect its strength. As a consequence, saturated blocks are not as strong as dry blocks (Houben *et al*, 2008; Hall *et al.*, 2012). A variety of methods are used to examine the differences in strength between the blocks. First of all, moisture lowers van der Waals bonds between cement hydrates and sand particles in a block. The clay minerals in CSEBs have a high affinity for water, so they absorb unstabilised grains and disperse them. In the long run, this can weaken the block's bonding. Thirdly, saturation can result in the development of internal pore pressure within a block under loading. In cement-based materials, such pressure build-up can occur as a result of disrupting interphase and interparticle bonding. It is likely that differences in the compressive strength of a block when dry and wet are an indicator of the rate of the bonding made inside the block. It is therefore expected that the stronger the bond will be, the smaller the gap between them.

As well as affecting the strength of a block, the temperature can also have an impact on its durability. Green blocks tend to have a high effect on strength in their early stages.

As a result, it has been established that temperature determines how water and cement reacts. (Illston, 1994; Young, 1998). In response to an increase in temperature, hydration speed increases. High temperatures can still be counterproductive later in the life of a block. If a block is maintained at a higher temperature for the duration of its service life, it is likely to gain strength temporarily, but have a lower long-term strength. The present study, however, does not investigate this fact experimentally. Further, OPC stabilizer hydration increases with age, which determines a green block's strength. Early in the manufacturing process, a block's strength increases with increasing hydration, and it also improves with curing age. This statement was experimented for the purpose of this research. Additionally, OPC may not experience a complete hydration reaction (Taylor, 1992). Therefore, the strength of CSEB is expected to increase for many years, but after a period of time, the rate will start to decrease.

Blocks' strength can also be influenced by the sand and fine gravel particles. An increase in the roughness of sand particle surfaces may promote better bonding and improve sand particle interaction with OPC hydrates through mechanical interlock. In contrast, using soil grain particles that are larger has a tendency to cause disadvantages. The reason being that larger soil fractions have been known to have a small surface area, which means a weak transition. Hence, limiting the maximum soil fraction and its size can result in an improved bonding, and therefore block strength. For this research, a 5 mm aperture sieve was used to screen the coarse fraction to a maximum of 5 mm during the block production stage.

2.13.1.3 Procedure for investigating the compressive strength of Compressed Stabilised Earth Blocks

A key factor in the testing process was the moisture condition of the samples. It is a lot more reproducible to test the blocks when wet, rather than when dry. It is not helpful to test a block sample in the latter state due to its wide variations in dryness. Using such a test for comparison would not be that accurate. It is also possible to record higher strength values when conducting the test in a dry state (Hall *et al.,* 2012). The results can be misleading in real-world conditions where blocks are continuously moist. Therefore, testing the block in a wet environment is more representative of real-life applications. A few blocks were tested for compressive strength for research purposes. Based on the properties of the stabilizer used in the sample, the curing age of the sample was selected. As mentioned earlier, curing is determined by the rate at which the stabilizer is hydrated. The strength of OPC increases with age of hydration, particularly when it is at its early stages (Weidemann *et al,* 1990). “In practice, OPC hydrates virtually completely in 28 days” (Illston, 1994). A cured block should show full strength during this time period based on compressive strength tests. All blocks samples were tested after 28 days, but no significant increase in strength was observed. (BS 890, 1972).

Another factor that could affect the seeming strength of test specimens was the rate at which loading was applied (compression testing machine). In general, the higher rate at which stresses are applied to a block, the lower will be the compressive strength report the block will produce (BS 6073: Parts 1 and 2, 1981). A faster application of load can permit higher strength values to be recorded on the blocks. The rate at which strain increases over time is the cause of such outcomes. Concrete studies have reported that premature failure occurs when the breaking point is reached quickly (Chandra and Berntsson, 2002). Therefore, it is essential that all samples tested are stressed at the same rate. This will enable comparable results to be obtained. All specimens were tested at 15 kN/min when loading was applied slowly without shock (BS 6073: 1 & 2, 1981; Hall *et al.,* 2012; BS 3921, 1985). Nevertheless, most blocks samples failed between 2 and 4 minutes after they were exposed.

To estimate the crushing strength of block specimens, the maximum load recorded was divided by the cross-section area of the block sample (mm^2). The strength at which it crushed was approximated to the nearest to 0.05 kN/mm^2 (MPa).

2.13.2 Block Dry Density (BDD)

A block’s density is an important criterion for determining its quality. According to the block's pre-existing moisture condition, it can be expressed in several ways:

i. Dry density of 105°C oven-dried blocks for a total of 26 hours.
ii. Bulk density which is gotten immediately the blocks have been demoulded).
iii. Density which is gotten from blocks immersed in water for about 24 hours - 48hours

As discussed in this thesis, dry density is more practised in building and construction standards (BS 6073: 2, 1981). As well as solid phases, blocks also contain pore spaces that contain both air and water (Obonyo *et al,* 2010). A block's moisture content (varies from block to block) determines how much of each phase is present. The block dry density value is obtained by forcing both air and water out of the block (by drying to constant mass in the oven). The density of a block depends on the following factors:

i. There is a standard compaction range of 4 to 8 MPa.

ii. The density of the coarse sand particles. Sand has been found to have a dry density of 2,200 kg/m^3. However, Houben and Guillaud, 2008 records the density of clay to be 2000 kg/m^3.

iii. Particle size distribution

iv. Block type (solid, hollow, frogged)

The resistance or friction between soil grains and cement hydrates results in the strength of any block, which means that the higher the density of the solid fractions, the stronger the block. The mechanical interlock of grains achieved after stabilization with OPC can be maintained by densifying the soil after stabilization. In addition to restricting excessive movements, the stabilizer limits them more than they would have been if there had not been an interlock.

In the absence of a binder, whether omitted or through continuous decay, blocks would likely be weak. A block's density can influence most of its other bulk properties in such a situation (Obonyo et al, 2010) and "the impact of densification can be gradually reversed in such a case" (Hall *et al.,* 2012). There are some characteristics that affect the performance of a block, such as its water absorption, compressive strength, thermal capacity, permeability, porosity, sound insulation, durability and hardness (Hall *et al.,* 2012; Minke, 2009, 1983; BRE, 1980) and a high block density leads to a better performance. The relationship between density and strength has been commonly linked to the WCS of the block (Minke, 2009; UN, 1964). Experimental investigations on the connection that exists between density and block strength to ascertain whether density can serve as a substitute for block strength. To determine the density value of a block, experimentation is also performed to determine the relationship between water absorption and density, using the test methods given in the standard BS 6073: Part 2, 1981.

2.13.3 Total Water Absorption (TWA)

It has been shown by Keddi and Cleghorn (1980) that "almost all bricks and blocks are capable of absorbing water through capillarity". There is a marked capillarity in these materials due to the presence of pores of various magnitudes. A good indicator of bulk quality is the overall quantity of water that is absorbed. This is because the amount of water a block can absorb is instrumental in estimating the depth of voids. This property differs from how easy it is for water to permeate through a block" (Neville, 1995). It is important to know the TWA of a sample block since it is useful for:

i. Checking the quality of blocks on a regular basis (surrogate test)
ii. The purpose of the comparison is to compare the material with others of similar quality and value
iii. A classification of blocks based on their durability and structural purpose
iv. Estimation of the voids in a block

A block's performance is generally improved if it absorbs and retains less water Hall *et al.,* (2012). In order to improve a block's quality, one method is to reduce its TWA capacity. Temperature moisture variations can cause repeated shrinkage and swelling of a block that readily absorbs water. A block fabric may progressively weaken as it experiences repeated swelling and shrinkage (either directly or indirectly). When water has been absorbed into a block, it is often weaker and softer. A chemical process that has been dormant can also resume and accelerate when absorbed water is present (BSI, 1950; BS 7543, 1992). A block that does not absorb a lot of water is found to be durable, since it has a lower capacity to absorb water.

To measure the TWA capacity of a block, it is often necessary to determine how much water the block can absorb Hall *et al.,* (2012). A block should be dried to constant mass first, as the amount of water absorbed is affected by its moisture condition (BS 3921, 1985).

To determine whether constant mass could be achieved, an electronic weighing scale was calibrated to a precision of 0.01% of the sample mass. It is possible to achieve incomplete absorption and saturation by simply immersing the specimen without evacuation beforehand. A dry block exerts much greater suction than a wet one (PCA, 1970). A block's total water absorption capacity can be determined using various procedures (BS 3921: 1985):

i. The immersion of the mass in cold water (24 to 48 hours) after it has been dried in an oven.

ii. Five-hour boiling test.

iii. Test of absorbency under vacuum.

It is still possible to obtain widely divergent results using the above methods (Bungey and Millard, 1996). None of the methods described above could demonstrate a convergence that is definite (BS 3921, 1985). Responses derived from the methods can vary and are not equal or proportional to each other” (Neville, 1995). Drying in an oven followed by dipping in cold water proved really suitable and easy.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Materials Collection and Preparation

3.1.1 Soil

The soil used for this research was collected from the Department of Soil Science, Alabama A & M University, Normal, Alabama (Plate 3.1). It is located between latitude 34.7838^{o}N and latitude 86.5722^{o}W. Ordinary builders' sand was collected and supplied in its clean state, after the clay fraction was washed out. The totality of the soil used comprised of sand, gravel, clay and silt. Henceforth, the model soil was named modified soil. The soil variables consisted of gravel (2%), sand (76%), silt (8%) and clay (14%). For the experiments, 27 blocks of size 290 mm x 140 mm x 100 mm were produced, so keeping the soil type the same would aid in increasing test reliability. A smaller sample size was also obtained for further experiments from the full block sizes. Consistency, repeatability, and controllability can all be improved by keeping the soil type constant for all specimens. It was essential that the carefully chosen soil composition conformed to the criteria for producing CSEB, which stipulated the soil must contain almost every fraction of soil size within the range of maximum particles. Gravel is given at less than 20 mm, or about 6 mm) as well as minimum particles with clay usually less than 0.002 mm. In order to stabilize soil with OPC more effectively, an optimal composition of soil fractions was chosen. Using particle size distribution as a criterion for soil classification, soils were classified. The above procedure was followed by the mixing of artificial soil in the laboratory.

3.1.2 Cement

The predominant type of stabilizer used was Ordinary Portland Cement (OPC), grade 42.5R, sourced from the Cement Laboratory of the Department of Civil Engineering, Alabama A&M University, Normal, Alabama, USA (Plate 3.2). The OPC, which conforms to BS 12, 1996, was batched in a confined room temperature and kept in a dry and cool place prior to the commencement of blocks for production.

Plate 3.1: Soil sample used


Plate 3.2: Sample of Cement Used

3.1.3 Palm Kernel Shell Ash

The Palm Kernel Shell Ash (PKSA) used for this research was obtained from a local crude palm oil producing mill in Aba Odan in Egbeda LGA, Ibadan, Oyo State, Nigria (Plate 3.3). The palm kernel shell used in the CSEB preparation had been subjected to drying under the sun to reduce the moisture content, combustion at 700ºC, and cooled on a clean surface. The ash was then collected and sieved to pass through a BS standard sieve of 75 µm in order to collect a very fine ash, after which it was stored air tight in a Ziploc bag to prevent contamination as well as moisture loss (Plate 3.4). The chemical composition of PKSA was determined, and so was the bulk density and specific gravity test.

3.1.4 Water

Clean water was obtained from the tap in the laboratory, which was used to blend the materials to the point of homogeneity. The water used to blend the materials was fixed at 12% by weight of soil and stabilizer mix for all the mixtures. Also, the water temperature was approximately 23°C.

3.2 Preparation of Materials for Moulding

In order to be sure of the suitability of the materials for earth blocks moulding, different preliminary tests and chemical analysis were performed on the PKSA and soil sample. The laboratory tests conducted include sieve analysis, compaction test, liquid limit, plastic limit, bulk density and specific gravity. The tests were carried out according to BS 1377, 1990.

3.2.1 Laboratory Tests on Samples

Laboratory tests of the materials are important for large-scale production of CSEBs. Clods in the soil samples were pulverized (Plate 3.5) to achieve a homogeneity of the mineral constituents, stabilizer and water. Lump higher than a diameter of 200 mm were broken up. The materials were hit with a great force which caused disintegration. Hence, any large leftover piece was removed utilizing a screen. Properties of soil that were determined were: sieve analysis (Plate 3.6), specific gravity, bulk density, moisture content, liquid limits, plastic limits, plasticity limits and linear shrinkage test.

Plate 3.3: Sample of Palm Kernel Shell Ash Used

Plate 3.4: Storage Method for Palm Kernel Shell Ash

Plate 3.5: Break down of lumps more than 200mm in diameter

Plate 3.6: Sieve Analysis

The following are the preliminary tests carried out. The methods used to carry out these tests are recorded in Appendices A-F. During all laboratory tests, three essential requirements were met: precision, reliability and reproducibility. As a result, CSEB samples were produced using only standard methods. Moreover, block samples were measured based on their dimensions, weights, shapes, and appearances. Furthermore, specimens were marked and labelled in order to undergo more extensive testing.

3.2.2 Chemical Analysis

Palm kernel shell ash was also analysed in the laboratory using X-ray fluorescent analyser (modelox) 1279. This was done in order to determine the pozolanity based on its chemical components and percentage composition. This was necessary because the presence of soluble salts and organic matter is not beneficial. Chemical analysis can either be qualitative or quantitative. Quantitative analysis detects whether some certain substances are present goes ahead to quantify them either by using a spectrometer or by filtration. On the other hand, qualitative analysis detects the existence of certain substances only without quantifying or assessing them. The essence is to use soil or pozzolans with the best chemical composition suitable for optimum result. In performing the chemical analysis on palm kernel shell ash, the procedure is outlined below:

1. Sample Preparation:

a. A representative sample of palm kernel shell ash (10g) was obtained by collecting multiple samples from different parts of the ash pile.

b. The ash sample was pulverized to a fine powder using a mortar and pestle till the particle size was consistent and small enough to obtain accurate results.

2. Instrument Calibration:

a. The XRF analyser was turned on and allowed to warm up for the 10 minutes

b. It was then calibrated by measuring known reference samples with known concentrations of elements of interest as instructed by the manufacturer.

3. Sample Measurement:

a. The powdered palm kernel shell ash was then placed into a sample cup, ensuring it was evenly distributed.

b. The sample cup was inserted into the XRF analyser, making sure it was properly aligned.

c. The measurement process was then started using the XRF analyser's software interface. 4. Data Analysis and Interpretation:

a. Once the measurement was complete, the XRF analyser provided data on the elemental composition of the palm kernel shell ash.

b. The obtained data was analysed, to determine the concentrations of various elements such as silicon (Si), aluminium (Al), potassium (K), calcium (Ca), etc.

c. The results were then compared with ASTM standards to determine the quality or suitability of the palm kernel shell ash for specific applications.

3.2.3 Stabilisation Procedures

This involved the stabilization of the soil samples with percentages of cement and PKSA contents which varied from 2-10% by weight in increments of 2%. It was necessary to analyse the effect of stabilization on the capacity or characteristics of CSEBs. Blocks that were manufactured in each of the categories was monitored as stabilizer content and type were altered over time. A great deal of interest and significance is given to the degree to which properties change. According to Olutoge (2012), PKSA, a siliceous or aluminium siliceous material that contains moisture, reacts chemically with the calcium hydroxide that was released by cement hydration and creates calcium silicate hydrate as well as other cementitious compounds for the secondary binding in a block when it is partially replaced with OPC. Consequently, it is estimated that such a block would have a much stronger intergranular bond, higher density, and a much stronger resistance to surface abrasion than a conventional block. Because of this, these improved blocks have been called Cement-PKSA Blocks (CPBs).

3.2.4 Mix-water Content

Mix water added was fixed at 12% by weight of the soil sample and stabilizer mix. Ordinary laboratory tap water was used for each block sample.

3.2.5 Compaction Pressure

Throughout the process, pressure used for compaction was kept at 6 MPa. Only for a very limited number of blocks, was it increased to 10 MPa. As such high values are rarely encountered in practice, the 10 MPa pressure was used basically for the purpose of comparison. The compaction pressure of CSEBs typically ranges from 4 MPa to 8 MPa because the selection of the compaction pressure range of 4 MPa to 8 MPa for CSEBs strikes a balance between achieving sufficient strength and practical considerations, ensuring consistent quality and performance of the blocks. (Houben and Guillaud, 2008). Table 3.1 shows the various categories of compaction pressure.

3.2.6 Curing Conditions

The primary and secondary curing processes are important steps in the production of compressed earth blocks (CEBs). The methodology for primary and secondary curing is explained as follows:

1. Primary Curing:

a. After the compressed earth blocks were formed, they were stacked and left undisturbed for a specific period of 7-14 days known as the primary curing period. This allows the blocks to gain initial strength and stability.

b. During the primary curing, the blocks were protected from direct sunlight, wind, and excessive moisture. This was achieved by covering the stacked blocks with a polythene sheet to create a controlled environment.

2. Secondary Curing:

a. After the primary curing period, the blocks were made to undergo the secondary curing process from 21-28 days. This step further enhances the strength and durability of the blocks.

b. The secondary curing involved exposing the blocks to a controlled level of moisture to facilitate further chemical reactions within the block material, which was done by sprinkling water over the blocks.

Table 3.1: Categorization of Compaction Pressure Used

	Compaction Pressure (MPa)	Categorization
1	6	Medium
2	10	High

The primary and secondary curing processes allow the compressed earth blocks to develop strength, reduce shrinkage, and improve resistance to weathering and cracking. These curing methods are essential to ensure the long-term performance and durability of the CEBs. Cured blocks were then cut to size.

3.3 Summary of Production Variables

The quality and performance of blocks can be impacted by variations of any of the many production input variables. Among them are soil proportions and type, stabilizers (types and contents), and compaction pressure. In order to create an effective experimental design, some variables were fixed while others were varied. The control blocks and cement-palm kernel blocks were investigated using different compaction pressures and stabilizer content. Table 3.2 summarizes the variables used in designing the samples.

3.4 Preparation of CSEB Samples

The production of CSEB samples involves a systematic approach that encompasses soil selection, sample preparation, mixing, compression, and curing. Each step is crucial in achieving blocks with desirable properties, such as adequate strength, durability, and resistance to environmental conditions.

3.4.1 Production of CSEBs

i. Soil Selection:

The first step in the methodology was the careful selection of soil which had been determined to have suitable characteristics for stabilization and compaction. Soil properties such as particle size distribution, plasticity, and organic content were evaluated to ensure optimal block production.

ii. Sample Preparation:

Once the soil was selected, it went through the drying, screening and sieving process to remove debris and large particles (Plate 3.7). Pulverization was also done to break lumps and homogenize the soil types to achieve a consistent mixture.

