# Structural Performance of Drystack Hollow Sandcrete Blocks Produced Using Non-Conventional Blended Sand and Cement Blended with Sugarcane Bagasse Ash

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**A research thesis submitted in partial fulfillment for the award of a Degree of Master of Science in Civil Engineering Structural option in the Pan African University Institute for Basic Science, Technology and Innovation**

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## DECLARATION

**Declaration by student**

This research thesis is my original work and has not been submitted before in this university or any other university for award of a degree.

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# DEDICATION

I dedicated this project to my parents Mr. and Mrs. Charles Arasa for their hard work and dedication in ensuring that my studies are a success.

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## LIST OF ABBREVIATIONS

**AASHTO -** American Association of State Highway and Transportation

**ASTM -** American Society for Testing and Materials

**ATSS** - Abundant Treated Sea Sand

**BLA -** Bamboo Leaf Ash

**BS -** British Standard

**CMU** - Concrete Masonry Units

**DHSBs** - Drystack Hollow Sandcrete Blocks

**LVDT-** Linear Variable Displacement Transformers

**NIS -** Nigeria Industrial standard

**OPC -** Ordinary Portland Cement

**R-DHSBs -** Round-DHSBs

**RHA -** Rice Husk Ash

**SBA** - Sugarcane Bagasse Ash

**SDA -** Sawdust Ash

**SG -** Strain Gage

**T-DHSBs** - Trapezoidal-DHSBs

## LIST OF NOMENCLATURES

**σ** - Compressive force per square meter

**τ** - Shear force per unit area

**₦** - Nigerian naira

**μ** - Representing × 10^-4 units

**k** - Representing $\times 10^3$ units

**Mpa**- An equivalent of $N/mm^2$

## ABSTRACT

River sand and cement are the major components of building materials used in the making of sandcrete blocks. The extraction of these materials have caused a negative impact on the environment and mining sources have been depleted. The cost of construction has also increased significantly causing a shortage of decent housing. This research investigates the structural performance of sandcrete blocks produced using lateritic sand and marine sand as complete replacement of river sand, and sugarcane bagasse ash as partial replacement of cement. The performance of dry stacked sandcrete blocks and wall models made from optimum mixture of these materials are also assessed. Sandcrete hollow blocks (450 × 225 × 225 mm) were made by blending varying contents of marine sand and lateritic sand using the nominal mix ratio of 1:6 (cement: sand). A total of 90 sandcrete blocks were casted and the compressive strengths of the blocks determined at 7, 14 and 28 days. The 28 day compressive strength of mixes containing 0%, 10%, 20%, 30%, 40%, 50%, 60%, 80% and 100% marine sand were 4.47 N/mm$^2$, 5.10 N/mm$^2$, 5.25 N/mm$^2$, 5.33 N/mm$^2$, 5.20 N/mm$^2$, 4.63 N/mm$^2$, 4.58 N/mm$^2$, 3.88 N/mm$^2$ and 3.76 N/mm$^2$ respectively. The 28 days strength at all percentage replacement exceeded the minimum strength value of 3.45 N/mm$^2$ specified by NIS 87 (2000). Sandcrete blocks made with 30 to 70 percent marine-lateritic sand blending produced the highest compressive strength. At 30% replacement level the smaller sized particles of marine sand fills the spaces between the bigger lateritic ones, this creates a more compact sandcrete block and increases the strength. Using the 30:70 ratio, 90 sandcrete blocks were casted by replacing cement with Sugar Bagasse Ash (SBA) in the ratio of 0%, 5%, 10%, 15%, 20% and 25% by weight of cement. The 28 day compressive strength were 5.33 N/mm$^2$, 5.29 N/mm$^2$, 5.18 N/mm$^2$, 4.71 N/mm$^2$, 3.42 N/mm$^2$ and 3.08 N/mm$^2$ for 0%, 5%, 10%, 15%, 20% and 25% replacement respectively. Up to 15% replacement levels met the minimum compressive strength recommended in standards. The results for water absorption and density were also within the acceptable limits of 12% and 1500 kg/m$^3$ respectively. An optimal mixture for production of non-conventional sandcrete block was established as 15% SBA replacement of cement with a 30 to 70 percent marine to lateritic sand blended mixture i.e. the optimum of Cement/SBA: Marine/lateritic sand: water ratio was 1(0.85/0.15):2(0.30/0.70):0.5.This optimum mix was adopted in the casting of two types of dry stack hollow sandcrete blocks (DHSBs) which were identified as T-DHSBs and R-DHSBs .The T and R prefixes represents the Trapezoidal and Round shapes of the interlocking joints respectively. The 28 compressive strength of T-DHSBs and R-DHSBs were found to be 3.58 Mpa and 4.04 Mpa respectively. The water absorption values for T-DHSBs and R-DHSBs were 8.98% and 9.39% respectively. The loss of weight due to abrasion for 28 days sandcrete blocks were 0.056% and 0.051% for T-DHSB and R-DHSBs respectively. The strength and durability of the blocks met the specifications in NIS 87 (2000) and BS 5628-1 (2005) respectively. The performance of wall models made from T-DHSBs and R-DHSBs under The axial compression and shear was determined. Shear performance of DHSBs masonry walls were determined by triplet shear test set-up modified to establish shear strength of the interlocking features of the DHSBs masonry. The compressive strength for T-DHSBs and of R-DHSBs wall models were established to be 1.28 N/mm$^2$ and 1.41 N/mm$^2$ respectively. The ultimate load of T-DHSBs wall model under shear were