Table 3.2: Component materials and variables used for producing block samples

S/N	Materials	Unit	Quantity	Design	
				Fixed	**Altered**
A	**Soil**			✓	
	Gravel	%	2	✓	
	Sand	%	76	✓	
	Silt	%	8	✓	
	Clay	%	14	✓	
B	**Stabilizer**				
	OPC	%	10, 8,6,4,2		✓
	PKSA	%	2,4,6,8		✓
C	**Mix-water**				
		%	12.0	✓	
D	**Compaction Pressure**				✓
	High	MPa	10		
	Medium/Normal	MPa	6		✓
E	**Curing**				
	Time	Days	28	✓	
	Humidity	%	100	✓	
	Temperature	^{0}C	23	✓	

Plate 3.7: Sand drying process

iii. Stabilization:

For each batch, soil was mixed with stabilizing agents (OPC and PKSA) and water in four stages. The proportions for the different stabilizers and soils used is shown in Table 3.3. The stabilizer is thoroughly mixed with the soil to achieve uniform distribution and maximize stabilization effects.

iv. Mixing:

Mixing was primarily concerned with ensuring that the water and stabilizer were evenly distributed throughout the mixture. For proper sampling, consistency was required when proportioning, mixing, and wetting. A weight-based proportioning was used for soil and stabilizer. For each weigh, a 20 kg capacity electronic scale, accurate up to about 0.05 grams was used. The machine mixer was used to mix both the wet and dry ingredients. About three to four minutes of dry mixing were spent. This was followed by adding uniform quantities of water (12% by weight) to the dry soil and stabilizer mix. It was determined that this amount of moisture would provide an ideal optimum moisture content. It was also intended that the stabilizer(s) would be adequately hydrated with the water. Several consistency tests were conducted after each mix achieved uniform coloration. Tests conducted also include the mix holdback time, which refers to the duration during which the mixed soil is held before compression.

v. Compression:

The compression process involves placing the soil mixture into a mould or press chamber and applying pressure to compact it into the desired block shape and size. Block specimens were constructed using an Alabama Brick block making machine obtained from North Birmingham, AL. This machine was used for the compression of damp soil and stabilizer mix. In addition to its maximum block size of 290 x 140 x 100 mm, the machine could produce 300 blocks per day. Maximum moulding pressure ranged between 2 and 10 MPa as well. Following the block manufacture, the blocks were demoulded and handled carefully (since they were still fragile). The demoulded block was weighed (Plate 3.8). And a measurement of the dimensions of the exterior of the blocks was also taken. Mitutoyo shockproof dial calliper was used for measuring with accuracy to 0.05 mm. In accordance with BS 6073: 1 & 2, 1981 and BS 3921, 1985, several measurements were taken along the block edges and mid-sections.

Table 3.3: Mix composition used

S/N	% of Stabilizer Used		Mass (g)				
	Cement (%)	**PKSA (%)**	**Coarse aggregate (86%)**	**Clay (g) (14%)**	**Cement (g)**	**PKSA (g)**	**Total (g)**
1	8	2	6647.0	1173.0	680	170	8500
2	6	4	6502.5	1147.5	510	340	8500
3	4	6	6358.0	1122.0	340	510	8500
4	2	8	6213.5	1096.5	170	680	8500

Plate 3.8: Block weighing process

After carefully labelling each block with a soft-nib permanent marker, the blocks were assembled. The purpose of this procedure was to spot each block based on the date of production, the stabilizer content, as well as moulding pressure.

vi. Curing:

Curing is a crucial step to ensure the strength and durability of the CSEB samples. The blocks were covered using some polythene sheets, cured as earlier described. In addition to primary curing periods ranging from seven to fourteen days, there was also a period of secondary curing which lasted 28 days and was maintained for stabilised blocks containing OPC. In addition to the primary curing, the secondary curing temperature (23°C) was maintained. After the blocks were cut to size, they were divided into the categories based on their size. Following this methodology, CSEB samples were produced with consistent quality and desirable characteristics. The careful selection of soil, proper sample preparation, stabilization, mixing, compression, and curing are all integral parts of the process. Understanding and implementing this methodology contributed to the production of sustainable and cost-effective building blocks, promoting eco-friendly construction practices while utilizing locally available resources.

3.4.2 Number of Specimens Produced

It was necessary to obtain sufficient numbers of CSEB specimens for all of the planned laboratory experiments. Different sized specimens were required for the initial performance testing of blocks pertaining to their surface and bulk properties. This necessitated cutting down the full-scale CSEBs into smaller shapes. Brick saw machines: Clipper, model EN 2-40-3) were used to cut the blocks. An electric circular saw with a sprinkler was used to drive the lathe. The lathe was used to cut through the blocks once they had been accurately pre-demarcated with their dimensions (Plate 3.9). There was a lot of neatness and precision to the cut surfaces due to the machine's efficiency. Consequently, blocks with normal dimensions 290 mm x 140 mm x 100 mm were cut into these: 100 mm x 100 mm x 100 mm (twice each); 100 mm x 100 mm x 40 mm (twice each); 100 mm x 100 mm x 90 mm (once each). Although the stabilizer and soil mix were the same, blocks that were compressed at 10 MPa proved more difficult to saw through than blocks 6 MPa compressed blocks.

Plate 3.9: Concrete lathe machine

There were three specimens required for each test, made in the same manner and with the same composition. Three full size blocks were required for each soil and stabilizer mix. Over 160 samples of various dimensions were obtained for this study (Plate 3.10). Several tests were performed on the specimens, namely, (wet compressive strength, block dry density and total water absorption tests). Table 3.4 shows the various types of blocks produced and samples obtained from them.

Time constraints caused the amount of specimens necessary to be limited due to delays caused by curing periods at the planning, design, and implementation stages. Following the testing, three samples of blocks were produced for each test because of the degree of repeatability, accuracy as well as reliability achieved.

3.5 Testing of block samples

3.5.1 Compressive Strength Tests

Blocks measuring $100m^3$ were tested for their compressive strength by measuring the failure stress normal to their faces. Standard test analysis in accordance with BS 6071: Parts 1 and 2: 1981; Neville 1995; BS 3921: 1985 were used throughout the CSEB's test programme. Details of the test are as follows:

i. Three samples were taken from each type of block, and their unique areas and volumes were measured and recorded.
ii. The samples were immersed for 24 hours in a tank of water that is between 10 and 25 °C in temperature.
iii. The blocks were then removed and allowed to drain on a stillage or damp sacking for about half an hour. The blocks were then placed with a 5 mm overhang on each edge between two new sheets of 4 to 20 mm plywood, ensuring that the specimen's mass centre and the machine's axis were in line.

Plate 3.10: Block samples

Table 3.4: Summary of list of CSEB produced

Sample No	Cement Content (%)	PKSA Content (%)	No. of Blocks 290x140x100 mm	100x100x100 mm	100x100x90 mm	100x100x40 mm	100x90x40 mm
Compacted at 6 MPa							
Control 1	10	0	3	6	3	6	3
Compacted at 6 MPa							
6S1	8	2	3	6	3	6	3
6S2	6	4	3	6	3	6	3
6S3	4	6	3	6	3	6	3
6S4	2	8	3	6	3	6	3
	Subtotal		12	24	12	24	12
Compacted at 10 MPa							
10S1	8	2	3	6	3	6	3
10S2	6	4	3	6	3	6	3
10S3	4	6	3	6	3	6	3
10S4	2	8	3	6	3	6	3
	Subtotal		12	24	12	24	12
	Grand Total		**27**	**54**	**27**	**54**	**27**

iv. A final check was performed to make sure the alignment and packing were correct, after which the load at a rate of 15 kN/min was applied without shock. This load was maintained for one to five minutes or until failure.

v. The loading rate and the maximum load before failure were recorded (the machine automatically recorded these figures and a printout provided).

vi. To determine the crushing strength, note the type of failure mode and use the formula below:

$$WCS = \frac{ML\ (kN)}{A\ (mm^2)}$$

ML = Maximum load

A = cross section area while

WCS = wet compressive strength (MPa).

The same mix batch and processing method was used to run three tests on each type of material and then the average of the results was gotten.

The dry compressive strength (DCS) value was calculated using the same steps as above, except that the samples did not need to be soaked in water for 24 hours. Instead, after being oven-dried to a consistent mass, they were evaluated as previously indicated.

Compressed Stabilised Earth Blocks were tested for their wet compressive strength (WCS) when varying stabilizer content and moulding pressure. Stabilizers and compaction pressure were also examined for their effect on WCS. Also studied was the mean wet/dry compression ratio, as well as mix holdback time effect on WCS.

3.5.2 Block Dry Density

The ASTM C140/C140M standard provides specific procedures for testing the dry density of concrete masonry units, including blocks. Below is a general outline of the procedure:

i. Sample Preparation: Representative samples of the blocks to be tested were obtained. The samples were free from visible defects, surface contaminants, and excessive moisture.

ii. Measurement of Dimensions: The length, width, and height of the block were measured using suitable measuring instruments and multiple measurements were taken at different locations to account for any variations in dimensions.

iii. Calculation of Volume: The volume of the block was calculated by multiplying its length, width, and height. This gives the gross volume of the block.

iv. Determination of Dry Weight: The block was dried in an oven at a temperature of 105°C until a constant weight was achieved to ensure that all moisture is removed from the block. In order to determine whether a block's mass has remained constant when weighed twice at an interval of 24 hours, its difference in mass must be less than 0.1% of its initial mass. After removing the block from the oven, it was left open for two hours to breathe (i.e. allowing it to cool down and release any residual moisture or gases that may have accumulated during the drying process. By exposing the block to the ambient air, any trapped moisture or volatile compounds can escape, promoting further drying and stabilization of the block's properties). The block was then weighed using a suitable weighing scale to obtain the dry weight.

v. Calculation of Dry Density: The dry weight of the block was then divided by its volume to calculate the dry density. The dry density is typically expressed in kilograms per cubic meter (kg/m^3).

vi. Reporting: All the measurements, calculations, and test results were reported accurately, including any relevant information such as block identification, test conditions, and any deviations from the standard procedure.

This study investigated the impact of stabilizer and compaction pressure on density. Analyses were also conducted on the density-WCS relationship.

3.5.3 Water Absorption Tests.

For the water absorption tests, standard test analysis in accordance with BS 1881: Part 122: 1983; ASTM C 642: 1990; BS 3921: 1985 were used throughout the CSEB's test programme.

Testing Methods:

i. The samples from each category of blocks were dried in the oven at 110°C to 115°C until they reached a consistent mass.

ii. After each specimen had cooled, it was weighed with an accuracy of 0.1% of the specimen mass.

iii. Immediately after weighing, the specimens were submerged in a single layer tank so that water could easily flow over the sample's bottom and all sides. A 10 mm gap was left between neighbouring samples.

iv. After 24 hours, the specimens were taken out of the water tank, the surface wiped off water while shaking them gently, and each specimen was weighed again within two minutes after removing it.

v. The formula below was used to determine the water absorbed by each sample expressed as a proportion of the dry mass:

$$\frac{(MW - MD)}{MD} \times 100 = TWA$$

where TWA = total water absorption (%).

MW = Wet mass (g)

MD = dry mass (g)

The average value was gotten from three samples that fall into the same mix and processing category. Additionally, there was good consistency and accuracy in the method. Throughout the entire process, the TWA was determined exclusively using this method for both CMB and CPBs. TWA in blocks were analysed by varying stabilizer content and compaction pressure. It was also examined whether TWA and density are correlated.

3.6 Summary of the Laboratory Procedures

Regarding the experiment, CSEBs are produced by recognizing the main constituents and variables such as type of soil, stabilizer content and type, mix-water ratio, and compaction pressure. Sample production was designed with a fixed soil type. In this soil, fine gravel and sand made up about 75% of the material, and silt and clay made up about 25%. As a result, the exact soil could be used for the whole the test. There was a variation in the content of cement from 2% to 10%, with 10% as the control value. There was also a fixed amount of PKSA at 2% in increments of 2% to 8%. The term used to describe blocks made with PKSA and cement is CPB, while CMB refers to blocks that were not made with PKSA. Based on the stabilizer type, it was possible to categorize the blocks by their performance, since this variable remains the most influential factor. In order to achieve uniformity in the all variables were kept at the same levels. The curing time and condition was kept at standard required levels. A small number of blocks were cured at 100% humidity for the purpose of evaluating the effect of such conditions on their performance.

The blocks were divided into smaller specimen sizes based on the mix type. There were 27 blocks produced with dimensions of 290 x 140 x 100 mm each. In total, more than 160 smaller specimens were obtained from this number of blocks. The number was considered sufficient for all tests planned. Three samples for each test were selected as reported by other researchers and preliminary calculations of variance. Block production was carefully monitored throughout, from preparation to mixing to compression to curing. It was found that all of the blocks were of high quality and could be used for further testing. A meticulous labelling process was followed to make it easy to identify the samples of block and specimens that were obtained.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Preliminary Tests

The result of the sieve analysis for the samples used for this study are presented in Figure 4.1. AASHTO soil classification system was used to categorize the samples. According to the general classification, each sample passed less than 35% of the 75 µm sieve, which falls under the granular materials category. The results align with 29.25% recorded by Amu *et al* (2011). Specific gravity, moisture content, liquid limit, plastic limit and plasticity index values were 3.3, 17.7, 53.4, 59.5 and 6.1%, respectively. Based on these values, the soil can be classified using the Atterberg Limits which reveals that the soil contains a significant amount of moisture and has a high liquid limit as well as plastic limit, indicating it is highly plastic hence, it will not become brittle and crumble easily. The soil is therefore suitable for the manufacture of compressed earth blocks.

4.2 Chemical Composition of Palm Kernel Shell Ash and OPC

The chemical properties obtained for PKSA and OPC used in this study are shown in Table 4.1. In comparison with ASTM C150 (2016), the properties of OPC was found to be higher than the minimum requirements. The specific gravity was also found to be higher compared to that of PKSA due to greater carbon content of PKSA, which was the reason for the higher loss on ignition. Palm kernel shell ash was found to have a considerable amount of silica (46.64%) which is a great factor in increasing the strength and durability of CSEB.

The total percentages of SiO_2, Al_2O_3 and Fe_2O_3, gives a total of 71.88% which is more than the minimum 70% requirement as recommended by ASTM C618 (2019) for any pozzolanic material. This shows that the PKSA used for this study can be adjudged as a pozzolanic material. This result also compares well with the 66.572% reported by Olutoge *et al.* (2012).

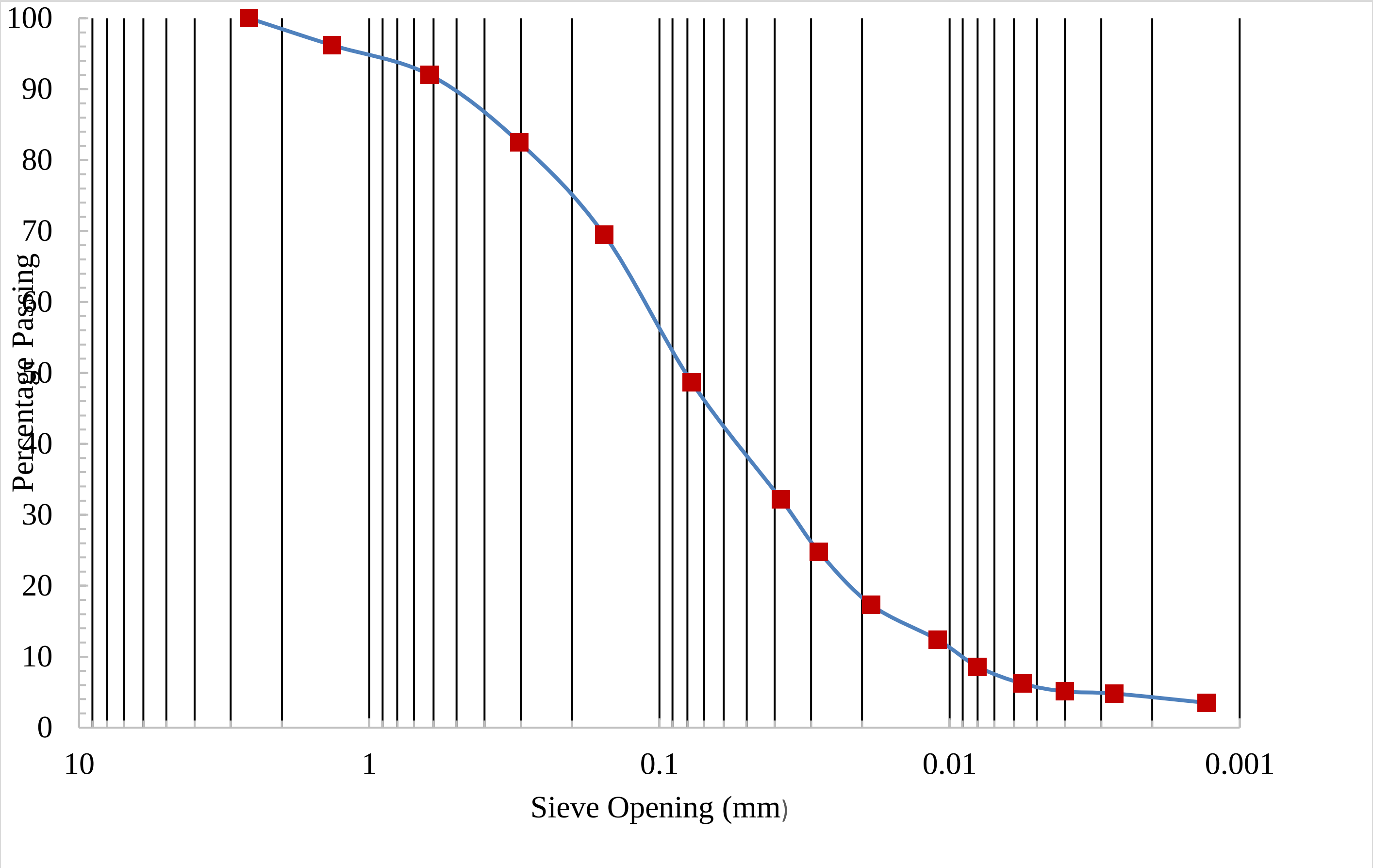

Fig 4.1: Particle size distribution

Table 4.1: Chemical composition of PKSA and OPC

Chemical Constituents	**PKSA (%)**	**OPC (%)**
SiO_2	46.64	19.21
Al_2O_3	13.46	3.57
Fe_2O_3	11.78	4.80
SO_3	0.52	1.96
MgO	1.01	1.71
K_2O	1.51	0.37
Na_2O	1.38	0.33
CaO	9.82	65.70
$SiO_2 + Al_2O_3 + Fe_2O_3$	71.88	27.58
LOI	2.58	1.25
Specific Gravity	2.00	3.12

4.3 Compressive Strength Test Results

4.3.1 The Effect of Varying the Compaction Pressure and Stabilizer Proportions on the Wet Compressive Strength of CSEBs

Results from the compressive strength test that lasted for 28 days for CMBs and CPBs are presented in Tables 4.3 to 4.5. A diagram depicting the same results is shown in Figure 4.2. Also, data points shown in Figure 4.2 are averaged from three different experiments. Subsequent diagrams and graphs will follow this same form. The values plotted in Figure 4.2 are summarized in Table 4.6.

The results ranged from 3.21 MPa to 9.84 MPa for the CPBs while at 8.99 MPa for the Control Mix Block. The results with values that are lower in both cases are linked to PKSA content of 8%, and cement content of 2% but the results with values that are higher are linked to PKSA content of 2% and cement content of 8%. As observed in Table 4.4, the values of wet compressive strength in CPB at 2% PKSA were considerably superior or higher than those in the control mix (Table 4.3) made in the same manner but without the addition of PKSA due to stronger bonds formed by the pozzolanic reaction of PKSA when mixed with cement in the presence of water. As a result of adding PKSA to blocks, the strength of the blocks increased on average. Palm kernel shell ash can therefore be used to replace cement in block preparation in a way that reduces the total amount of cement consumed.

There are a number of suggested minimum results, including 2.4-3.5 MPa (Awoyera and Akinwumi, 2014), 8.27 MPa (Obonyo *et al.*, 2010) and.6.2 MPa (Akhter and Mahmud, 2018). There is a 63% increase in strength from 3.21 to 9.84 MPa value for CPBs. The value of 1.2 MPa is achieved by incorporating all the values plotted for CPBs below the point of 3% cement content only requiring approximately 1% of the binder content. A significant new finding has been made based on these results.