24.8, 27.4 and 30.1 kN and that of R-DHSBs wall were 6.47, 7.90 and 9.25 kN for pre-compression stresses of 0.2, 0.6 and 1.0 Mpa respectively. The cohesion ($\tau_o$) were 0.73 and 0.42 for T-DHSBs and R-DHSBs respectively whereas friction coefficient value were 0.21 and 0.25 for T-DHSBs and R-DHSBs specimens respectively. The general failure mode of the two DHSBs walls model under compression stress were by formation of tensile cracks parallel to the axis of loading at approximately center of the block units. In this research, 15% SBA replacing cement by weight in a 30:70 marine to lateritic sand matrix is established as the optimal mixture required in the manufacture of non-conventional hollow sandcrete blocks. These optimal mixture of SBA and blended lateritic and marine sand produces dry stacked hollow sandcrete blocks that meets the strength and durability requirements for hollow sandcrete block. Owing to its better shear strength properties and less volume of materials used in its production, the study recommends T-DHSBs in preference to R-DHSBs for use as an alternative to the existing load bearing hollow sandcrete blocks. The use of mortar-less blocks made from non-conventional materials reduces the over reliance of river sand and cement in blocks production, reduces environmental effects by spreading the burden of extraction on different sources, and at same time minimizes the cost of wall construction.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the study

The growth in the economy of most developing countries has resulted in an increase of activities in the construction sector. The provision of housing as a basic need and the erection of highly sophisticated commercial buildings are now realized in these countries. Fine aggregates has been widely used in the construction industry in making concrete, mortar, precast elements and building blocks. River sand has been used as one of the major components of the building materials due to the ready availability and its well-graded nature with the sand grains of different sizes well distributed (Dongapure & Shivaraj, 2014).

In the manufacture of sandcrete blocks river sand is extensively used. Sandcrete blocks are predominantly used as walling materials in construction of residential houses and other infrastructures. The percentage of walling materials made of sandcrete blocks account for over 95% of all walling materials. Sandcrete blocks has been in use throughout the world and Africa. For example, Oyetola and Abdullahi (2006) argued that sandcrete has been in use throughout West Africa for over 5 decades as a popular building material for preparation of building blocks and bricks. Block molding or sandcrete technology is becoming the backbone of infrastructural development of every country (Onwuka et al., 2013).

Sandcrete blocks are widely used as walling units in building, construction of drainages and other masonry works .The walling units can either be load bearing and non-load bearing walls. The composition of a sandcrete block is usually in the ratio of 1:6 of cement and sand moistened with water and allowed to dry naturally (Anosike & Oyebande, 2012).The quality of sandcrete blocks is influenced by so many factors such as the quality of constituent materials, the process adopted in manufacture, duration of curing, forms and sizes of blocks (Adewuyi et al., 2013).

Sandcrete blocks are either of solid or hollow rectangular types. Hollow sandcrete blocks are the common types of sandcrete blocks. They are usually 450 × 225 × 225 mm for load bearing walls and $450 \times 150 \times 225$ mm for non-load bearing walls. The hollow blocks have a void that is approximately a third of the volume of the blocks. While a solid sandcrete block does not have any void. Hollow sandcrete blocks are good construction material for building. It is the main building material for walls of single-storey buildings (such as houses and schools) in countries such as Ghana and Nigeria (Adewuyi et al., 2013). Sandcrete blocks are advantageous walling unit because of the rapid execution of work, increase in floor area, reduction in construction cost, better insulation properties, more durability, employment of unskilled labour and good bonding of mortar and plaster, among other advantages. Houses built with sandcrete blocks are better in withstanding hurricane, tornado and earthquake with the help of steel reinforcement ("Advantages of hollow," 2017).

Sand is an important component in the production of sandcrete blocks. Over time, river sand has been the major source of natural fine aggregate. However continued extraction of river sand has resulted in a serious environmental degradation. These problems includes; loss of water retaining soil strata, deepening of the river beds and causing bank slides, loss of vegetation on the bank of rivers and disturbance of the aquatic life as well as agriculture. For this reason, coupled with the need of providing an affordable housing to all, there is need to explore the use of other alternative to fine aggregates.

Use of alternative sources to fine aggregate in sandcrete blocks such as laterites have been investigated across Africa (Agbede and Manasseh, 2008; Ibearugbulem et al., 2015). However, laterites have not been extensively used in the construction of medium to large-size building structures, probably because of lack of adequate data needed in the analysis and design of structures built of lateritic soils (Ukpata et al., 2012). In lieu of the abundance of lateritic soils and its availability, its optimum use in building production could positively affect the cost of buildings leading to the production of more affordable housing units (Opeyemi et al., 2014). Marine sand on the other hand has properties that are suitable for use in sandcrete block. While the presence of chloride minerals provides a corrosive thatch to concrete, researches have shown that up to 50% of marine sand is as good as river sand especially in its performance under compressive strength. Girish et al. (2015) found that the structural properties of marine sand keeps improving after replacing the finer particles of marine sand with the river sand.