4.3.2 Descriptive Statistics of Mix Composition Used

From Table 4.2, Cement and PKSA vary similarly in grams and percentage, with both standard deviation equalling 2.58, while Gravel+Sand+Silt (g) and Clay (g) vary less, and had lesser variation from their means (averages).

Table 4.2: Analysis of Mix Composition used

Variables	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
Cement (%)	2	8	5	2.58	51.64
PKSA (%)	2	8	5	2.58	51.64
Gravel+Sand+Silt (g)	6213.5	6647	6430.25	186.55	2.90
Clay (g)	1096.5	1173	1134.75	32.92	2.90
Cement (g)	170	680	425	219.47	51.64
PKSA (g)	170	680	425	219.47	51.64

Table 4.3: Wet Compressive Strength (Control Mix)

S/N	Sample No CSA = 10,000 mm^2 Loading Rate = 15 KN At 6 MPa	Cement Content (%)	PKSA Content (%)	Maximum Load (KN)	Wet Compressive Strength (28 days)	Mean Wet Compressive Strength (28 days)
1	Control 1a	10	0	90.6	9.06	8.99
	Control 1b	10	0	88.8	8.88	
	Control 1c	10	0	90.3	9.03	

Table 4.4: Wet Compressive Strength (6 MPa)

S/N	Sample No CSA = 10,000 mm^2 Loading Rate = 15 KN	Cement Content (%)	PKSA Content (%)	Maximum Load (KN)	Wet Compressive Strength (28 days)	Mean Wet Compressive Strength (28 days)
1	6S1a	8	2	98.1	9.81	9.84
	6S1b	8	2	98.4	9.84	
	6S1c	8	2	98.7	9.87	
2	6S2a	6	4	74.8	7.48	7.51
	6S2b	6	4	75.0	7.50	
	6S2c	6	4	75.5	7.55	
3	6S3a	4	6	52.4	5.24	5.29
	6S3b	4	6	53.3	5.33	
	6S3c	4	6	53.0	5.30	
4	6S4a	2	8	31.5	3.15	3.21
	6S4b	2	8	32.9	3. 29	
	6S4c	2	8	31.9	3.19	

Table 4.5: Wet Compressive Strength (10 MPa)

S/N	Sample No CSA = 10,000 mm^2 Loading Rate = 15 KN	Cement Content (%)	PKSA Content (%)	Maximum Load (KN)	Wet Compressive Strength (28 days)	Mean Wet Compressive Strength (28 days)
1	10S1a	8	2	99.8	9.98	10.11
	10S1b	8	2	106.7	10.67	
	10S1c	8	2	96.8	9.68	
2	10S2a	6	4	83.2	8.32	8.41
	10S2b	6	4	82.8	8.28	
	10S2c	6	4	86.4	8.64	
3	10S3a	4	6	70.4	7.04	6.72
	10S3b	4	6	62.9	6.29	
	10S3c	4	6	68.3	6.83	
4	10S4a	2	8	53.3	5.33	5.76
	10S4b	2	8	61.5	6.15	
	10S4c	2	8	58.0	5.80	

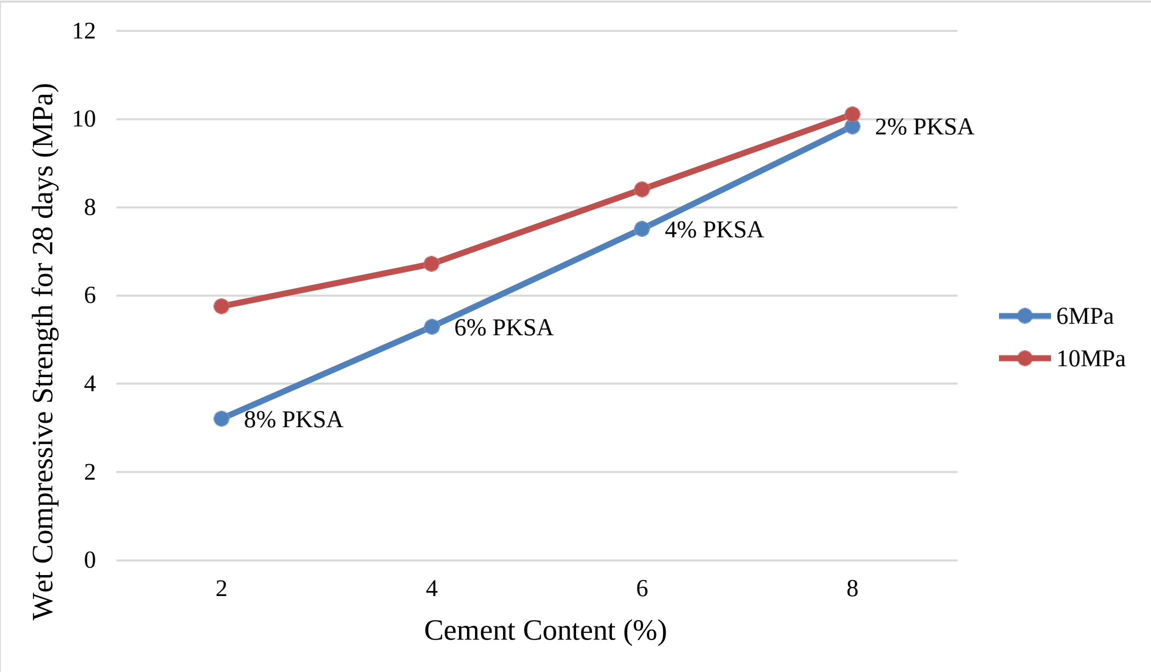

Fig 4.2: The Effect of Varying the Compaction Pressure and Stabilizer Content on the Wet Compressive Strength of CSEBs

Table 4.6: Mean wet compressive strength values after 28 days for CSEBs

Cement (%)	PKSA (%)	Wet Compressive Strength (MPa)	
		CSEB (10 MPa)	**CSEB (6 MPa)**
8	2	10.11	9.84
6	4	8.41	7.51
4	6	6.72	5.29
2	8	5.76	3.21
Control Mix at 10% Cement			**8.99**

The discussion above only pertains to stabilizer content variation. For CPBs, the results were also shown in Table 4.6 when compaction pressure was varied from 6 MPa to 10 MPa. Results reveal that a high compaction pressure causes a rise in wet compressive strength for exactly the same stabilizer content. Increasing compaction pressures from 6 MPa to 10 MPa (which is about 70%) with low cement content and high PKSA content, wet compressive strength increased by about 79%. At higher cement contents (8%) and lower PKSA contents (2%), the same increase in compression pressure yielded only a 3% increase. With 4-6% PKSA-cement content as the range of interest, WCS rose between 12 to 27%.

Other researchers have also found that adding stabilizer content to blocks increases their wet compressive strength more economically as a result of reduced utilization of cement (Hall *et al.*, 2012). Low compaction pressure and high stabilizer contents were found to perform satisfactorily on blocks stabilised at high stabilizer contents. Changing stabilizer content appears to have more influence on a block's wet strength than compaction pressure. Furthermore, results show that even though higher compaction pressure improves performance, the degree of improvement diminishes with increased pressure. Therefore, the operation of compaction machines ranging from 4-8 MPa for block manufacture should be sufficient to yield results that are satisfactory and acceptable (Houben and Guillaud, 2008).

4.3.3 Descriptive Statistics of Wet Compressive Strength at 6 MPa and 10 MPa

The results of the progressive development of the compressive strength of the block types, compressed at 6 and 10 MPa, are presented in Table 4.7. Results of the coefficient of variation, which can be expressed as the ratio of the standard deviation to the mean, showed that wet compressive strength was found to be less variable at 10 MPa with a value of 22.79, than at 6 MPa with a value of 39.97. Wet Compressive Strength at 10 MPa with a coefficient of variation of 22.79 indicates that the wet compressive strength measurements at 10 MPa had a lower relative variability compared to the mean. A coefficient of variation of 22.79% suggests a moderate level of variability, meaning the data points are relatively close to the mean value. It implies that the wet compressive strength measurements at 10 MPa were more consistent or less scattered around the average value.

Table 4.7: Statistics of Wet Compressive strength at 6 MPa and 10 MPa

Variables	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
WCS (6 MPa)	3.15	9.87	6.46	2.58	39.97
WCS (10 MPa)	5.33	10.67	7.75	1.77	22.79

Wet Compressive Strength at 6 MPa with a coefficient of variation of 39.97 on the other hand, indicates that the wet compressive strength measurements at 6 MPa exhibited a higher relative variability compared to the mean. A coefficient of variation of 39.97% indicates a higher level of variability or dispersion of data points around the mean value. This suggests that the wet compressive strength measurements at 6 MPa were more widely scattered or less consistent compared to the 10 MPa measurements. The rate of dispersion around the mean rises as the coefficient of variation increases. Also, the impact of cement content and PKSA variation on WCS at 6 MPa compaction pressure, showed that increasing the percentage PKSA content reduces WCS, as seen in Figure 4.3. The results of the impact of cement content and PKSA variation on WCS at 10 MPa also showed that increasing the percentage PKSA content reduces WCS, as presented in Figure 4.4. Notwithstanding, the result recorded at 6/4 (Cement/PKSA content) was found to be higher than the recommended minimum values recorded by 2.4-3.5 MPa (Awoyera and Akinwumi, 2014), 8.27 MPa (Obonyo et al., 2010) and.6.2 MPa (Akhter and Mahmud, 2018)). Comparing the compaction pressure of 6 and 10 MPa, it is seen that a rise in the percentage of PKSA content reduces the wet compressive strength. However, WCS at maximum PKSA ratio to Cement performed better at 10 MPa that at 6 MPa, as seen in Figure 4.5.

4.3.4 Analysis of Variance (ANOVA) of WCS at 6 MPa and 10 MPa due to Varying CC/PKSA content

Since the significance level of 0.00 is less than 0.05, then a significant difference exists in the wet compressive strength of CSEBs. Hence, a variation in the compaction pressure and stabilizer content significantly influenced the WCS at 6 MPa, as seen in Tables 4.8 to 4.11. It is therefore inferred that the addition of PKSA to cement increased the blocks' resistance to impact and subsequently, its compressive strength, which in turn reduces its susceptibility to shrinkage and swelling by providing a waterproofing effect achieved by shutting all voids and pores present (Amin *et al*, 2022). By strengthening the soil, the stabilizer content worked to reduce excessive cracking, contraction and expansion. Therefore, the more the compaction, the higher the impact of stabilisation.

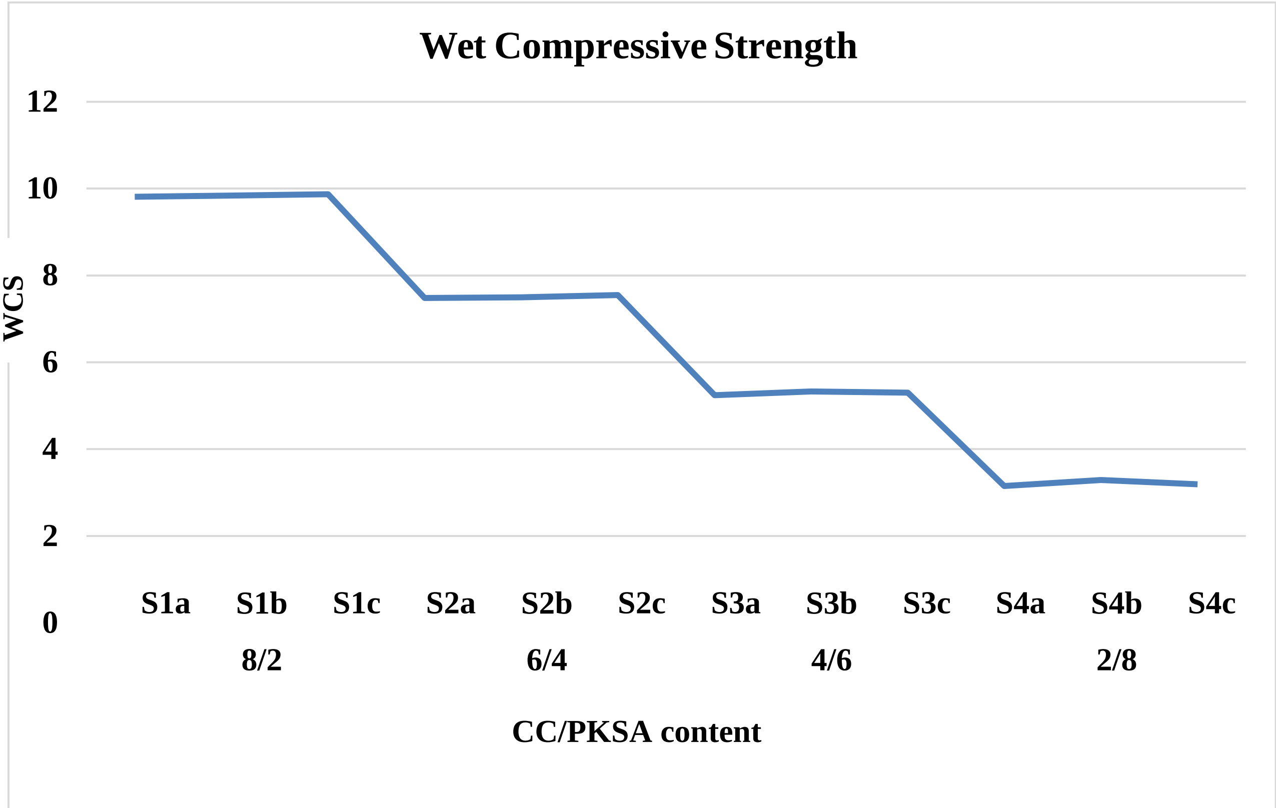

Figure 4.3: Graph Showing Impact of Cement Content and PKSA variation on WCS (6 MPa)

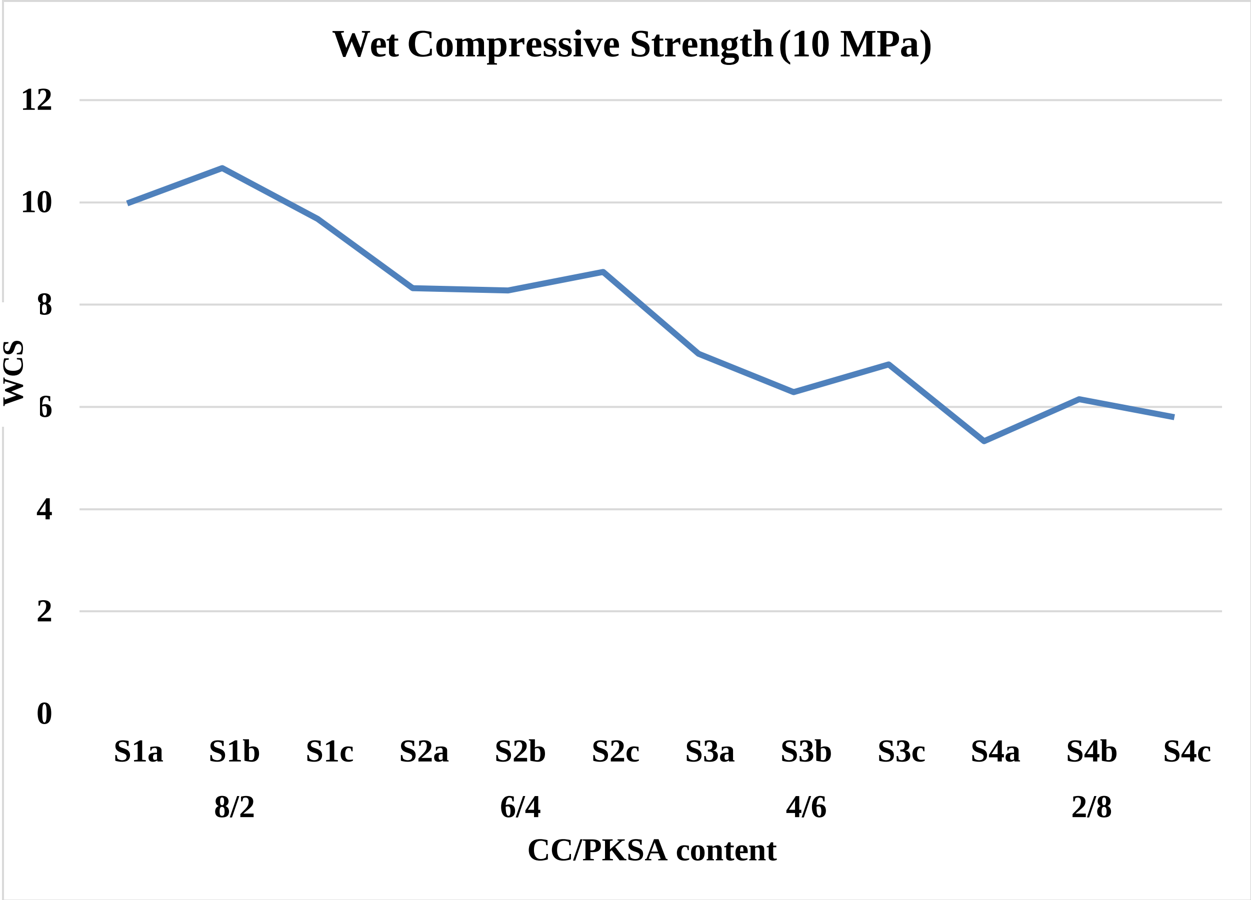

Figure 4.4: Graph Showing Impact of Cement Content and PKSA variation on WCS (10 MPa)

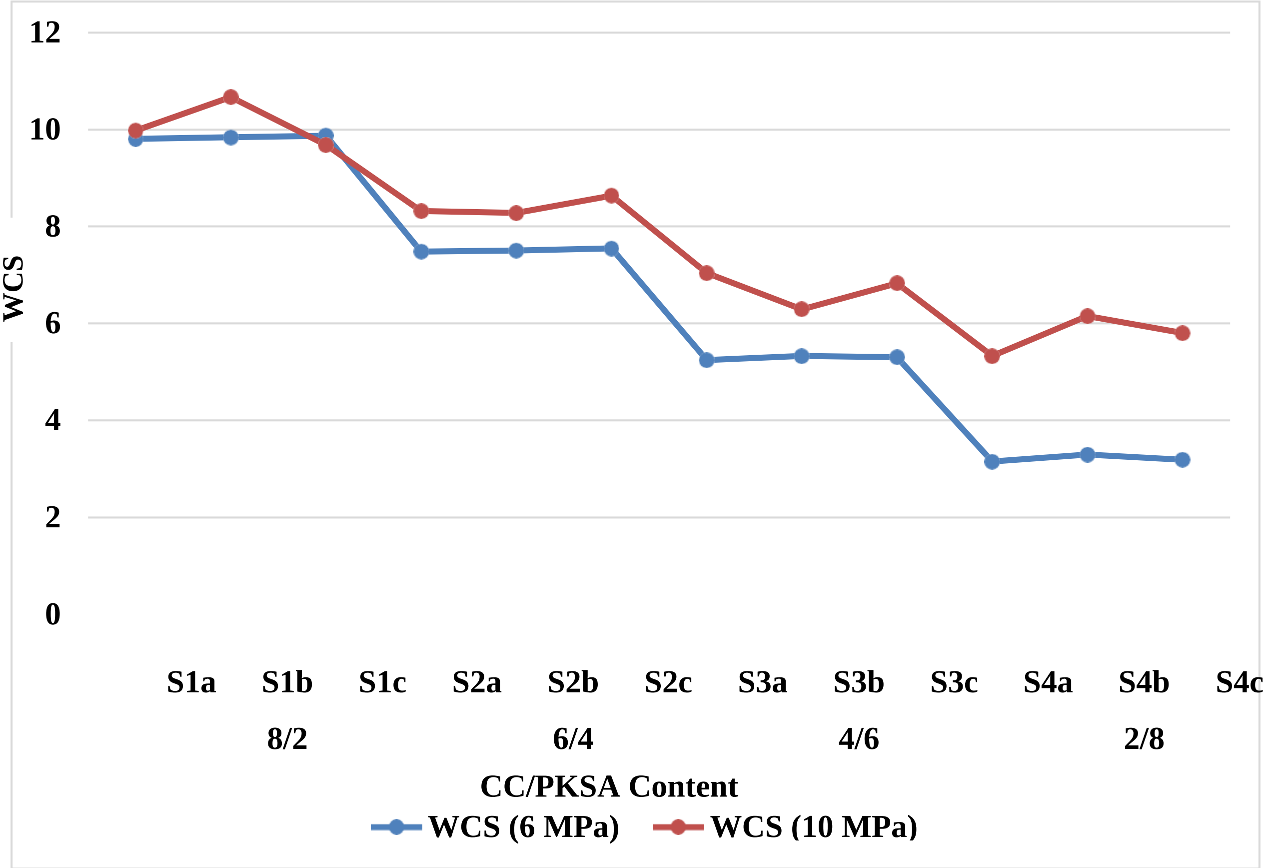

Figure 4.5: Impact of Cement Content and PKSA variation on WCS (6 and 10 MPa)