Cement is another important component in the sandcrete production. The environmental effects of cement production such as emissions of $CO_2$ has necessitated the need for studies on use of agro wastes materials as as pozzolanic ingredients cement. Agro wastes sources such as rice husk ash (RHA), Bamboo leaf ash (BLA) and corn cob ash (CCA) can be used up to an optimum of 30% in replacing cement (Oyekan & Kamiyo, 2011; Adewuyi et al., 2013). Research on use of Sugarcane Bagasse ash (SBA) on sandcrete blocks have been limited. Sugarcane bagasse ash (SBA) increases compressive strength in concrete up to 10% cement replacement (Srinivasan & Sathiya, 2010). Sugarcane bagasse is a fibrous waste-product of the sugar refining industry, along with ethanol vapor. The product is already causing serious environmental pollution, which calls for urgent ways of handling the waste.

In this study lateritic sand, marine sand and sugarcane bagasse ash were utilized in producing sandcrete blocks. The good performance of lateritic and marine sand in sandcrete and concrete respectively, is an indication that these materials if combined can produce dry stack hollow sandcrete block of adequate strength. Sugarcane bagasse ash was used to replace cement hence reducing the quantity of cement required in the manufacture of the blocks. The use of these locally available non-conventional materials to produce dry stack hollow sandcrete blocks would lead to production of comparatively cheaper building blocks which shall be utilized in construction of houses in both rural and urban areas. These will subsequently contribute towards reduction of the housing deficit. The study shall also provide adequate data to encourage the utilization of dry stack hollow sandcrete block in both rural and urban areas.

## 1.2 Statement of the Problem

River sand and cement are the major components of the building materials in the construction industry. The manufacturing of sandcrete blocks heavily relies on river sand and cement. As construction activities continue to increase, there is an over reliance of river sand and cement in sandcrete blocks production and in the entire building industries. This has caused negative impact on the environment. Sand harvesting and mining activities during cement production causes the destruction of vegetation, reduces fertile land and farm productivity and exposes the local community to food shortage (Kavilu, 2016). According to Lawane and Pantet (2012), the building sector is responsible for more than 50% of $CO_2$ emissions and energy consumption due to production of building materials and construction operations. The process involved in the manufacture of cement has also led to high emissions of $CO_2$ to the environment.

Building materials are the largest single input in housing construction. According to Adedeji (2010) about sixty per cent (60%) of the total housing expenditure goes for the purchase of building materials; Arayela (2005) on the other hand says that cost of building materials constitute about 65% of the construction cost. Oyewobi and Ogunsemi (2010) states that building materials form the main factors that restrict the supply of housing and ascertain that they account for between 50-60 percent of the cost of buildings.

The significant increase in cost of construction has resulted into a shortage of decent housing in Africa. For example Kenya's housing deficit is estimated at 200,000 housing units per year (Mwololo, 2016). This is a figure that local developers and the government are unable to meet due to the ever-rising costs of conventional building materials (Mwololo, 2016). These housing deficit means that majority of the population lives in substandard housing. New and cheaper sources of masonry system such as use of prefabs and compressed stabilized soil blocks are being exploited (Thuita, 2016). The use of alternative sources of the materials are limited due to inadequate data to encourage their utilization.

The available sources of natural fine aggregate are also getting exhausted (Palaniraj, 2003). This has lead formation of exigent legislation regarding the environment. Consequently, quality building materials have be transported from long distance, adding to the cost of construction. In some cases, natural fine aggregate may not be of good quality. Therefore, it is necessary to replace or supplement natural fine aggregate used in sandcrete. Locally available fine aggregate and pozzolanic materials needs to be exploited and used partially or completely in sandcrete blocks production without compromising the quality of sandcrete blocks.

Studies have reported a loss of strength when cement is replaced with an agro waste material (Adewuyi et al. 2013; Oyekan & Kamiyo, 2011). A blend of coarse lateritic sand and fine marine sand, proposed in this research, has potential of producing high strength sandcrete block. This allows less cement to be blended together with an agro waste pozzolanic materials such as SBA without compromising the recommended sandcrete strength.

Studies and subsequent use of nonconventional materials in sandcrete production would lead to the reduction of the environmental impact, reduce cost of construction, reduce house shortage, supplements the available sand and cement sources and provide data to encourage their utilization. The dry stacked hollow sandcrete blocks (DHSBs) made with non-conventional materials proposed in this research would help in reducing these problems.

## 1.3 Objectives

### 1.3.1 Main Objective

To investigate the structural performance of dry stack hollow sandcrete blocks produced using lateritic sand and marine sand, as complete replacement of fine aggregate, and sugarcane bagasse ash as partial replacement for cement.

### 1.3.2 Specific Objectives

1. To assess the performance and determine the optimal mix of lateritic sand and marine sand as fine aggregates, and bagasse ash as partial replacement of cement for production of sandcrete blocks.
2. To assess the performance of dry stack hollow sandcrete blocks made from optimal mix.
3. To assess the structural behavior and failure mode of wall models made from the dry stack hollow sandcrete blocks.

## 1.4 Research questions

1. What is the performance and the optimal mix of lateritic sand and marine sand as fine aggregate, and bagasse ash as partial replacement of cement for production of sandcrete blocks?

2. Does the optimal mix of SBA, and blended lateritic and marine sand produces DHSBs that meets the strength and durability requirements for hollow sandcrete block?
3. What is the structural behavior and failure mode of wall models made from the types of DHSBs?

## 1.5 Justification

The most common walling materials are building stones, blocks and clay bricks. The escalating price of building stones and clay bricks coupled with the depletion of the natural sources for the materials necessitates the development of an alternative walling materials. Use of laterite and marine sand eliminates use of river sand in sandcrete blocks, also cement use is reduced by use of pozzolanic sugarcane bagasse ash in cement. Reducing the amount of cement used in building will decrease the amount of $CO_2$ emitted and energy used for construction. The large carbon emissions come from electricity generation, transport, industries and building operations. Also, when compared with fired clay bricks, the production of sandcrete blocks does not involve the firing process.

Research shows that there is an over reliance of natural fine aggregate in construction industry. The conventional river sources are also getting depleted. The inherent properties of lateritic sand and marine sand make them suitable for use as fine aggregate in producing dry stack hollow sandcrete block. The technique of building with dry stack hollow blocks eliminates the need for mortar and consequently reduces volume of the required building materials and subsequently the cost of construction.

## 1.6 The scope and limitations of the study

### 1.6.1 The scope of the study

This research will be limited to the structural performance of DHSBs produced using optimal mix of lateritic sand and marine sand as complete replacement of river sand, and sugarcane bagasse ash as partial replacement of cement. Structural performance of wall models made from the DHSBs were determined by conducting axial compression and shear test. The lateritic samples and bagasse ash used in the study were obtained from Kakamega County in Kenya (0.2827° N, 34.7519° E). Marine sand was obtained from coastal Kenya (3.9386° S, 39.7498° E).

### 1.6.2 Limitations

The main limitation in the study was on the use of manual methods of molding in the production of the DHSBs as opposed to the block molding machine. Compaction was by tamping using wooden rammer. This hampered the speed of block production. The advantage of block molding machine as opposed to the manual production used in study would be the ease in block manufacture, uniformity in compacting effort, increased block strength as well as reduction of irregularities in the interlocking features. Through careful procedures in casting and replication it was possible to produce DHSBs to simulate their performance.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

This chapter is devoted to reviewing literature relevant to the study on the performance of sandcrete blocks and dry stack masonry walls. The chapter looks at theoretical review and empirical studies by other researchers on sandcrete blocks and dry stack sandcrete block. Sandcrete blocks produced using different methods of production, mix ratios, different blended cement materials, different aggregate materials and admixtures were reviewed. Existing research on dry stack masonry blocks and wall models were reviewed. It ends by a summary and identification of the research gaps for the study and the conceptual framework.

## 2.2 Theoretical review.

### 2.2.1 Building Blocks.

Blocks are the major walling materials used in wall construction. Many types of blocks exists in the market depending on the constituent materials. The major types blocks are; building stones, concrete blocks, sandcrete blocks, soil blocks, bricks and mud blocks. The blocks are of various sizes and shapes and can be classified as hollow or solid blocks and are bonded with binders, usually sand-cement mortar or lime.

Through research, dry stacked or interlocking blocks have recently been introduced in the building industry. This type of blocks are used in building walls without use of motor or binder. In South Africa, a new technology developed but now used in several parts of Africa known as hydraform technology is also used in manufacturing dry stack blocks. Hydraform block, usually solid, is a type of sandcrete block that could be stacked together to form a wall without cement. Nair et al. (2006) explained that the hydraform interlocking blocks lock front, back, top and bottom, eliminating the need for mortar joints in the super structures. Ganesan et al. (2008) explained that these ridges lock into one another to lock the blocks into place. Hydraform blocks lock on four sides; front and back; top and bottoms, which ensures each block is locked into place. The foundation is laid in mortar as normal; blocks from the first course are dry-stacked. The top 3-4 courses below the roof structure must be bedded in mortar (ring beam). This secures the wall ensuring each block is perfectly locked and in place. Presently, hydraform machines are manufactured worldwide. (Thwala et al., 2012; Abdullahi, 2005; Eze et al., 2005).

### 2.2.2 Sandcrete blocks

Nigerian Industrial Standard (NIS: 87, 2004) defines sandcrete as a composite material made up of water, cement and sand. Sandcrete blocks are similar to concrete, however, unlike concrete it is produced without inclusion of coarse aggregate in the mix. They are majorly made from water, cement, and sand mixed in the appropriate ratios. These blocks are popular especially in the western part of Africa due to the speed in laying and ease in production. A typical sandcrete wall is shown in plate 2.1.

Plate 2.1: Typical Sandcrete wall under construction.

Source: http://www.nairaland.com, (2015)

Sandcrete blocks are classified as solid or hollow blocks. Hollow blocks have cavities in them while the solid ones have no cavities. Hollow sandcrete blocks plays a major role in the building industry (Morenikeji et al.,2015). Oyekan and Kamiyo (2011) says that hollow sandcrete blocks containing a mixture of sand, cement and water are used extensively in many countries of the world especially in Africa. They are predominantly used and suitable for load and non-load bearing walls, or for foundations. Other uses includes making of a fence, building a generator house or any other house that have vibrating machines inside it. And also toilet pits or soak away tanks. The material constituents, their mix, presence of admixtures and the manufacturing process are important factors that determine the properties of sandcrete blocks.

### 2.2.3 Binder materials used in sandcrete blocks

Cement is used in the manufacture of sandcrete blocks as a bidding material. Cements are generally adhesive and cohesive materials which are capable of bonding together particles of solid matter into a compact durable mass. There are several types of cement, such as, Portland cement, white cement and pozzolanic cement (Putero et al., 2013). Portland cement is defined as a product obtained by finely pulverizing clinker produced by calcining to incipient fusion, an intimate and properly proportioned mixture of argillaceous and calcareous materials. Care must be exercised in proportioning the raw materials so that the clinker of proper constitution may be obtained after burning. The Ordinary Portland Cement has been classified as 33 Grade (IS269:1989), 43 Grade (IS 8112:1989), and 53 Grade (IS 12669-1987) (Duggal,2009).