Table 4.8: Descriptive Statistics of WCS at 6 MPa due to varying Cement/PKSA content

Descriptive								
WCS (6 MPa)								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
6S1	3	9.8400	.03000	.01732	9.7655	9.9145	9.81	9.87
6S2	3	7.5100	.03606	.02082	7.4204	7.5996	7.48	7.55
6S3	3	5.2900	.04583	.02646	5.1762	5.4038	5.24	5.33
6S4	3	3.2100	.07211	.04163	3.0309	3.3891	3.15	3.29
Total	12	6.4625	2.58305	.74566	4.8213	8.1037	3.15	9.87

Table 4.9: ANOVA of varying CC/PKSA at 6 MPa

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	73.375	3	24.458	10298.22	0.00
Within Groups	0.019	8	0.002		
Total	73.394	11			

Table 4.10: Descriptive Statistics of WCS at 10 MPa due to varying Cement/PKSA content

Descriptive								
WCS (10 MPa)								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
6S1	3	10.1100	.50764	.29309	8.8489	11.3711	9.68	10.67
6S2	3	8.4133	.19732	.11392	7.9232	8.9035	8.28	8.64
6S3	3	6.7200	.38691	.22338	5.7589	7.6811	6.29	7.04
6S4	3	5.7600	.41146	.23756	4.7379	6.7821	5.33	6.15
Total	12	7.7508	1.76643	.50992	6.6285	8.8732	5.33	10.67

Table 4.11: ANOVA of varying Cement/PKSA Content at 10 MPa

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	33.092	3	11.031	71.67	0.00
Within Groups	1.231	8	0.154		
Total	34.323	11			

4.3.5 Assessing the difference between WCS at 6 MPa and 10 MPa due to Varying CC/PKSA content and Control using T-test Analysis

The results of the above analysis are presented in Table 4.12. A significance level of 0.00 was recorded, which is lesser than 0.05 in all mixes, which implies that Cement/PKSA of 8/2 increases WCS and this increase is significant. The significance level of 0.00 indicates that the observed increase in wet compressive strength for the Cement/PKSA ratio of 8/2 is highly unlikely to have occurred by chance. It suggests that the difference in wet compressive strength between this specific mixture and the others is not due to random variation but is a genuine effect.

Wet compressive strength was significantly lower than the control in all mix except 6S1, whose significant value is greater than 0.05 when compaction pressure of 10MPa was applied. This implies that CC/PKSA of 8/2 increases the WCS but this increase is not significant, as seen in Table 4.13. Statistical rules define high significance as values less than 0.05 which is not the case here. The difference between the WCS at both compaction pressures further proves that changing the stabilizer content while increasing the compaction pressure has more influence on the wet compressive strength (Houben and Guillaud, 2008). The impact of the addition of PKSA at 2% was quite significant at 6 MPa but not at 10 MPa. This accounted for the recorded 79% increase in wet compressive strength.

4.3.6 Comparing the Ratio between the Mean Wet and Dry Compressive Strength

The values of dry compressive strength of CPBs, based on varying the stabilizer content, are shown in Table 4.14. The rate at which the disparity between mean wet and dry compressive strengths changes are shown in Table 4.15. Plots of the obtained values are shown in Figures 4.6 and 4.7. Table 4.15 summarizes the plotted values shown in Figure 4.6.

In CPBs, WCS values varied between 3.21 MPa and 9.84 MPa. Their DCS ranged from 4.61 MPa to 11.79 MPa. There was an approximate difference of 20% (for 8% cc) and 44% (for 2% cc) between mean WCS and DCS. This means that an increase in cement content provides a reduced difference between a block’s mean dry and wet strength in a block, whereas a lower PKSA content provides a higher disparity between the average DCS and WCS in the same block.

Table 4.12: Difference between WCS at 6 MPa due to Varying CC/PKSA content and Control using T-test Analysis

Class	Control = 8.99 T	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
6S1	49.075	2	0.00	0.85	0.7755	0.9245
6S2	-71.097	2	0.00	-1.48	-1.5696	-1.3904
6S3	-139.847	2	0.00	-3.7	-3.8138	-3.5862
6S4	-138.831	2	0.00	-5.78	-5.9591	-5.6009

Table 4.13: Difference between WCS at 10 MPa due to Varying CC/PKSA content and Control using T-test Analysis

	Control = 8.99					
Class	**T**	**Df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
10S1	3.821	2	0.062	1.12	-0.1411	2.3811
10S2	-5.062	2	0.037	-0.57667	-1.0668	-0.0865
10S3	-10.162	2	0.01	-2.27	-3.2311	-1.3089
10S4	-13.597	2	0.005	-3.23	-4.2521	-2.2079

Table 4.14: Dry Compressive Strength

S/N	Sample No CSA = 10,000 mm^2 Loading Rate = 15 KN	Cement Content (%)	PKSA Content (%)	Maximum Load (KN)	Dry Compressive Strength (28 days)	Mean Dry Compressive Strength (28 days)
1	6S1a	8	2	119.7	11.97	11.79
	6S1b	8	2	119.4	11.94	
	6S1c	8	2	114.6	11.46	
2	6S2a	6	4	96.9	9.69	9.66
	6S2b	6	4	96.4	9.64	
	6S2c	6	4	96.5	9.65	
3	6S3a	4	6	73.1	7.31	7.33
	6S3b	4	6	73.0	7.30	
	6S3c	4	6	73.8	7.38	
4	6S4a	2	8	46.6	4.66	4.61
	6S4b	2	8	45.7	4.57	
	6S4c	2	8	46.0	4.60	

Table 4.15: Values of the average WCS and DCS of CPBs at 28 days

Cement Content (%)	PKSA Content (%)	Mean Compressive Strengths (MPa)	
		6 MPa (WCS)	6 MPa (DCS)
8	2	9.84	11.79
6	4	7.51	9.66
4	6	5.29	7.33
2	8	3.21	4.61

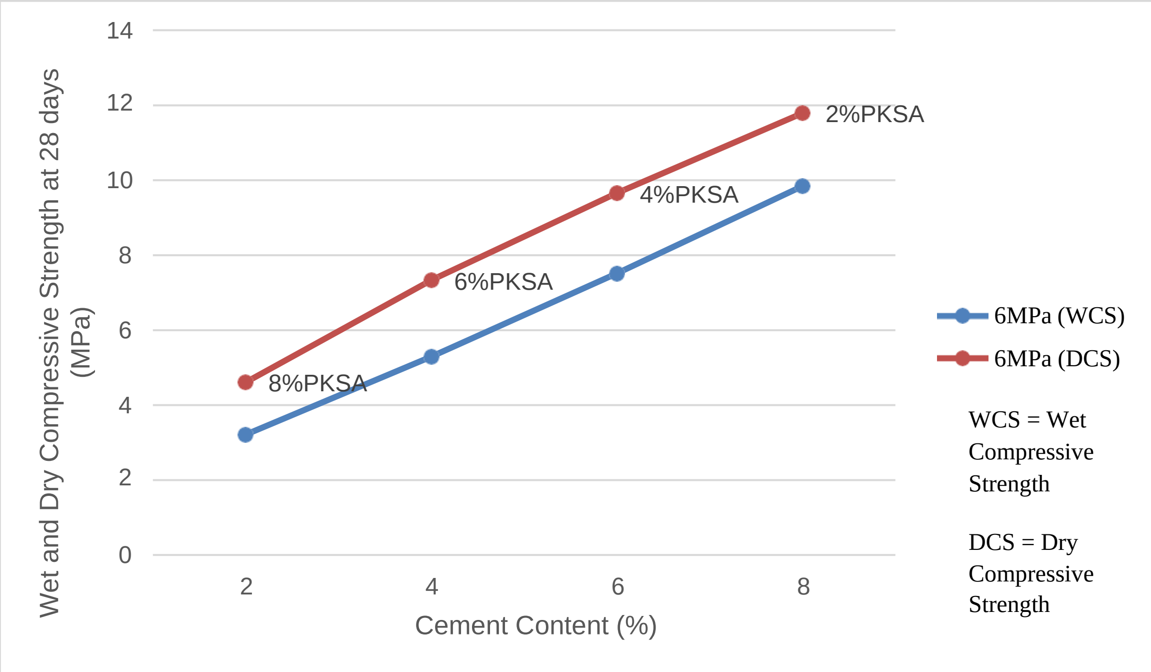

Fig 4.6: Comparing the Average WCS and DCS in CPB

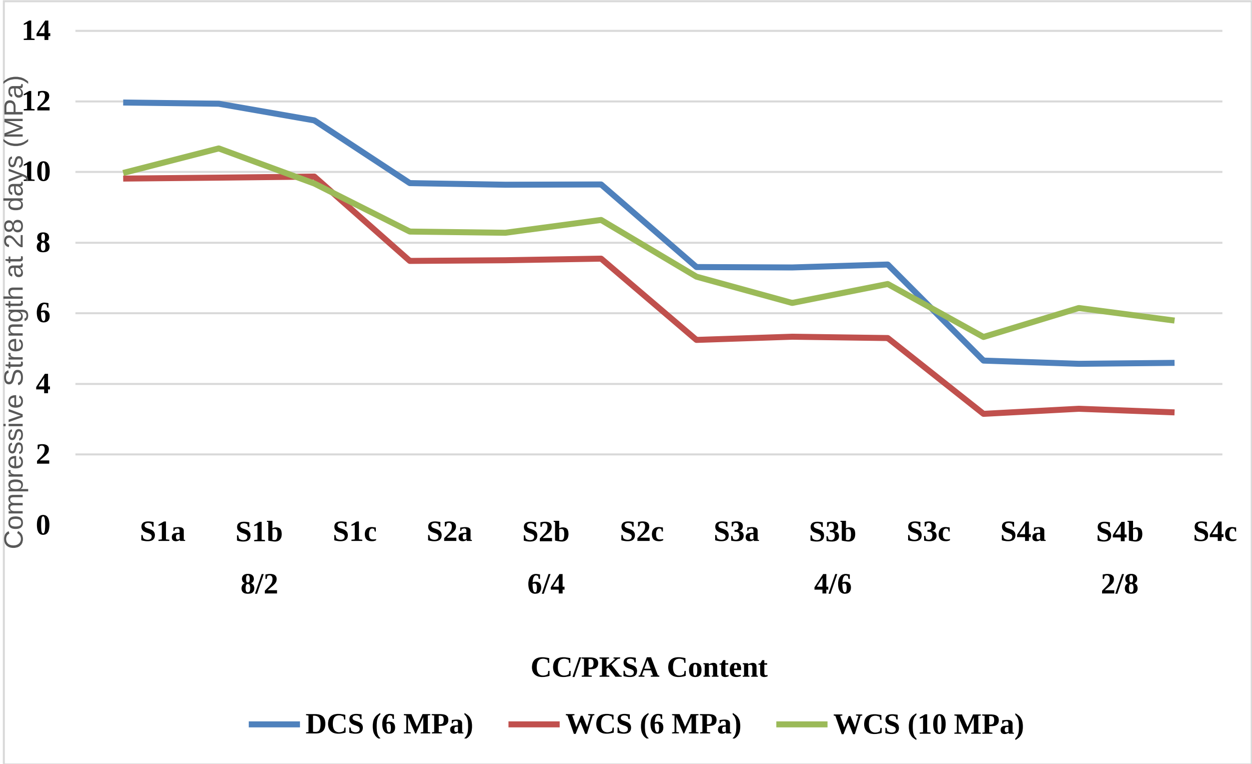

Figure 4.7: Comparing the Ratio between Mean Wet and Dry Compressive Strengths

Similarly, results for CMBs are in agreement with those from earlier research. Stabilised blocks were observed to differ between 35% and 120% in strength (Hall *et al.*, 2012). In CPBs, the disparity between the mean wet and dry compressive strengths has been reduced substantially, representing a breakthrough in CSEB development. In general, the larger the gap between the average wet and dry compressive strength, the weaker the bonding strength is likely to be (Houben *et al*, 2008). A greater degree of bonding within the block is attributed to the greater strength of CPBs compared to CMBs. In this case, PKSA, when added to the mix, caused the pozzolanic reaction that led to an improvement in this case. Using this Cement-Palm Kernel Ash mix in average proportions (2 to 8% of cement content) is preferred to mixing just OPC in particular situations because the rate at which the strength increased can be credited to the pozzolanic reaction between PKSA and OPC.

During the hydration reaction of Ordinary Portland Cement (OPC) in traditional blocks, it is observed that the resulting OPC hydrates tend to move away from the cement grains (Taylor, 1998; Weidemann et al., 1990). As a consequence, blocks tend to remain weak, permeable, and sparse. However, the presence of Palm Kernel Shell Ash (PKSA) brings about a significant change in this behaviour. When PKSA is incorporated into the mixture, notable transformations occur due to the added strength brought about by its pozzolanic reaction with cement in the presence of water. As anticipated, the outcome is a matrix that is impermeable, more homogeneous, and denser than what was previously achievable. The resulting matrix exhibits a significantly higher density and homogeneity. The data obtained from this study demonstrates a remarkable improvement in the properties of the blocks. This improvement encompasses various benefits, including increased strength, density, and hardness, as well as enhanced resistance to abrasion. Therefore, the incorporation of PKSA in the mixture leads to the formation of a more compact and uniform matrix, which contributes to the enhanced properties of the blocks. These findings have important technical implications for the manufacturing and utilization of blocks, offering the potential for superior performance and durability in various applications.

Comparing wet compressive strength and dry compressive strength is important for several reasons. It helps assess the material's sensitivity to moisture, evaluate its durability, understand its performance under realistic conditions, and ensure compliance with quality control standards. By comparing the strength values in wet and dry conditions, potential weaknesses related to moisture-induced degradation can be identified and informed decisions can be made regarding material selection and structural design. Overall, this comparison provides valuable insights into the material's behaviour and performance in different environments.

4.3.7 Analysis of the Ratio of Average Dry Compressive Strength (DCS) and Wet Compressive Strength (WCS)

A high positive correlation exists between WCS and DCS. The Pearson Correlation of 0.995 is significant at 0.05 p-level since significance is 0.00, which is less than 0.05. This is presented in Table 4.16. Dry compressive strength was found to have 33.48% variation from its mean, which is lesser than that of wet compressive strength. All the results are shown in Table 4.17. A high positive correlation between WCS and DCS implies that the relationship between these two variables move in the same direction, that is, in tandem (Houben *et al*., 2008). In the case of block samples compacted at 6 MPa and with varying proportions of stabilizer (such as PKSA), it was observed that both the wet compressive strength and dry compressive strength values increased. However, an interesting trend was noticed with respect to the effect of PKSA content on the compressive strength values.

i. Wet Compressive Strength: Increasing the percentage of PKSA content resulted in an increase in wet compressive strength. This suggests that incorporating more PKSA into the mixture led to improved bonding and hydration, resulting in higher strength values when the blocks were tested in a saturated state. This increase in wet compressive strength indicates a positive impact of PKSA on the overall strength performance of the blocks.
ii. Dry Compressive Strength: Contrary to the trend observed in wet compressive strength, increasing the percentage of PKSA content had a diminishing effect on dry compressive strength. While the dry compressive strength values still remained higher than the recommended values, the increase in PKSA content led to a reduction in strength compared to the blocks with lower PKSA content.

Table 4.16: Analysis of the Ratio of Average DCS and WCS of CPBs at 28 days

		WCS (6 MPa)	**DCS (6 MPa)**
WCS (6 MPa)	Pearson Correlation	1	0.995**
	Sig. (2-tailed)		0.00
DCS (6 MPa)	Pearson Correlation	0.995**	1
	Sig. (2-tailed)	0.00	

Table 4.17: Descriptive Statistics of DCS at 6 MPa

	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
6S	4.57	11.97	8.3475	2.79458	33.48

This observation suggests that while PKSA incorporation improves the wet compressive strength, it may have a slightly detrimental effect on the dry compressive strength. The reason for this discrepancy could be attributed to the characteristics of PKSA itself, such as its impact on the hydration process. It is worth noting that despite the reduction in dry compressive strength with increasing PKSA content, the values remained higher than the recommended levels. This implies that the blocks with higher PKSA content still exhibited sufficient strength for their intended applications.

In summary, the results indicate that increasing PKSA content enhances the wet compressive strength of the blocks while having a slight negative impact on the dry compressive strength. However, even with the reduction in dry strength, the blocks still met or exceeded the recommended strength requirements, suggesting that the addition of PKSA can be a beneficial component in improving the overall performance of the blocks. The results are shown in Figure 4.8.

An analysis of variance (ANOVA) test was performed to examine the impact of varying the cement/PKSA content on the dry compressive strength (DCS) of compressed stabilized earth blocks (CSEBs) at a compaction pressure of 6 MPa. The results of the ANOVA test indicated a significance level of 0.00, which is lower than the conventional threshold of 0.05 used to determine statistical significance. In statistical analysis, a significance level below 0.05 suggests that the observed differences are unlikely to have occurred by chance alone. In this case, the results indicate that there is a significant and notable difference in the dry compressive strength of the CSEBs when the cement/PKSA content is varied. The variations in the proportions of cement and PKSA, along with the applied moulding pressure, have a statistically significant impact on the dry compressive strength at the 6 MPa compaction pressure.

The findings from this ANOVA test provide strong evidence to support the conclusion that altering the stabilizer proportion (cement/PKSA content) and the moulding pressure lead to significant changes in the dry compressive strength of the CSEBs. These variables have a discernible influence on the structural integrity and strength characteristics of the blocks and by understanding the statistical significance of these factors, it becomes possible to optimize the composition and production process of CSEBs. The analysis of the ratio of average DCS and WCS of CPBs at 28 days are presented in Tables 4.18 and 4.19.

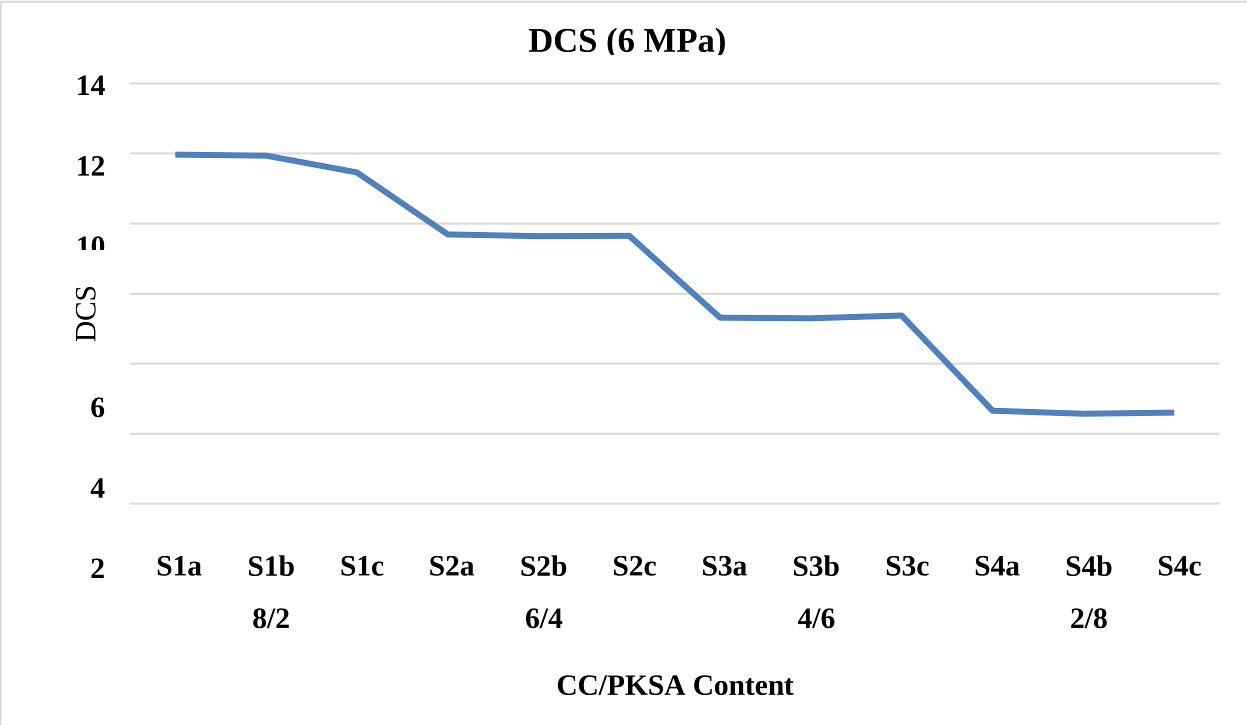

Figure 4.8: Impact of Cement Content and PKSA variation on DCS (6 MPa)

Table 4.18: Descriptive Statistics of DCS at 6 MPa due to varying Cement/PKSA content

Descriptive								
DCS (6 MPa)								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
6S1	3	11.7900	.28618	.16523	11.0791	12.5009	11.46	11.97
6S2	3	9.6600	.02646	.01528	9.5943	9.7257	9.64	9.69
6S3	3	7.3300	.04359	.02517	7.2217	7.4383	7.30	7.38
6S4	3	4.6100	.04583	.02646	4.4962	4.7238	4.57	4.66
Total	12	8.3475	2.79458	.80672	6.5719	10.1231	4.57	11.97

Table 4.19: Analysis of Variance (ANOVA) of DCS at 6 MPa due to Varying CC/PKSA content

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	85.733	3	28.578	1319.985	0.00
Within Groups	0.173	8	0.022		
Total	85.906	11			

4.3.8 The Impact of Mix Holdback Time on WCS of Blocks

Wet compressive strength can be affected by introducing mix holdback time experimentally, thereby determining how much it affects this variable. In this study, only control blocks were investigated, which were stabilized with 6% cement and compressed at 6 MPa, under normal curing conditions, and contained the same mix-water content as the other blocks. It was also discovered that CPBs had a similar effect. During fieldwork, it was observed that large batches could not be moulded within one hour, as evidenced by experimental results.

Table 4.20 and Figure 4.9 show the mean values corresponding to the experimental results. Three block specimen samples are averaged for each point. As the holdback time increased from 5 to 120 minutes, at 28 days, WCS decreased at the range of 5.28 - 2.07 MPa (which is approximately a 61% loss).

The results indicate that the blocks that were compacted immediately after wet mixing exhibited 14% higher strength and resilience compared to the blocks that underwent a holdback period of 60 minutes before compaction. This observation is particularly evident when the wet mixing process was completed within 30 minutes. Other researchers have reported similar results. As an example, Rigassi (1995) found that strength diminished by 50% after two hours. Additionally, the samples that were compressed in 20 minutes of mixing with water showed a 30 to 40% increase in strength compared to the blocks compacted after about 45 minutes, according to Houben and Guillaud (2008).

Weidemann *et al*. (1990) used 45 minutes as a yardstick to approximate the time when OPC is beginning to set. When OPC is used as a stabilizer, results show that a gradual reduction in strength should be expected. It is therefore recommended to compact OPC stabilised blocks between 20 to 45 minutes of mixing. Still, mixing batches for hourly production is a common field practice that ends up not being used up immediately. According to this discussion, production methods used during block production can significantly affect the final product's quality. Thus, all stages of CSEB production should be conducted with equal degree of supervision, competence, and skill.

Table 4.20: Wet compressive strength values (28-day) of CSEBs compacted at various holdback times

Time (mins)	WCS 28-day (MPa)
5	5.28
30	5.13
60	4.41
90	2.59
120	2.07

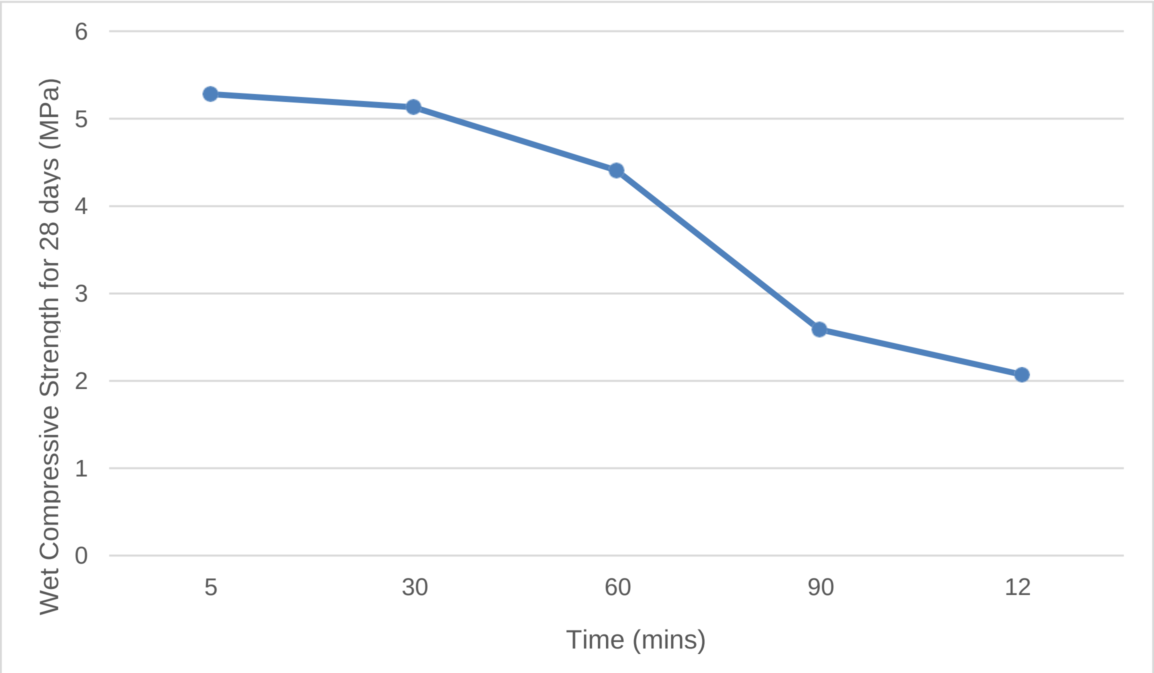

Figure 4.9: Decline of WCS with Increase in Holdback Times of CPBs

4.4 Block Dry Density

A total of three samples from each category were tested for the block specimens and their means were used for further analysis. Densities were calculated to the nearest 10 kg/m^3 in each case (BS 3921, 1985; BS 6073: Part 2, 1981). All the results are presented in Tables 4.21 to 4.23.

4.4.1 Effect of Altering Stabiliser and Pressure on Density

In addition to the above variables, the impact of changing them on the density was also experimented. There was a limited number of CMBs that were compressed at different compaction pressures from 6 to 10 MPa. Figure 4.10 illustrates the plotted results, and Table 4.24 summarizes the scale of dry density results recorded for both CMBs and CPBs. Increased compaction pressure led to an increase in density. Further, partially replacing cement with other materials may be an economical way to achieve high densities. A partial cement replacement material like PKSA was found to have further beneficial effects on the results. Increasing the percentage of PKSA content reduces volume and Density. However, volume rises between CC/PKSA ratio of 4/6 and 2/8, as seen in Figure 4.11.

The descriptive statistics analysis reveals interesting findings about the block dry density (BDD) at different compaction pressures. At 6 MPa, the BDD shows lower variability, as indicated by a coefficient of variation of 0.60. However, the density itself is relatively lower compared to the density observed at 10 MPa, as presented in Table 4.25. The higher variability of BDD at 10 MPa, with a coefficient of variation of 1.24, can be attributed to factors such as friction and tightness or locking among the particles (Jackson and Dhir, 1996). These factors affect the compaction process and particle arrangement, resulting in variations in density measurements.

When comparing the BDD ratio between 6 MPa and 10 MPa, an interesting trend emerges. An increase in the percentage of PKSA content leads to a reduction in block dry density at both compaction pressures, as shown in Figure 4.12. This suggests that incorporating more PKSA as a partial replacement for cement affects the overall density of the blocks. However, it is important to note that even with the decrease in density due to increased PKSA content, the values recorded at 6/4 (CC/PKSA) content still exceed the recommended values of 2100 kg/m^3. This implies that the blocks with this composition still meet or exceed the minimum density requirements for their intended applications.

Table 4.21: Block Dry Density (Control at 6 MPa)

s/ n	Sample No	Cement/ pksa content	Dimensions				Oven dry mass			Density	
			L	W	H	Gross Volume	1	2	3	Sum	Mean
			mm	mm	mm	m^3 ($x10^{-3}$)	g	g	g	Kg/m^3	Kg/m^3
1	Control 1a	10/0	101.2	99.5	101.3	1.0200	2171.7	2171.6	2171.6	2129	2128
	Control 1b	10/0	101.1	99.7	101.3	1.0211	2168.9	2168.9	2168.8	2124	
	Control 1c	10/0	101.2	99.7	101.4	1.0231	2180.3	2180.3	2180.2	2131	

Table 4.22: Block Dry Density (6 MPa)

s/n	Sample No	cement pksa content	Dimensions				Oven dry mass			Density	
			L	W	H	Gross Volume	1	2	3	Sum	Mean
			mm	mm	mm	m^3 $(x10^{-3})$	g	g	g	Kg/m^3	Kg/m^3
1	6S1a	8/2	101.1	99.9	101.2	1.0221	2179.2	2178.2	2178.1	2131	2132
	6S1b	8/2	101.4	99.8	101.1	1.0231	2185.8	2185.3	2185.33	2135	
	6S1c	8/2	101.3	99.9	101.1	1.0231	2178.6	2178.2	2178.2	2129	
2	6S2a	6/4	101.3	99.5	101.1	1.0190	2172.8	2172.6	2172.6	2132	2127
	6S2b	6/4	101.2	99.7	101.1	1.0200	2167.9	2167.6	2167.6	2125	
	6S2c	6/4	101.2	99.5	101.3	1.0200	2167.8	2166.8	2166.5	2124	
3	6S3a	4/6	101.1	99.7	101.1	1.0190	2153.1	2152.3	2152.2	2112	2114
	6S3b	4/6	101.0	99.6	101.0	1.0160	2149.6	2149.2	2148.9	2115	
	6S3c	4/6	101.0	99.8	101.0	1.0180	2153.4	2153.2	2153.2	2115	
4	6S4a	2/8	101.1	99.6	101.4	1.0210	2153.9	2153.4	2153.4	2109	2102
	6S4b	2/8	101.2	99.6	101.4	1.0220	2146.8	2146.3	2146.3	2100	
	6S4c	2/8	101.4	99.7	101.3	1.0241	2147.9	2147.6	2147.5	2097	

Table 4.23: Block Dry Density (10 MPa)

s/n	Sample No	cement pksa content	Dimensions				Oven dry mass			Density	
			L	W	H	Gross Volume	1	2	3	Sum	Mean
			mm	Mm	mm	m^3 ($x10^{-3}$)	g	g	g	Kg/m^3	Kg/m^3
1	10S1a	8/2	101.2	99.6	101.4	1.02514	2247.3	2247.2	2247.1	2191	2194
	10S1b	8/2	101.1	99.8	101.3	1.02209	2247.9	2247.8	2247.6	2199	
	10S1c	8/2	101.4	99.8	101.4	1.02614	2248.5	2248.4	2248.3	2191	
2	10S2a	6/4	101.1	99.8	101.2	1.02109	2221.3	2221.0	2220.9	2175	2176
	10S2b	6/4	101.3	99.7	101.3	1.02309	2230.5	2230.3	2230.0	2180	
	10S2c	6/4	101.2	99.6	101.2	1.02005	2216.7	2216.7	2216.6	2173	
3	10S3a	4/6	101.3	99.7	101.1	1.0211	2193.4	2193.3	2193.3	2148	2149
	10S3b	4/6	101.3	100.1	101.0	1.0242	2201.9	2201.9	2201.9	2150	
	10S3c	4/6	101.1	99.9	101.2	1.0221	2196.8	2196.8	2196.5	2149	
4	10S4a	2/8	101.3	99.5	101.1	1.01902	2172.8	2172.6	2172.6	2132	2127
	10S4b	2/8	101.2	99.7	101.1	1.02006	2167.9	2167.6	2167.6	2125	
	10S4c	2/8	101.2	99.5	101.3	1.02003	2167.8	2166.8	2166.5	2124	

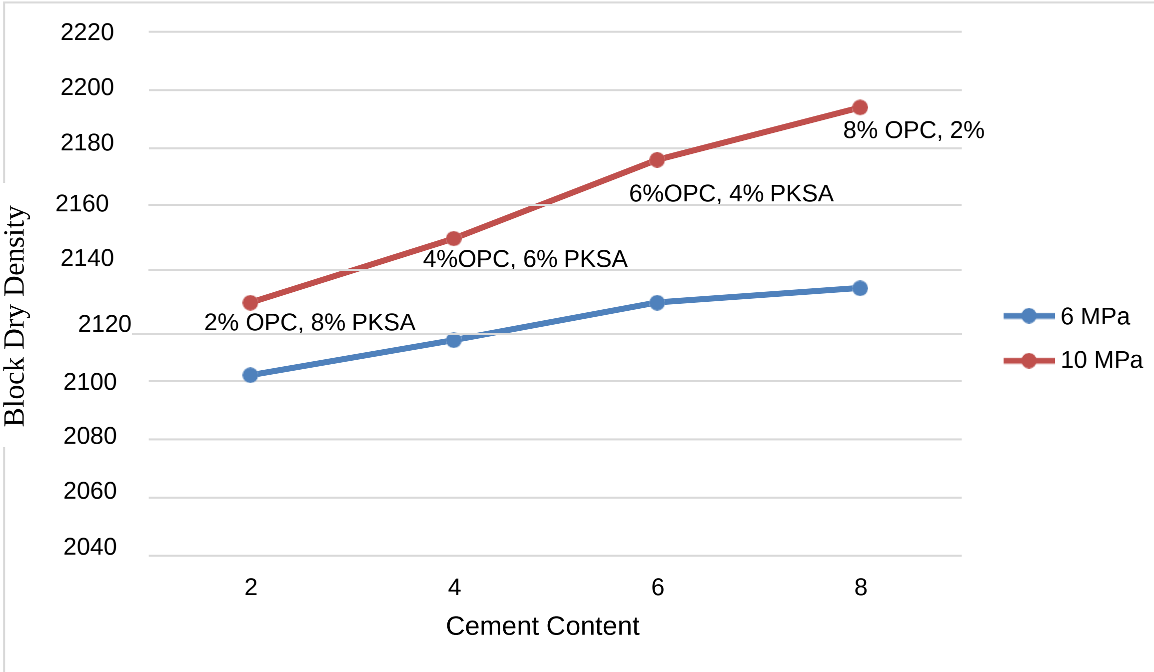

Fig 4.10: The Impact of Varying Compaction Pressure and Stabiliser Content and on Block Dry Density

Table 4.24: Block dry density values for Control blocks and cement-palm kernel blocks

Type	Compaction Pressure MPa	BDD range values Kg/m^3	Density increase in OPC from 2% to 8% %
Control Mix	6	2128 (Mean)	-
CPB	6	2102 - 2132	1.0
CPB	10	2127 - 2194	3.1

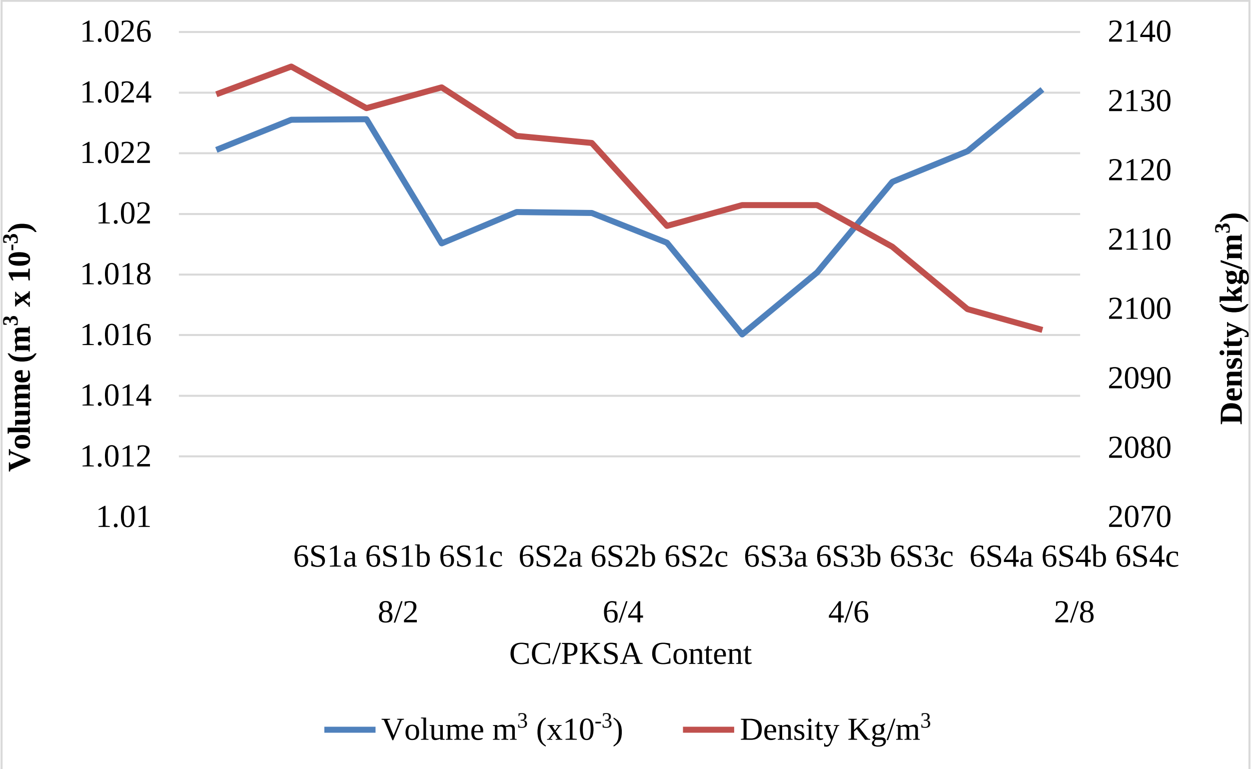

Figure 4.11: Relationship between Stabilizer Content, Compaction Pressure and Density