Pozzolana may be defined as a siliceous material which whilst itself possessing no cementitious properties, either processed or unprocessed and in finely divided form, reacts in the presence of water with lime at normal temperatures to form compounds of low solubility having cementitious properties. Pozzolanas may be natural or artificial, fly ash being the best known in the latter category. Pozzolanic material is composed of $SiO_2$, $Al_2O_3$, $Fe_2O_3$, MgO and $SO_3$. To form pozzolanic cement, 15%-40% of pozzolanic materials are added into a Portland cement. High $SiO_2$ content in pozzolanic material reacts with remaining $Ca(OH)_2$ to form more CSH (to bermorite) that functions in cement hardening (Putero et al., 2013).

Pozzolanas are classified as natural and artificial. All natural pozzolanas are rich in silica and alumina and contain only a small quantity of alkalis. Examples of natural pozollana are; Clays and shales, diatomaceous earth and opaline cherts and shales, volcanic tuffs and pumicites and, rhenish and bavarian trass. Example of artificial pozzolanas are sugarcane bagasse ash, bamboo leaf ash, rice husk Ash, silica fume, Fly ash, ground blast-furnace slag, calcinated clay pozzolana (Surkhi) (Duggal, 2009).

### 2.2.4 Fine aggregates

River sand is the conventionally used fine aggregates in sandcrete block. It forms the body of the sandcrete block constituting at least 80 per cent of the volume, and have considerable influence on the properties of the sandcrete block (NIS 87, 2000). Fine aggregates can be natural aggregates or artificial aggregates. Natural fine aggregates are those obtained by crushing from quarries of igneous, sedimentary or metamorphic rocks, and reduced to their present size by the natural agencies. The most widely used aggregate are from igneous origin. Other natural sources includes; pits or dredged river sand, sea sand (Neville, 1994). Artificial aggregates comes from broken bricks, blast furnace slag and synthetic aggregates (Duggal, 2009).

Quarry dust, sawdust and laterites have, through research, been incorporated in the manufacture of sandcrete blocks (Adebakin et al., 2012; Dongapure & Shivaraj, 2014; Agbede & Manasseh, 2008). As compared to other rocks materials, laterites are fine grained and more porous. The physical properties of Laterite depend on its formation. It's the physical properties of rocks that determines its applications and use.

Fine aggregate for use in sandcrete blocks should be clean and free from deleterious materials and organic impurities such as organic matters, clay, shale, coal, iron pyrites, etc., which are weak, soft, fine or may have harmful physical or chemical effects. These materials are harmful since they affects the development of bond between aggregate and the cement paste. The properties to be considered while selecting fine aggregate for use in sandcrete blocks are; strength, particle shape (grading), specific gravity, bulk density, voids, porosity, moisture content and bulking (Neville, 1994).

### 2.2.5 Specifications of sandcrete blocks

According to Anwar (2000), sandcrete walls have adequate strength and stability, provide good resistance to weather and ground moisture, durable and easy to maintain. They also provide reasonable fire, heat, airborne and impact sound resistance. They are cost effective and better alternative to burnt clay bricks by virtue of their good durability. Sandcrete blocks, when properly produced, meet BS 2028 (1975) recommendations for density and compressive strength of structural masonry. Also building construction with hollow blocks provides facility for concealing electrical conduit, water and sewer pipes wherever so desired, and requires less plastering. Improper use of these blocks leads to micro cracks on the wall after construction (Anosike & Oyebande, 2012; Baiden & Tuuli, 2014).

According to BS 2028 (1975) blocks are classified into three types: Type A: Dense aggregate blocks; Type B: Lightweight aggregate blocks for load bearing walls; and Type C: Lightweight aggregate blocks for non-load bearing partitions. The classification is according to specified properties and uses and without reference to materials or method of manufacture. The distinction between types A, B, and C is therefore based on density as follows: Type A: Density not less than 1500 kg/m$^3$; and Types B and C: Density less than 1500 kg/m$^3$ but not less than 625 kg/m$^3$.

Sandcrete blocks properly manufactured according to BS 2028 recommendations on mix ratio, curing, and quality of constituent materials has a wide range of properties, making them very suitable construction material. These properties includes; high compressive strength, low shrinkage, low moisture movement, low thermal movement and denseness, and durability.

### 2.2.6 Specifications for solid and hollow blocks

BS 6073-1 (2008) provides guidance for production of solid and hollow blocks. Solid blocks are void less but can have end grooves to improve handling and bonding. Hollow blocks have a much more obvious cavity right through the block. The total volume of the cavity is, however, restricted to 50% of the gross volume of the block (Tovey, 1981; Hendry et al., 2014).

Solid and hollow concrete bricks and blocks are produced in a great variety of sizes, and are generally described in BS 2028, BS 1364, and BS 1180. BS EN 771–3 makes no differentiation between bricks and blocks but includes all concrete masonry elements under this one specification (Curtin et al., 2006) .Table 2.1 below provides the ‘concrete block’ sizes specified in BS 2028 and BS 1364.