Table 4.25: Descriptive Statistics of Block Dry Density at 6 MPa and 10 MPa

Variable	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variance
Density(6 MPa)	2097	2135	2118.67	12.63	0.60
Density(10 MPa)	2124	2199	2161.42	26.77	1.24

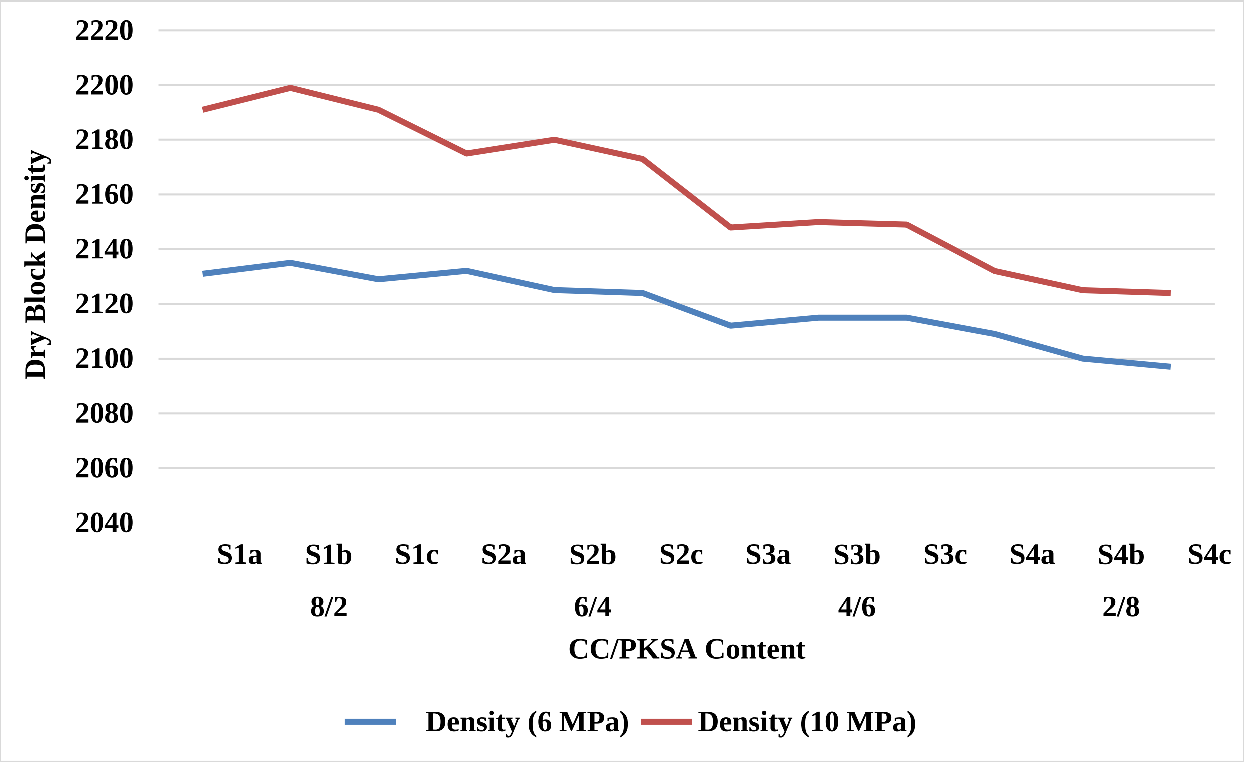

Figure 4.12: Comparison of the Ratio between Block Dry Density at 6 and 10 MPa

These findings provide valuable insights for optimizing the composition of the blocks by considering the appropriate percentage of PKSA content. The results suggest that using more than 4% PKSA content as a replacement for cement may lead to a decrease in block dry density beyond acceptable limits. Therefore, it is recommended to limit the PKSA content to no more than 4% to ensure that the blocks maintain the desired density for structural integrity.

In summary, the analysis highlights the variability in block dry density at different compaction pressures and the influence of PKSA content on density. The findings underscore the importance of carefully selecting the PKSA percentage and considering the target dry density requirements to ensure the blocks meet the recommended standards for density and overall performance.

4.4.2 The relationship between Density and Strength

Denser blocks offer better performance, so density is an important benchmark of durability and strength in a block. In Table 4.26 and Figure 4.13, block dry density experimental results are compared to those achieved for 28-day WCS.

As can be seen in Figure 4.13, wet compressive strength and block dry density are positively correlated for all types of blocks tested. Increasing density translates into greater strength, as shown in the graph. The coefficient or measurement of correlation, as well as the P-values are: CMBs (0.972; 0.008), CPBs (0.995; 0.001). Thus, density and strength are strongly correlated, and this correlation has been widely reported (Jackson and Dhir, 1996).

Materials with similar dry density values are:

i. Bricks that have been fired: 2260-2850 kg/m^3

ii. Bricks made with calcium silicate: 1800-2200 kg/m^3

iii. Concrete blocks: 600-2200 kg/m^3

In most parts of the world, clay brick is the most popular building material and these values are similar to those determined experimentally for CSEBs (Minke, 2009). These blocks have a higher density, higher strength, and longer durability than comparable materials. Higher densities may have some drawbacks in terms of handling and transportation, although it is expected that these types of blocks will be produced on-site. In addition to their difficulty in laying on the ground, very heavy blocks are usually very expensive to transport (Hall *et al.*, 2012).

Table 4.26: Block Dry Density and Wet Compressive Strength Values for CPBs

Compaction Pressure	Block Samples	OPC (%)	PKSA (%)	WCS (MPa)	BDD (kg/m^3)
6 MPa	6S1	8	2	9.84	2132
	6S2	6	4	7.51	2127
	6S3	4	6	5.29	2114
	6S4	2	8	3.21	2102
10 MPa	10S1	8	2	10.11	2194
	10S2	6	4	8.41	2176
	10S3	4	6	6.72	2149
	10S4	2	8	5.76	2127

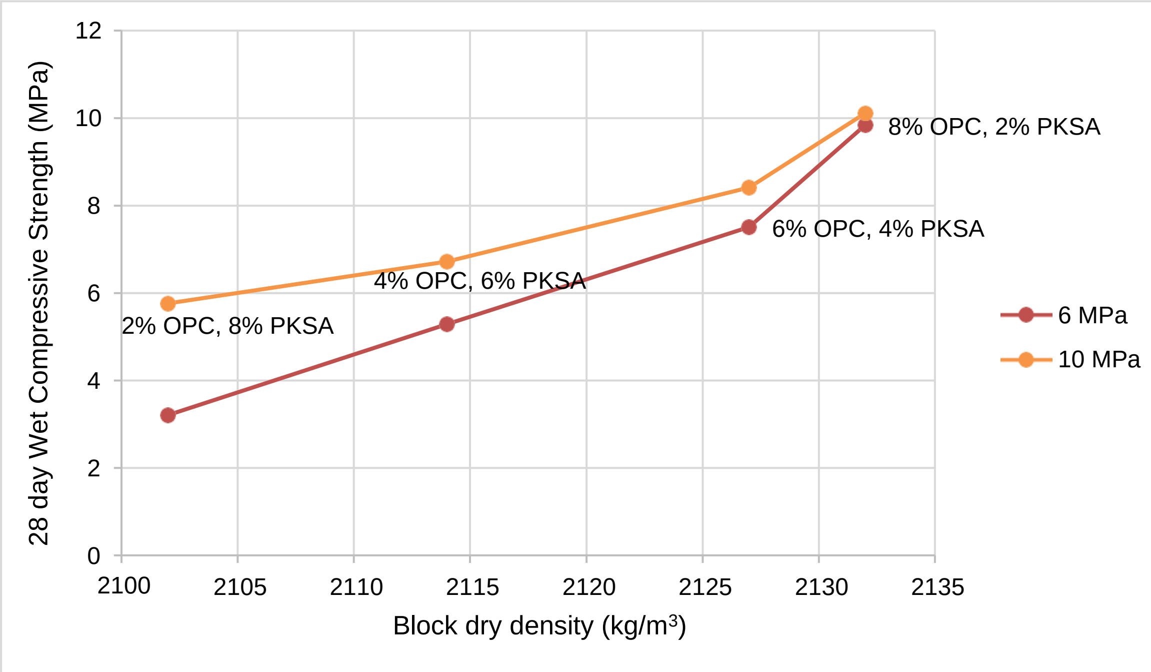

Fig 4.13: Correlation between Block Dry Density and Wet Compressive Strength

4.4.3 Analysis of Variance (ANOVA) of Density at 6 MPa and 10 MPa due to Varying CC/PKSA content

The statistical analysis reveals that there is a significant and notable difference in the Block Dry Density (BDD) of Compressed Stabilized Earth Blocks (CSEBs) based on the obtained significance values. The significance level of 0.00, which is lower than the conventional threshold of 0.05, indicates that the observed differences in BDD are highly unlikely to have occurred by chance alone. This implies that the results are statistically significant.

If the significance value were greater than 0.05, it would suggest that the variation in the Stabilizer Content and Moulding Pressure had a non-significant impact on the BDD. However, this is not the case in the analysis. The obtained significance values of 0.00 indicate a significant impact of varying the Stabilizer Content and Moulding Pressure on the BDD at 6 MPa, as presented in Tables 4.27 and 4.28.

Similarly, at 10 MPa, the obtained significance value of 0.00 confirms a significant and notable difference in the BDD of CSEBs. The same statistical rules apply here as well, where the significance value being less than 0.05 indicates the presence of a significant impact. The compaction pressure of 6 MPa and the specific stabilizer content used play crucial roles in determining the density of the compressed earth blocks (Hall *et al.*, 2012).

Thus, the results demonstrate a statistically significant relationship between the variation in moulding pressure, stabilizer content, and the resulting BDD at both 6 MPa and 10 MPa, as presented in Tables 4.29 and 4.30. These findings emphasize the importance of considering the compaction pressure and the selection of stabilizer content when aiming to achieve desired densities in CSEBs.

In conclusion, the statistical analysis confirms that the variation in stabilizer content and moulding pressure significantly affects the Block Dry Density of CSEBs at 6 MPa and 10 MPa. These findings highlight the importance of carefully controlling these factors to achieve the desired density and optimize the performance of the compressed earth blocks.

Table 4.27: Descriptive Statistics of Density at 6 MPa due to varying Cement/PKSA content

Descriptive								
Density (6 MPa)								
	N	**Mean**	**Std. Deviation**	**Std. Error**	**95% Confidence Interval for Mean**		**Minimum**	**Maximum**
					Lower Bound	**Upper Bound**		
6S1	3	2131.6667	3.05505	1.76383	2124.0775	2139.2558	2129.00	2135.00
6S2	3	2127.0000	4.35890	2.51661	2116.1719	2137.8281	2124.00	2132.00
6S3	3	2114.0000	1.73205	1.00000	2109.6973	2118.3027	2112.00	2115.00
6S4	3	2102.0000	6.24500	3.60555	2086.4866	2117.5134	2097.00	2109.00
Total	12	2118.6667	12.62993	3.64595	2110.6420	2126.6913	2097.00	2135.00

Table 4.28: ANOVA of Density at 6 MPa due to Varying CC/PKSA content

	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	1614	3	538	30.597	0.00
Within Groups	140.667	8	17.583		
Total	1754.667	11			

Table 4.29: Descriptive Statistics of Density at 10 MPa due to varying Cement/PKSA content

Descriptive								
Density (10 MPa)								
	N	**Mean**	**Std. Deviation**	**Std. Error**	**95% Confidence Interval for Mean**		**Minimum**	**Maximum**
					Lower Bound	**Upper Bound**		
6S1	3	2193.6667	4.61880	2.66667	2182.1929	2205.1404	2191.00	2199.00
6S2	3	2176.0000	3.60555	2.08167	2167.0433	2184.9567	2173.00	2180.00
6S3	3	2149.0000	1.00000	.57735	2146.5159	2151.4841	2148.00	2150.00
6S4	3	2127.0000	4.35890	2.51661	2116.1719	2137.8281	2124.00	2132.00
Total	12	2161.4167	26.76992	7.72781	2144.4079	2178.4255	2124.00	2199.00

Table 4.30: ANOVA of Density at 10 MPa due to Varying CC/PKSA content

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7774.25	3	2591.417	190.779	0.00
Within Groups	108.667	8	13.583		
Total	7882.917	11			

4.4.4 Assessing the difference between Density at 6 MPa and 10 MPa due to Varying CC/PKSA content and Control using T-test Analysis

The analysis of density measurements reveals interesting findings for the different mixes of Compressed Stabilized Earth Blocks (CSEBs). In the case of blocks compacted at 6 MPa, it was observed that the density was generally lower compared to the control mix, except for the mix denoted as 6S1, which showed an increase in density. However, this increase was not statistically significant as the p-value of 0.173 was higher than the conventional threshold of 0.05. On the other hand, for mixes 6S3 and 6S4 (with CC/PKSA ratios of 4/6 and 2/8, respectively), the density was significantly decreased compared to the control mix. The significance level of 0.00, which is lower than 0.05, indicates that these variations in mix proportions had a significant and notable impact on reducing the density of the CSEBs, as shown in Table 4.31. In contrast, for blocks compacted at 10 MPa, the density was significantly higher than the control mix for all mixes except 10S4. The decrease in density observed in 10S4 was not statistically significant, with a p-value of 0.729, which is greater than 0.05.

The significance levels of 0.00 for mixes 10S1, 10S2, and 10S3 (with CC/PKSA ratios of 8/2, 6/4, and 4/6, respectively) indicate that these mix variations led to a significant increase in density compared to the control mix. These results are presented in Table 4.32. These findings demonstrate the influence of the mix proportions on the density of the CSEBs at different compaction pressures. The mix denoted as 6S1 showed an increase in density, but it was not statistically significant. In contrast, the mixes 6S3 and 6S4 led to a significant decrease in density at 6 MPa. Similarly, at 10 MPa, the mixes 10S1, 10S2, and 10S3 resulted in a significant increase in density, while the mix 10S4 did not show a significant change.

These results highlight the importance of carefully selecting the mix proportions, particularly the CC/PKSA ratios, to achieve the desired density in CSEBs. The significant impact observed in some mixes emphasizes the potential to optimize the density of CSEBs through appropriate mix design and compaction parameters.

Table 4.31: T-test of Varying CC/PKSA (6 MPa)

	Control Value = 2128					
Class	**t**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
6S1	2.079	2	0.173	3.66667	-3.9225	11.2558
6S2	-0.397	2	0.729	-1	-11.8281	9.8281
6S3	-14	2	0.005	-14	-18.3027	-9.6973
6S4	-7.211	2	0.019	-26	-41.5134	-10.4866

Table 4.32: T-test of Varying CC/PKSA (10 MPa)

	Test Value = 2128					
Class	**T**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	Upper
10S1	24.625	2	0.002	65.7	54.2	77.1
10S2	23.058	2	0.002	48.0	39.0	57.0
10S3	36.373	2	0.001	21.0	18.5	23.5
10S4	-0.397	2	0.729	-1.0	-11.8	9.8

4.5 Total Water Absorption (TWA) Test Results

In order to obtain the percentage or fraction of the initial mass of the specimen while dry, the total amount of water absorption was expressed to the nearest 0.1%. Tables 4.33 to 4.35 summarize all individual measurements.

4.5.1 Descriptive Statistics of Total Water Absorption (TWA) at 6 MPa and 10 MPa

The analysis of Total Water Absorption (TWA) reveals interesting findings regarding its variability at different compaction pressures. At 6 MPa, TWA shows lower variability, as indicated by a lower coefficient of variation compared to that at 10 MPa. The relatively lower TWA values at 10 MPa, as shown in Table 4.36, suggest a trend of reduced water absorption with higher compaction pressure. When comparing the ratio of TWA between 6 MPa and 10 MPa, it becomes evident that an increase in the percentage or proportion of PKSA content leads to an increase in TWA at both compaction pressures, as depicted in Figure 4.14. This observation suggests that incorporating more PKSA content in the mix influences the water absorption properties of the blocks. However, it is worth noting that the recorded TWA values fall within the range of recommended values, particularly at a CC/PKSA content of 6/4. This indicates that the blocks, even with increased PKSA content, still meet the acceptable standards for water absorption.

These findings support the understanding that higher compaction pressures, such as 10 MPa, tend to reduce the rate of water absorption in the blocks. This is attributed to the reduction of pore spaces within the blocks, as mentioned by Hall *et al.*, (2012). The denser structure achieved through higher compaction pressures limits the movement of water and reduces the rate of water absorption.

In summary, the analysis highlights the variability in Total Water Absorption at different compaction pressures and its relationship with the percentage of PKSA content. The lower variability at 6 MPa and the trend of reduced TWA at 10 MPa demonstrate the influence of compaction pressure on water absorption properties. The recorded TWA values within the recommended range further confirm the effectiveness of higher compaction pressures in reducing water absorption rates by minimizing pore spaces in the blocks. These findings contribute to the understanding of optimizing water absorption characteristics in Compressed Stabilized Earth Blocks.

Table 4.33: Total Water Absorption for Control Mix at 6 MPa

		Dry Mass 1	Dry Mass 2	Dry Mass 3	Wet Mass	TWA	Mean TWA
		g	g	g	g	%	%
Control 1	a	750.6	749.9	749.8	807.5	7.7	7.5
	b	744.8	744.7	744.6	801.9	7.7	
	c	754.4	753.4	753.3	806.8	7.1	

Table 4.34: Total Water Absorption for CPBs at 6 MPa

		Dry Mass 1	Dry Mass 2	Dry Mass 3	Wet Mass	TWA	Mean TWA
		g	g	g	g	%	%
6S1	**a**	781.8	781.7	781.7	835.6	6.9	6.8
	b	782.6	782.4	782.4	838.0	7.1	
	c	796.9	796.9	796.8	847.8	6.4	
6S2	**a**	770.4	770.1	770.1	827.1	7.4	7.0
	b	761.7	761.5	761.5	812.5	6.7	
	c	763.9	763.5	763.4	816.1	6.9	
6S3	**a**	740.8	739.9	739.8	801.2	8.3	7.8
	b	741.3	741.0	740.9	800.2	8.0	
	c	742.5	742.3	742.3	795.0	7.1	
6S4	**a**	722.9	722.8	722.8	792.2	9.6	9.8
	b	722.5	722.2	722.2	791.5	9.6	
	c	731.7	721.6	731.6	806.2	10.2	

Table 4.35: Total Water Absorption for CPBs at 10 MPa

		Dry Mass 1	Dry Mass 2	Dry Mass 3	Wet Mass	TWA	Mean TWA
		g	g	g	g	%	%
10S1	**a**	770.6	770.4	770.3	801.9	4.1	3.9
	b	769.9	769.7	769.5	797.2	3.6	
	c	772.5	771.8	771.8	801.1	3.8	
10S2	**a**	760.4	760.1	760.1	789.0	3.8	4.4
	b	765.3	764.8	764.8	803.0	5.0	
	c	763.5	763.5	763.4	796.2	4.3	
10S3	**a**	781.3	781.3	781.1	820.9	5.1	5.3
	b	776.7	776.6	776.5	821.5	5.8	
	c	782.7	782.4	782.4	821.5	5.0	
10S4	**a**	770.4	770.1	770.1	827.1	7.4	6.9
	b	761.7	761.5	761.5	812.5	6.7	
	c	763.9	763.5	763.4	816.1	6.9	

Table 4.36: Descriptive Statistics of Total Water Absorption (TWA) at 6 MPa and 10 MPa

Variable	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
TWA(6 MPa)	6.4	10.2	7.85	1.29	16.49
TWA(10 MPa)	3.6	7.4	5.13	1.31	25.55

Fig 4.14: Ratio between TWA at 6 MPa and 10 MPa

4.5.2 Effects of Varying the Stabilizer Content and Compaction Pressure on the TWA in Blocks

This segment examined both control mixes and CPBs. The result of the mean numbers recorded is shown in Figure 4.15 as well as Table 4.37. Also, an overview of the extreme values obtained is shown in Table 4.37. There is a negative relationship existing between increased stabilizer content and the total water absorption, as shown in Figure 4.15: the coefficient of correlation for CMBs was -0.947 (P = 0.014), and the coefficient of correlation for CPBs was -0.832 (P = 0.080). Increasing cement content and compaction pressure resulted in general reductions in water absorption. With a variation in cement content from 2% to 8%, the decrease averaged about 44% (Table 4.37). Water was found to be absorbed more readily by blocks with higher PKSA contents. This can be attributed to several factors, including the presence of additional porosity created by the PKSA material, a larger surface area available for water interaction and potential modifications to the pore structure within the blocks. In the presence of increased stabilizer content, absorption decreases gradually, but it diminishes over time. Almost all further reductions in absorption cease for both blocks once certain cement contents are reached. It is not feasible to reduce TWA significantly with an increase in OPC content beyond certain limits. Total water absorption values obtained in this study match well with those obtained for other materials of a similar nature and with the maximum value currently recommended for CSEBs, which is 15% (Hall *et al.*, 2012). However, despite the fact that this value is not absolute or widely accepted by researchers, it still has some value. Compared to the recommended values, the experimental values of TWA for CPBs were considerably lower. The results recorded were favourable and agreeable when put in comparison with the values of similar materials, for example, clay bricks 0 to 30%; calcium silicate bricks 6 to 16%; concrete blocks 4 to 25% (Jackson and Dhir, 1996). A total water absorption of less than 7% is considered low by BS 5628 Part 1, and one greater than 12% as high. It is therefore concluded that all blocks tested, including the control mix, have low TWA values. Based on these results, CSEBs are capable of absorbing substantial amounts of water and retaining it as well. Furthermore, CRMs (Cement Replacement Materials) can reduce water absorption by using them. Furthermore, the findings confirm that changing the stabilizer content of a block leads to improvement in block quality. Further sections will discuss the correlation between TWA and other bulk properties.

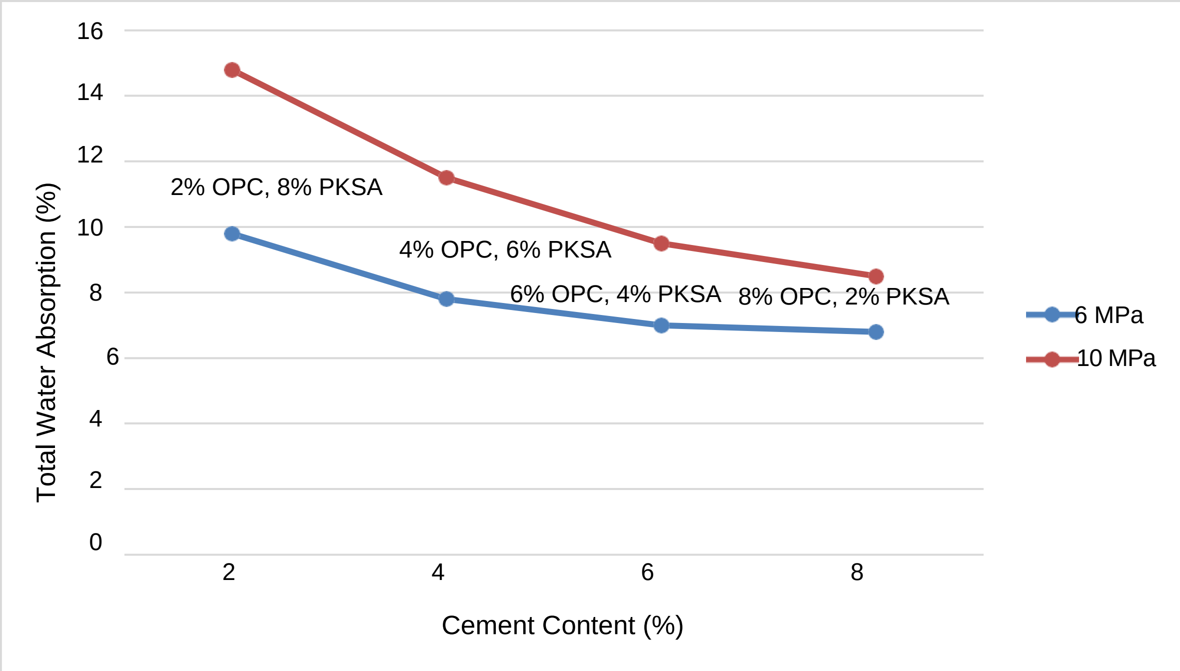

Fig 4.15: The Impact of Altering Stabiliser and Pressure on TWA

Table 4.37: Range of TWA values obtained

Block Type	Compaction Pressure Used MPa	Range of TWA values 2% OPC	8% PKSA	Overall decrease in TWA %
CPB	6	9.8	6.8	31
CPB	10	6.9	3.9	44

4.5.3 The Relationship between Total Water Absorption and Density

Below is an analysis of the relationship or correlation that exists between water absorption and dry density. Both properties are plotted in Figure 4.16, however, it is evident from Figure 4.16 that TWA and BDD are negatively correlated. As for both CMBs and CPBs, the correlation coefficient and P-values are given as -0.975; 0.003 and –0.720; 0.099 respectively. As can be seen, a significant negative relationship is present among the properties of these materials. Increasing one will likely lead to decreasing the other. It is estimated that by using only stabilized blocks from traditional OPC, water absorption was reduced by 44%, due to the density rising from 2084 kg/m^3 to 2132 kg/m^3 (approximately 2.3% increase). TWA decreased by 39% in improved blocks with the same increase in density using the exact cement content proportion.

In addition, the testing shows that TWA is not appreciably reduced beyond a certain density value in the samples tested. Accordingly, further increases in BDD are not necessarily going to lead to further reductions in TWA. It is still possible for the blocks to absorb water, but it is almost uniform in the amount absorbed. Similarly, WCS and TWA exhibited a correlation. It is simple to understand that the more water a block absorbs, the weaker it becomes (Neville, 1995).

A very significant positive relationship or correlation exists between Density at 6 MPa and 10 MPa. The same also exists between TWA at 6 MPa and 10 MPa. The Pearson Correlation of -0.882 exist between density and TWA at 6 MPa and -0.911 at 10 MPa. Which are significant at 0.05 p-level, since Sig. is 0.00, which is less than 0.05 as seen in Table 4.38.

Analysis of variance (ANOVA) was used to analyse TWA at 6 MPa and 10MPa, due to varying cement and PKSA content. Since significance of 0.00 at 6 MPa is less than 0.05, there is a significant difference in the TWA of the CSEBs. Hence, a variation in the stabilizer proportion and moulding pressure significantly impacts the total water absorption at 6 MPa as seen in Tables 4.39 and 4.40. The same can be said for blocks compacted at 10 MPa. Since significance of 0.00 is less than 0.05, a significant difference exists in the TWA of the CSEBs. Therefore, varying the Stabilizer Content and Moulding Pressure significantly impact the TWA at 10 MPa as seen in Tables 4.41 and 4.42.

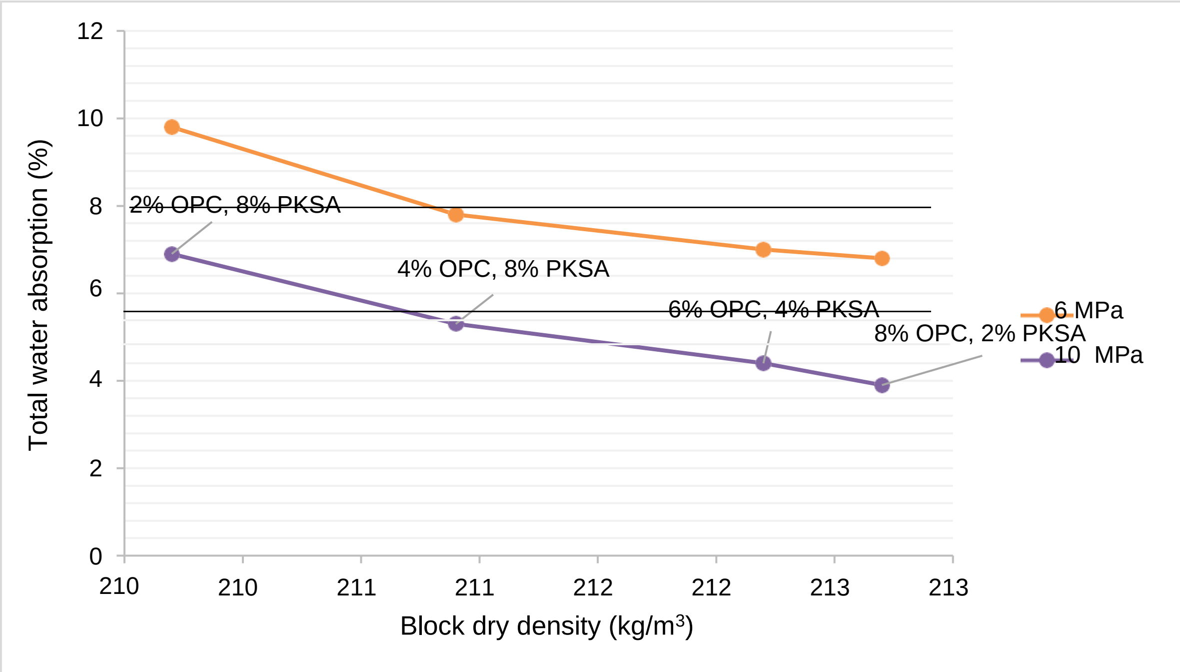

Fig 4.16: Correlation between TWA and BDD

Table 4.38: Correlation between TWA and BDD at 6 MPa and 10 MPa

		Density (6 MPa)	Density (10 MPa)
Density (6 MPa)	Pearson Correlation	1	0.967**
	Sig. (2-tailed)		0.00
Density (10 MPa)	Pearson Correlation	0.967**	1
	Sig. (2-tailed)	0.00	
TWA (6 MPa)	Pearson Correlation	-0.882**	-0.890**
	Sig. (2-tailed)	0.00	0.00
TWA (10 MPa)	Pearson Correlation	-0.911**	-0.916**
	Sig. (2-tailed)	0.00	0.00

Table 4.39: Descriptive Statistics of TWA at 6 MPa due to varying Cement/PKSA content

Descriptive								
TWA (6 MPa)								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
6S1	3	6.8000	.36056	.20817	5.9043	7.6957	6.40	7.10
6S2	3	7.0000	.36056	.20817	6.1043	7.8957	6.70	7.40
6S3	3	7.8000	.62450	.36056	6.2487	9.3513	7.10	8.30
6S4	3	9.8000	.34641	.20000	8.9395	10.6605	9.60	10.20
Total	12	7.8500	1.29439	.37366	7.0276	8.6724	6.40	10.20

Table 4.40: ANOVA of TWA at 6 MPa due to Varying CC/PKSA content

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	16.89	3	5.63	29.247	0.00
Within Groups	1.54	8	0.193		
Total	18.43	11			

Table 4.41: Descriptive Statistics of TWA at 10 MPa due to varying Cement/PKSA content

Descriptive								
TWA (10 MPa)								
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
6S1	3	3.8333	.25166	.14530	3.2082	4.4585	3.60	4.10
6S2	3	4.3667	.60277	.34801	2.8693	5.8640	3.80	5.00
6S3	3	5.3000	.43589	.25166	4.2172	6.3828	5.00	5.80
6S4	3	7.0000	.36056	.20817	6.1043	7.8957	6.70	7.40
Total	12	5.1250	1.30949	.37802	4.2930	5.9570	3.60	7.40

Table 4.42: ANOVA of TWA at 10 MPa due to Varying CC/PKSA content

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	17.369	3	5.79	31.016	0.00
Within Groups	1.493	8	0.187		
Total	18.862	11			

4.5.4 Assessing the difference between TWA at 6 MPa and 10 MPa due to Varying CC/PKSA content and Control using T-test Analysis

At 6 MPa, the TWA values for 6S1 and 6S2 were not significantly lower than the control, indicating that the addition of PKSA did not lead to a notable decrease in water absorption. However, for 6S3 and 6S4, which had higher percentages of PKSA, an increase in TWA was observed. Significantly, CC/PKSA of 2/8 (6S4) resulted in a notable increase in TWA, as indicated by the significance value of 0.00 (lesser than 0.05). This means that the inclusion of a higher proportion of PKSA content in the mix led to a significant increase in water absorption, as presented in Table 4.43.

In contrast, for blocks compacted at 10 MPa, the TWA values were significantly lower than the control in all mixes except for 10S4. This implies that the addition of PKSA, at different ratios, resulted in a notable decrease in water absorption compared to the control. However, it is worth noting that the decrease in TWA for 10S4 was not significant, as the significance value of 0.00 is greater than 0.05. This suggests that CC/PKSA of 2/8 (10S4) did not lead to a significant reduction in water absorption, as shown in Table 4.44.

These findings indicate that the addition of PKSA can have varying effects on water absorption properties depending on the CC/PKSA ratio and the compaction pressure. Higher percentages of PKSA content generally increased TWA at 6 MPa, while at 10 MPa, the inclusion of PKSA led to significantly lower water absorption values. The specific influence of PKSA on water absorption characteristics can be attributed to factors such as changes in porosity, surface area, and the hydrophilic nature of the PKSA material.

Overall, the analysis provides valuable insights into the relationship between CC/PKSA ratios and water absorption in the blocks, highlighting the significance of different proportions of PKSA content in altering water absorption properties.

Table 4.43: Assessing the difference between TWA at 6 MPa due to Varying CC/PKSA content and Control using T-test Analysis

	Test Value = 7.5					
Class	t	**Df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
6S1	-3.363	2	0.078	-0.7	-1.5957	0.1957
6S2	-2.402	2	0.138	-0.5	-1.3957	0.3957
6S3	0.832	2	0.493	0.3	-1.2513	1.8513
6S4	11.5	2	0.007	2.3	1.4395	3.1605

Table 4.44: Assessing the difference between TWA at 10 MPa due to Varying CC/PKSA content and Control using T-test Analysis

	Test Value = 7.5					
Class	t	**Df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
10S1	-25.236	2	0.002	-3.66667	-4.2918	-3.0415
10S2	-9.004	2	0.012	-3.13333	-4.6307	-1.636
10S3	-8.742	2	0.013	-2.2	-3.2828	-1.1172
10S4	-2.402	2	0.138	-0.5	-1.3957	0.3957

4.6 DERIVATION OF MATHEMATICAL MODELS

4.6.1 MODEL 1: To predict wet compressive strength of blocks at 6 MPa.

A mathematical model was developed to predict Wet Compressive Strength (WCS). The model is depicted in Eqn (4.1).

$$y = c + X_1CC + X_2PKSA + X_3ML \quad (4.1)$$

Where y is WCS, c is intercept of the fit, X_1 is coefficient of Cement Content, and X_2 is coefficient of PKSA Content, while X_3 is coefficient of Maximum Loading rate (kN).

After fitting the factors and the WCS in a regression model, their various coefficients were derived. The relationship is represented as Eqn (4.2).

$$WCS = 1.78E^{-15}X_1 + 3.33E^{-16}X_2 + 0.1X_3 \quad (4.2)$$

The coefficients of the variables used in this model, which represent the values for assessing the impact of the factors on WCS are shown in Table 4.45.

Table 4.45 reveals that the coefficient of cement content is $1.78E^{-15}$. This means that there is a component increase in WCS for every time cement content increases, all the while keeping the other variables constant. From the above, it is seen that the coefficient of the PKSA is $3.33E^{-16}$, meaning that there is a component or unit increase in WCS for every time PKSA increases, all the while keeping other variables constant. The table also reveals that the coefficient of the Maximum Load (ML) is 0.1, which means there is a component increase in WCS for each increase in ML, while keeping other variables constant. Also, the coefficient of the intercept representing other variables not included in the relationship equals zero. The p values also show that the coefficients are not statistically different from zero to a large extent since all the results obtained are greater than 0.05, except the ML which has a significance value of 0.000, which implies that the ML significantly impacts the WCS, while other variables' impacts are not significant. Coefficient of Determination (R^2) depicted in the table has a value of 1 that shows the measure of the overall strength of the model. It can be observed that since the R^2 is 1 it can be concluded that the model is adequate in determining the WCS using the experimentally derived properties of the aggregate. The table further shows the F test that is used to check the null hypothesis that all the model coefficients are equal to zero. Therefore, since the p value for the f test is less than 0.000 which is lesser than 0.05, it is concluded that all the derived coefficients are valid.

Table 4.45: Model Coefficient for WCS

Dep. Variable:	WCS	**R-squared:**	1.000
Model:	OLS	**Adj. R-squared:**	1.000
Method:	Least Squares	**F-statistic:**	9.633e+28
Date:	Sun, 05 Dec 2021	**Prob (F-statistic):**	3.25e-128
Time:	09:23:52	**Log-Likelihood:**	363.51
No. Observations:	12	**AIC:**	-721.0
Df Residuals:	9	**BIC:**	-719.6
Df Model:	2		
Covariance Type:	nonrobust		

	coef	**Std err**	**t**	**P>|t|**	**[0.025**	**0.975]**
Intercept	0	9.63e-15	0	1.000	-2.18e-14	2.18e-14
CC	1.776e-15	9.01e-14	0.020	0.985	-2.02e-13	2.06e-13
PKSA	3.331e-16	6.29e-15	0.053	0.959	-1.39e-14	1.46e-14
ML	0.1000	7.6e-15	1.32e+13	0.000	0.100	0.100

Omnibus:	1.919	**Durbin-Watson:**	0.031
Prob (Omnibus):	0.383	**Jarque-Bera (JB):**	0.875
Skew:	-0.092	**Prob (JB):**	0.646
Kurtosis:	1.690	**Cond. No.**	1.28e+19

4.6.2 MODEL 2: To predict to predict dry compressive strength of blocks at 6 MPa.

A mathematical model was developed to predict Dry Compressive Strength (DCS). The model is presented in Eqn (4.3).

$$y = c + X_1CC + X_2PKSA + X_3ML \tag{4.3}$$

Where y is DCS, c is intercept of the fit, X_1 is coefficient of Cement Content, and X_2 is coefficient of PKSA Content, while X_3 is coefficient of Maximum Loading rate (kN).

After fitting the factors and the DCS in a regression model their various coefficients were derived. The relationship is shown in Eqn (4.4).

$$DCS = 2.22E^{-16} - 3.55E^{-15}X_1 + 0.1X_3 \tag{4.4}$$

The coefficients of the model's variables, also the values for assessing the impact of the factors on DCS are presented in Table 4.46.