Table 2.1: Range of concrete block sizes (previously BS 2028 and BS 1364)

| **Block** | **Length and height (mm)** | | **Thickness** |
|---|---|---|---|
| | **Coordinating size** | **Work Size** | **Work size** |
| Type A | 400 ×100<br>400 × 200<br>450 × 225 | 390 × 90<br>390 ×190<br>400 × 215 | 75,90,100<br>140 and 190<br>75,90,100,140,190 and 215 |
| Type B | 400 ×100<br>400 × 200<br>450 ×200<br>450 × 225<br>450 × 300<br>600 × 200<br>600 × 225 | 390 × 90<br>390 ×190<br>440 ×190<br>440 × 215<br>440 × 290<br>590 ×190<br>590 × 215 | 75,90,100<br>140 and 190<br>75,90,100,140,190 and 215 |
| Type C | 400 ×100<br>400 × 200<br>450 × 250<br>450 × 300<br>600 × 200<br>600 × 225 | 390 ×190<br>440 ×190<br>440 × 215<br>440 × 290<br>590 × 190<br>590 × 215 | 60 and 75 |

The Figure 2.1 illustrates a solid, cellular and hollow types of blocks.

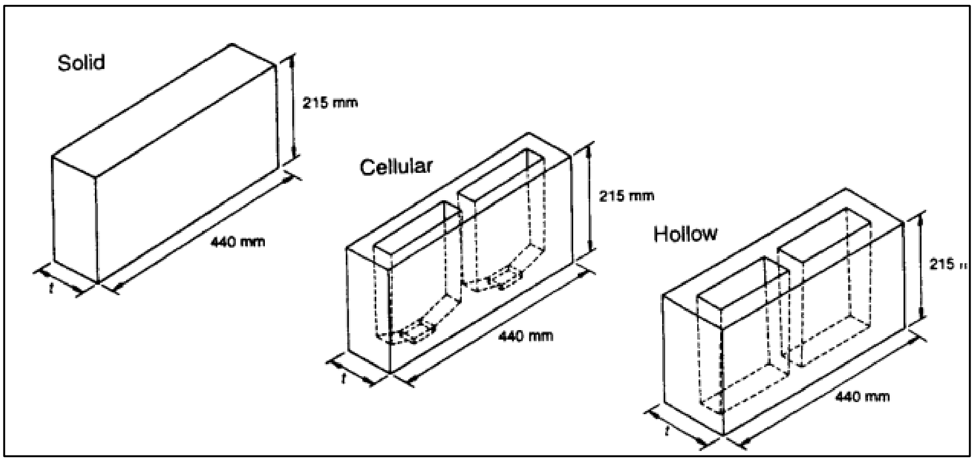



Figure 2.1: Concrete blocks (Curtin et al., 2006)

According to the most widely referenced ASTM standard for concrete masonry units, ASTM C90, physical requirements for masonry concrete include dimensional tolerances, minimum face shell and web thicknesses for hollow units, minimum strength and maximum absorption requirements, and maximum linear shrinkage. Table 2.2 below shows the minimum face shell and web requirements for hollow units. Table 2.3 shows the ASTM C90 specifications for concrete masonry units (CMU).

Table 2.2: Minimum face shell & web requirements for hollow units (ASTM C90-11b)

| | | **Webs** | |
|---|---|---|---|
| **Nominal width of unit, in. (mm)** | **Face shell thickness, in.(mm)** | **Web thickness in. (mm)** | **Normalized web area, min., $in^2/ft^2$ ($mm^2/m^2$)** |
| 3 (76.2) & 4 (102) | ¾ (19) | ¾ (19) | 6.5 (45.14) |
| 6 (152) | 1 (25) | ¾ (19) | 6.5 (45.14) |
| 8 (203) & greater | 11/4 (32) | ¾ (19) | 6.5 (45.14) |

Table 2.3: Strength, absorption and density classification requirement (ASTM C90-11b)

| **Density classification** | **Oven-Dry Density Of Concrete $lb/ft^3$($Kg/m^3$)** | **Maximum water absorption, Lb/ft3 ($kg/m^3$)** | **Minimum Net Area Compressive strength, lb/in (Mpa)** | | |
|---|---|---|---|---|---|
| | Average of 3 units | Average of 3 units | Individual units | Average of 3 units | Individual units |
| Lightweight | Less than 105 (1680) | 18 (288) | 20 (320) | 1900 (13.1) | 1700 (11.7) |
| Medium weight | 105 to less than 125(1680-2000) | 15 (240) | 17 (272) | 1900 (13.1) | 1700 (11.7 |
| Normal weight | 125(2000) or more | 13(208) | 15(240) | 1900 (13.1) | 1700 (11.7) |

The dimension tolerance provided in NIS 87 (2000) is as shown in the Table 2.4

Table 2.4: Dimension tolerance of sandcrete blocks (NIS 87, 2000)

| Block Width | Web thickness (mm) | | |
|---|---|---|---|
| | NIS | Manufacturers' | Laboratory produced |
| 225mm | 50 | 30-38 | 30-38 |
| 150mm | 37.5 | 30-38 | 30-38 |

### 2.2.7 Dry stack systems

Interlocking blocks construction is sometimes referred to as mortar less or "dry-stack" masonry construction. In this technique, masonry units are laid without mortar; however, limited amount of mortar is used for starter and top courses. The structural properties of the system relies on mechanical interlocking mechanism between units. This interlocking mechanism provides the wall's stability, levelling and self-alignment. The interlocking together imparts considerable strength to the wall structure. The system eliminates the use conventional cement mortar bonding and ensuring faster building. The blocks can be laid by unskilled workers who only require minimal training. They are also ideal for situations where the builder wants to conform to 'green' requirements; the manufacturer requires no power, minimal transport and makes little mess (Murray, 2017).

Uzoegbo and Ngowi (2004) provides Egyptian pyramids and the great Zimbabwean ruins, a capital of Shona kingdom, as live examples of ancient dry-stack construction. Soil-cement dry-stack system is one of the most common and cost-effective construction in Africa. The dry-stack method makes construction significantly easier and thus reduces the need for skilled labor. The biggest challenge in the construction of building with dry-stack blocks is the lack of standard code for a rational design established by worldwide research. Different types of interlocking blocks have been developed over the past years. The interlocking blocks may differ in shape, material composition, size, strengths and uses. In America for example, Murray (2017) identifies six type of dry-stacked blocks. These includes; haener block, azar block, sparlock, durisol, faswall and endura blocks.

Murray (2017) explains that the Haener block has been on the market longer than any other dry-stack system. It is an interlocking system; the individual blocks have raised lugs that align with the block 4 above. The system requires the same amount of grout as conventional concrete masonry unit (CMU) construction. Azar block walls are a similar dry-stack interlocking system. The bed and head joints are manufactured to interlock with adjacent blocks. Azar block, however, requires that all walls be solid grouted. The sparlock system uses unique shaped blocks that slide together. The blocks are placed in a stack bond arrangement. Sparlock is not typically used in bearing wall situations but has been employed heavily on the firewall market. Vertical reinforcement and grout may be used but typically are not required for non-bearing situations. The durisol and faswall systems are made of composite materials consisting of soft wood fibers and Portland cement. Because of their decreased compressive strength, these systems also require all walls to be solid grouted. Plate 2.2 shows examples of typical dystack hollow sandcrete blocks.

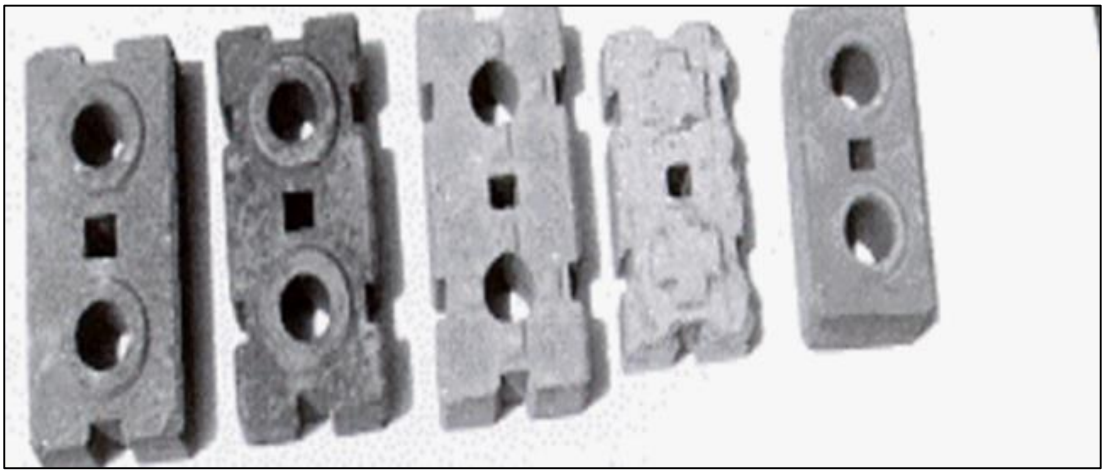


Plate 2.2: Different types of interlocking hollow blocks based on shape

(Amar and Shahrukh, 2015)

Another type of dry stacked block which is now gaining popularity especially in Africa is the hyraform dry stacked blocks. Hydraform interlocking blocks are produced by mixing soil and cement in predetermined ratios and extruding them vertically under a pressure of about 10 N/mm$^2$ using a hydraulic powered machine (Pave & Uzoegbo, 2007). The major material component is soil. Due to its abundance as a construction material in earth, hydraforms provide a cheap construction material. Dongapure and Shivaraj (2014) highlights the materials that can be used in the making of interlocking blocks, these include; soil-cement blocks, rice husk ash (RHA) cement blocks and concrete blocks.

## 2.3 Empirical Literature review.

### 2.3.1 Properties of non-conventional sandcrete blocks

Several studies have worked on sandcrete blocks using various methods of production, mix ratios, pozzolanic agro waste materials, aggregate materials and admixtures to produce good quality blocks (Raheem, 2006; Oyetola and Abdullahi, 2006). Laterites soil has been used to replace fine aggregate while in other studies rice husk ash (Oyekan & Kamiyo, 2011) and bamboo leaf ash have been used to replace cement in sandcrete blocks (Adewuyi et al., 2013).

Oyekan and Kamiyo (2011) investigated the effects of partial replacement of cement with rice husk ash (RHA) on some engineering properties of hollow sandcrete blocks with 1:6 cement-sand mix ratios. Single block size 225 × 225 × 450 mm were produced with a vibrating machine. Results show that the density of the blocks decreased as RHA content in the mix increased. 10% RHA content in the sand-cement mix was obtained as the optimum for improved structural performance. The result of the hydrothermal properties show that 10% rice husk ash would be the optimum content to replace cement in order to obtain a very compact block.