Table 4.46 shows that the coefficient of cement content is $-3.55E^{-15}$, which shows that there is a component increase in DCS for each time cement content decreases, all the while keeping the other variables constant. Also, it is seen that the coefficient of the PKSA is 0, meaning that PKSA is not required to derive a model for predicting DCS based on the experimentally obtained values. The table also shows the coefficient of the Maximum Load (ML) to be 0.1, meaning that there is a component increase in DCS for each increase in ML, all the while keeping the other variables constant. It is also shown in the table that the coefficient of the intercept, representing other variables not included in the relationship equals zero. All p values for the coefficient reveal that the coefficients are not statistically different from zero to a large extent, since all the results obtained are greater than 0.05, expect the ML which has a significance value of 0.000, which implies that the ML significantly impacts the DCS, while other variables' impacts are not significant. The table further shows the F test that was used in testing the null hypothesis that all the model coefficients are equal to zero. Also, since the p value for the f test is less than 0.000 which is lesser than 0.05, it can be deduced that all the derived coefficients are valid.

Coefficient of Determination (R^2) depicted in the table has a value of 1 that shows the measure of the overall strength of the model. It can be observed that since the R^2 is 1 it can be concluded that the model is adequate in determining the DCS based on the experimentally derived properties of the aggregate.

Table 4.46: Coefficient of Model Variables for DCS

Dep. Variable:	DCS	**R-squared:**	1.000
Model:	OLS	**Adj. R-squared:**	1.000
Method:	Least Squares	**F-statistic:**	3.387e+28
Date:	Tue, 07 Dec 2021	**Prob (F-statistic):**	3.59e-126
Time:	05:57:58	**Log-Likelihood:**	356.29
No. Observations:	12	**AIC:**	-706.6
Df Residuals:	9	**BIC:**	-705.1
Df Model:	2		
Covariance Type:	nonrobust		

	coef	**Std err**	**t**	**P>|t|**	**[0.025**	**0.975]**
Intercept	2.22e-16	8.79e-15	0.025	0.980	-1.97e-14	2.01e-14
CC	-3.553e-15	7.6e-14	-0.047	0.964	-1.76e-13	1.68e-13
PKSA	0	1.22e-14	0	1.000	-2.75e-14	2.75e-14
ML	0.1000	5.37e-15	1.86e+13	0.000	0.100	0.100

Omnibus:	1.965	**Durbin-Watson:**	0.029
Prob (Omnibus):	0.374	**Jarque-Bera (JB):**	0.874
Skew:	-0.044	**Prob (JB):**	0.646
Kurtosis:	1.681	**Cond. No.**	1.07e+19

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary

The performance of compressed earth blocks when stabilised with both cement and palm kernel shell ash compositions was investigated in bid to produce a more environmentally friendly construction material. The physical properties of lateritic soil used for the production of the compressed stabilised earth blocks were determined, as well as the chemical composition of palm kernel shell ash. The compressed stabilised earth blocks cubes were produced from lateritic soil, cement, palm kernel shell ash and water. The cement- palm kernel shell ash mixes were stabilised at various levels of composition. Wet and Dry Compressive Strengths (WCS and DCS), Block Dry Density (known as BDD) and Total Water Absorption (also known as TWA) of the blocks were determined according to standards. Lastly, data were analysed using a t-test and mathematical models were derived to predict wet compressive strength and dry compressive strength of blocks.

5.2 Conclusion

The following conclusion has been drawn from this study:

i. Test results proved that the properties of the lateritic soil sample used improved when stabilised with both cement and palm kernel shell ash, with the best performance obtained at 6% cement and 4% palm kernel shell ash. Due to the inclusion of the PKSA, the Cement-Palm Kernel Blocks performance was enhanced and their theoretical expectations were improved.

ii. There was a 63% increase in wet compressive strength of Cement-Palm Kernel Blocks upon adding 4% palm kernel shell ash and 6% cement, which improved their strength. There was also a 79% increase in wet compressive strength as moulding pressure increased from 6 MPa to 10 MPa. Also, due to the pozzolanic reaction of PKSA with cement, there was an increase in the strength of the bond that exist among the phases and particles in the sample block that accounted for the reduction in the gap between wet compressive strength and dry compressive strength.

iii. Within 28 days of production, concrete materials reach 80 to 90% of their ultimate strength. compressed stabilised earth blocks, however, achieved a comparable level of 60-70% within the same period. Thus, palm kernel shell ash is recommended for the replacement of partial cement in block design, due to its slow hydration time, to improve strength, durability and dimensional stability.

iv. A gap in compaction times after mixing the soil and stabilizers with water could result in significant reductions in the strength of block. Consequently, the strength of Cement-Palm Kernel Blocks decreased by 61% after two hours of delay. A block compacted within 30 minutes of wet mixing, on the other hand, was 14% stronger than a block compacted after 60 minutes.

v. As compared with Cement-Palm Kernel Blocks, Control blocks were less dense. Both categories of blocks gained density only by about 3% after the palm kernel shell ash content was reduced. In spite of an increase in density due to greater compaction, an increase of about 70% in pressure only increased density by about 1.2%. Supplementing the cement content with palm kernel shell ash seems to be an effective method of increasing density. In addition, the experimental density values obtained exceeded the recommended minimum (by about 9%) of 2000 kg/m^3. A good relationship existed among the BDD and the wet compressive strength and TWA properties. According to all complementary tests conducted, denser blocks perform better.

vi. Cement-Palm Kernel Blocks had TWAs between 6.8% and 9.8%, a significant reduction even at 4% palm kernel shell ash compared to the control mix value of 7.5%. In other words, Cement-Palm Kernel Blocks had lower TWAs than control mixes because of the use of palm kernel shell ash. A decline in TWA is uniform and observed at higher palm kernel shell ash contents rather than at lower palm kernel shell ash contents when cement content and compaction pressure increase. In Cement-Palm Kernel Blocks, however, cement content increased beyond a certain point (4% - 6%) without affecting TWA substantially. Therefore, all blocks used in this study for experimental tests had TWA values below 15%, which was the maximum value recommended. TWA showed a strong correlation with BDD and WCS, according to the study.

vii. The models developed were validated with empirical data which proves adequate representation of the real relationships among the measured properties.

5.3 Recommendations

i. Over the years, the use of compressed earth blocks had been associated with the word “dirt cheap”, hence the social hesitation or reluctance to use it for construction. Therefore, Cement-Palm kernel shell ash blocks is recommended to Architects and Engineers as a better alternative to the regular cement stabilised earth blocks. This would increase its social acceptance and thereby contribute to a cleaner and safer environment.
ii. Also, it is recommended to plan smaller groups or sets of wet mixes to be compacted in the space of 30 minutes rather than an hour). It is therefore not recommended to compact wet mixes for more than 60 minutes.
iii. It is recommended that compressed stabilised earth blocks be produced on site to reduce transportation costs.
iv. Further research can be carried out on the cost implications of using compressed stabilised earth blocks for construction.
v. Further research can also be carried out using different kinds of soils as available in various regions of the world.
vi. Further studies should be conducted on the impact of adding some other types of stabilizers derived from agricultural as well as industrial waste on the durability and strength of the blocks.

5.4 Contributions to Knowledge

i. This research provides insights into the optimization of CSEBs.
ii. It has been established that compressed earth blocks can be strengthened and stabilised to standards without totally depending on cement.
iii. Addition of PKSA made the cement more effective due to the stronger bonds formed as a result of its pozzolanic reaction.
iv. The information provided in this research, would aid the use of wastes generated by local populations as a result of establishing palm tree plantations.
v. This study would contribute to community development by empowering communities to construct affordable and sustainable housing.
vi. This research can contribute to the development of standards and guidelines, offering practical applications for the construction industry

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APPENDICES

APPENDIX A

Determination of Specific Gravity

Procedure

1. Clean and dry the density bottle
   a. Wash the bottle with water, leaving it to drain
   b. Wash it with alcohol and drain it to remove water
   c. Wash it with ether to get rid alcohol and drain ether
2. Weigh the empty bottle with stopper (W1)
3. Extract 10 to 20gm of oven soil sample which is made to cool in a desiccator. Transfer it to the bottle. Calculate the weight of the bottle and soil (W2)
4. Put 10ml of purified water in the bottle to leaving the soil to soak completely. Leave it for about 2hours.
5. Again fill the bottle completely with distilled water put the stopper and keep the bottle under constant temperature water baths (T ^{0}C)
6. Take the bottle outside, wipe it clean and dry. Then calculate the weight of the bottle and its contents (W3)
7. Then empty the bottle and clean it very well. Fill the bottle with only distilled water and weigh it. Let it be W4 at temperature (T ^{0}C)
8. Go over the same process for 2 to 3 times to take the average reading of it.

Calculations

$$\text{Specific gravity of soil} = \frac{\text{density of water at } 27^0\text{C}}{\text{Weight of water of equal volume}} \quad (1.1)$$

$$= \frac{(W2 - W1)}{(W4 - W1) - (W3 - W2)} \quad (1.2)$$

$$= \frac{(W2 - W1)}{(W2 - W1) - (W3 - W4)} \quad (1.3)$$

Specific gravity values recorded will then be based on water at 270C, so the specific gravity at 27^{0}C

$$= K \times \text{specific gravity at } T_x{}^0\text{C} \quad (1.4)$$

$$\text{Where } K = \frac{\text{density of water at room temperature}}{\text{Density of water at temperature } T_x{}^0\text{C}} \quad (1.5)$$

APPENDIX B

Determination of Bulk Density

Procedure

1. Prepare a smooth "undisturbed" vertical or horizontal soil surface at the depth to be sampled
2. Press the sampler into the soil far enough to fill the inner cylinder but not so far as to compress the soil
3. Carefully remove the sampler so as to preserve the sample. Separate the two cylinders, retaining the "undisturbed" soil in the inner cylinder
4. Carefully trim the soil sample flush with each end of the cylinder
5. Push the soil from the cylinder into a plastic bag
6. The soil from the cylinder is placed in a weighing tin and weighed. The weight of the wet soil + tin + cylinder is recorded as W_1. Record the weight of the tin as W_2 and the weight of the cylinder as W_3
7. The samples are then dried in an oven at 105^0C. The time required to dry the sample varies with the amount of soil present. Record the weight of the oven-dry sample + tin + cylinder as W_4.

$$\text{Bulk Density } D_b = \frac{W_4 - W_2 - W_3}{\text{Vol. of cylinder}} \qquad (1.6)$$

APPENDIX C

Determination of Moisture Content

The water content (w) of a soil sample is the same as the mass of water divided by the mass of solids expressed as percentage.

$$w = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \tag{1.7}$$

Where, M_1 = the mass of empty container with lid

M_2 = the mass of the container with wet soil and lid

M_3 = the mass of the container with dry soil and lid

Soil Specimen

The soil specimen should be a representative of the soil mass. The quantity of the specimen taken would depend upon the gradation and the maximum size of the particles. For more than 90% of the particles passing through 425micron IS sieve, the minimum quantity is 25g.

Procedure

1. Clean the container, dry it and weigh it with lid (M_1)
2. Take the desired amount of the wet specimen inside the container and close it with lid. Take the mass (M_2)
3. Put the container with the lid off in the oven till its mass becomes constant (usually for up to 24 hours)
4. Upon drying of soil, remove the container from the oven using tongs. Replace the lid on the container and cool it in a desiccator.
5. Calculate the mass (M_3) of the container with lid and dry soil sample

Calculations

Mass of water $M_w = M_2 - M_3$ (1.8)

Mass of solids, $M_s = M_3 - M_1$ (1.9)

$$\text{Water content} = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \tag{1.10}$$

APPENDIX D

Screening/ Sieve Analysis

The soil is sieved through a set of sieves. The material retained on different sieves is determined. The retention percentage of the material on any sieve is given by:

$$P_n = \frac{M_n}{M} \qquad (1.11)$$

Where M_n = mass of solid retained on sieve 'n'

M = total mass of the sample

The cumulative percentage of the material retained,

$$C_n = P_1 + P_2 + \ldots\ldots\ldots\ldots.. + P_n \qquad (1.12)$$

Where P_1, P_2, etc are the percentages retained on sieve 1, 2, etc which are more coarse than sieve 'n'.

The percentage finer than sieve 'n'

$$N_n = 100 – C_n \qquad (1.13)$$

Procedure: (I) Coarse Sieve Analysis

1. Take the quantity required of the sample. Sieve it through a 4.75mm IS Sieve. Take the soil fraction retained on 4.75mm IS Sieve for the coarse sieve analysis and that passing through the sieve for the fine sieve analysis.
2. Filter the sample through the set of coarse sieves by hand. While sieving through each sieve, the sieve should be agitated such that the sample rolls in irregular motion over the sieve. The material retained on the sieve could also be rubbed with probably a rubber pestle in the mortar if necessary. Care should be taken so as not to break the individual particles. The quantity of the material taken on each sieve shall be such that the maximum mass of material retained on each sieve does not exceed the specified value.
3. Confirm the mass of the material retained on each sieve.
4. Determine the proportion by percentage of the soil that is retained on each sieve on the basis of the total mass of the sample taken in step (1).
5. Determine the percentage passing through each sieve.

(II) Fine Sieve Analysis

6. Extract the portion of the soil passing through the 4.75mm IS sieve. Oven-dry it at 105 to 110^{0}C.weigh it to 0.1% of the total mass.

7. Sieve the soil through the nest of fine sieves. The sieves should be shaken so that the sample rolls in uneven motion over the sieves. But, no particles should be pushed through the sieve.

8. Take the sample retained on various sieves in a mortar. Rub it with rubber pestle, but do not try to break individual particles.

9. Reserve the sample through the nest of sieves. A minimum of 10min of agitation is needed if a mechanical shaker is used.

10. Collect the soil fraction left on each sieve in another container. Take the mass.

11. Determine the percentage retained, cumulative percentage retained and the percentage finer, based on the total mass taken in step (1).

Note: If the fraction contains a considerable amount of clay particles, then a wet sieve analysis is needed. Alternatively, the following method may be used:

Before conducting step (7), add the water containing sodium hexamataphosphate at the rate of 2g per litre of water to the soil fraction. Stir the mix thoroughly and leave for soaking. Wash the soaked specimen on a 75µ IS sieve until the water passing the sieve is clear. Take the fraction left on the sieve and oven-dry it. Sieve the oven-dried soil through the nest of sieves as mentioned in step (7). Perform further steps as before.

APPENDIX E

MIX COMPOSITION USED

S/N	% of Stabilizer Used		Mass (g)				
	Cement (%)	PKSA (%)	Coarse Aggregate (g)	Clay (g)	Cement (g)	PKSA (g)	Total (g)
1	8	2	6647.0	1173.0	680	170	8500
2	6	4	6502.5	1147.5	510	340	8500
3	4	6	6358.0	1122.0	340	510	8500
4	2	8	6213.5	1096.5	170	680	8500

APPENDIX F

SUMMARY OF LIST OF CSEB PRODUCED

Sample No	Cement Content (%)	PKSA Content (%)	No. of Blocks 290x140x100mm	100x100x100 mm	100x100x90 Mm	100x100x40 mm	100x90x40 mm
Compacted at 6 MPa							
Control 1	10	0	3	6	3	6	3
Compacted at 6 MPa							
6S1	8	2	3	6	3	6	3
6S2	6	4	3	6	3	6	3
6S3	4	6	3	6	3	6	3
6S4	2	8	3	6	3	6	3
	Subtotal		12	24	12	24	12
Compacted at 10 MPa							
10S1	8	2	3	6	3	6	3
10S2	6	4	3	6	3	6	3
10S3	4	6	3	6	3	6	3
10S4	2	8	3	6	3	6	3
	Subtotal		12	24	12	24	12
	Grand Total		**27**	**54**	**27**	**54**	**27**

APPENDIX G

WET COMPRESSIVE STRENGTH TESTING

Test for Wet Compressive Strength (WCS)

Title: Standard: BS 6071: Parts 1 and 2: 1981; Neville 1995; BS 3921: 1985

Goal: to measure the wet compressive strength of various block kinds. BS 1610: 1964 Grade A or B high accuracy

Limitations: The sample size, moisture content, age of curing, rigidity of the testing apparatus, kind of preparation employed, and rate of load application can all affect the results.

Time: each test takes 2 to 5 minutes.

Indications about the specimen: The cubes were 28 days old, chopped to a size of 100 mm cube, pre-immersed in water for 24 hours, and then tested.

Compression testing apparatus

1. A compression testing equipment. Accuracy meets BS 1610 grade A and B requirements. As contact is achieved, the apparatus' upper platen can readily align with the specimen. The sample is supported by a simple, non-tilting lower platen.
2. For each sample being evaluated, brand-new, knot-free 105 x 105 x 20 mm plywood packing.
3. Concrete lathe saw, 4Kw 50Hz T/M 2900 (Luxembourg), model (t W 2-40-3), Clipper serial number 606726. used to transform bricks measuring 290 x 140 x 100 mm into prisms measuring 100 x 100 mm.
4. A water tank that is 2000 mm x 1000 mm x 600 mm in size and has a hole at the bottom for open water circulation so that blocks can be submerged and soaked overnight.
5. Accuracy was within 0.1% of the mass of the specimen.

Testing procedures

Three samples should be taken, one from each type of block, and their unique areas and volumes should be measured and recorded. (ii) Immerse the samples for 24 hours in a tank of water that has water that is between 10 and 25 °C in temperature. (iii) Remove the blocks and let them drain on a stillage or damp sacking for about half an hour. Place the specimen with a 5 mm overhang on each edge between two new sheets of 4 to 20 mm plywood.

Ensure that the specimen's mass center and the machine's axis are in line. (v) Perform a final check to make sure the alignment and packing are correct, after which you should apply the load at a rate of 15 KN/min without shock. Maintain the load for one to five minutes or until failure. (vi) Write down the loading rate and the maximum load before failure (the machine automatically recorded these figures and a printout provided). (vii) To determine the crushing strength, note the type of failure mode and use the formula below:

WCS = ML (KN) Maximum load (KN) =

ML AS stands for cross section area (mm2), while WCS stands for wet compressive strength in MPa.

Use the same mix batch and processing method to run three tests on each type of material, and then average the results.

The dry compressive strength (DCS) value must be calculated using the same steps as previously, but this time the samples do not need to be soaked in water for 24 hours. Instead, after being oven-dried to a consistent mass, they are evaluated as previously indicated. Chapter 4 discusses the outcomes.

APPENDIX H
TOTAL WATER ABSORPTION TEST (TWA)

BS 1881: Part 122: 1983; ASTM C 642: 1990; BS 3921: 1985

To calculate the overall volume porosity and to ascertain the block water absorption values.

Medium to high accuracy in terms of precision

Limitations: When employing the cold immersion technique, it's possible that some air is still trapped inside the pores.

Timeframe: 24 hours

Description of the specimen (As before) Various CSEB categories

APPARATUS

Drying oven with ventilation (BS 2648).

2. A tank with a bottom grid to guarantee water circulation.
3. An electronic scale that can weigh objects with an accuracy of 0.1%.

TESTING METHODS

(i) Dry the samples from each category of blocks in the oven at 110°C to 115°C until they reach a consistent mass.

(ii) After each specimen has cooled, weigh it with an accuracy of 0.1% of the specimen mass.

(iii) Immediately after weighing, submerge the specimens in a single layer tank so that water can easily flow over the sample's bottom and all sides. In the tank, leave a 10 mm gap between neighboring samples.

(iv) After 24 hours, take the specimens out of the water tank, wipe off the surface water while shaking them gently, and then weigh each specimen again within two minutes after removing it.

(v) Use the formula below to determine the water absorbed by each sample (TWA) expressed as a proportion of the dry mass:

(MW - MD) X 100 = TWA

(1.16) MD 173

where TWA stands for total water absorption (%).

Wet mass (g) = MW

MD = gram of dry mass

Get the average value from three samples that fall into the same mix and processing category.