Adewuyi et al. (2013) in their study assessed the engineering properties of sandcrete blocks made with bamboo leaf ash (BLA) blended with Ordinary Portland Cement at 0%, 5%, 10%, 15%, 20% and 25%. The BLA had a specific gravity of 2.69. The compressive strength of the BLA cement sandcrete blocks increased with the curing age and decreases as the percentage of BLA increased. The mean strength of the blocks at the various percentage replacements of OPC with BLA satisfied the minimum strength requirement of 3.45 $N/mm^2$ by NIS 87 (2000) for load bearing walls up to 20% replacement level. The recorded water absorption values of the tested sandcrete blocks ranged between 0.36 – 0.55% up to 20% BLA content. Increase in loss in weight due to abrasion was observed as BLA content increases. It was concluded that BLA is a good pozzolanic material which can be used as a partial replacement of cement in the production of sandcrete blocks for housing construction provided the content level is not more than 20%.

Wilson et al. (2016) in their research titled "comparative review on the use of sandcrete blocks and laterite-cement bricks in Nigeria", revealed that the use of laterite-cement bricks can greatly reduce the cost of construction by up to 30% savings when compared to the use of sandcrete blocks. Apart from the addition of cement, lime can be used to further increase the strength of laterite-cement blocks. They asserted that the laterite-cement brick can be a good substitute for the sandcrete blocks in meeting the requirements and also for low cost building.

Opeyemi et al. (2014) explored ways in which lateritic soil could be utilized in hollow sandcrete block production. Sandcrete blocks were made with lateritic soil taken from different sources replacing the conventional fine aggregate (local river sand) in steps of 10% up to 60%. Their compressive strengths were determined to check for conformity with standard sandcrete block as specified in the Nigerian National Building Code (2006) with a view to determine the acceptable percentage replacement. Soil tests were performed on the lateritic soil samples to characterize the soils. Classification of the lateritic soil samples within Ota, revealed that the lateritic soils are mostly sandy clay of high plasticity and could replace sand by up to 20%, though an approximate linear decrease in strength with increasing sand replacement with lateritic soil was observed. This study recommended that 20% laterites can be used to replace sand in the block making industries within Ota with a view to encouraging utilization.

Ogunbiyi et al. (2014) analyzed the engineering properties and cost of production of cement stabilized clay bricks and sandcrete blocks with a view of comparing the findings with cement stabilized clay bricks and hollow sandcrete blocks sold in Oke-Baale area of Osogbo, Osun State, Nigeria. In the analysis they carried out Atterberg limit test in the laboratory to establish the plastic limit, liquid limit and plasticity index of the clay soil. The study showed that averagely, liquid limit is 58.5, plastic limit is 35.69 and plasticity index is 22.82. Other results also indicate that the compressive strength of 225mm and 150mm sandcrete hollow blocks vary from 0.85 $N/mm^2$ to 1.33 $N/mm^2$ for cement/sand mix ratio 1:12 and 0.92 $N/mm^2$ to 1.39 $N/mm^2$ for mix ratio

1.5:12 respectively, for curing period of 7 to 28 days respectively. The study recommended a reduction in the cement/sand and cement/clay mix ratios employed for both sandcrete hollow blocks and cement stabilized clay bricks to ratio 1:8 or 1:7 to enable the blocks to achieve the recommended 2-2.5 $N/mm^2$ compressive strength for load bearing wall recommended in NIS 87 (2000).

Swathy and Sugarbramam (2015) carried out experimental investigation consisting of different blocks of various material constituents subjected to the loading condition to investigate the behavior of the blocks. The Experimental study of the results carried out concluded that shrinkage, strength, water absorption and compressive load carrying capacity are high for laterite soil test, in comparison to red soil test samples. The results showed an average difference of 6.8-10.2% in every property of laterite soil samples over red soil samples. Most of the samples showed that a curing period change could make adequate changes in the properties. The study recommended for further studies on various materials combinations so as to produce a better building material that could give good strength and at a lower investment cost.

Asiedu and Agbenyega (2014) focused their research on the utilization of laterite fines as replacement for sand in the production of sandcrete bricks as masonry units. With a cement to sand ratio of 1:6 and water to cement ratio of 0.50, batches with 0% (control specimens), 10%, 20%, 30%, 40% and 50% laterite fines replacing the sand were adopted in this study. In all, 96 bricks were cast, tested and compared with those of conventional sandcrete bricks (control specimens). Tests conducted were density, compressive strengths (wet and dry) and water absorption. Results revealed that the laterite fines used could satisfactorily replace the sand up to 30% for the production of structural masonry units even though bricks need to be protected when used in waterlogged areas or below ground level by appropriate materials.

Ata et al. (2007) examined the effects of exposure of laterite/sand block to magnesium suphate environment. Changes in compressive strength of machine compacted hollow block specimens of cement to sand ratio of 1:6 and 10% laterite content were measured after 56 days of continuous immersion in 1%, 3% and 5% of magnesium sulphate solutions. Test results showed that the compressive strength significantly reduced with increase in magnesium sulphate concentration and immersion period. He concluded that, laterite/sand block made with ordinary portland cement cannot be recommended for use in sulphate-laden environment since it produced blocks of compressive strength than 2.07 N/mm$^2$, as required by the Nigerian Standards, after 28 days of immersion in magnesium sulphate solution.

According to Khairul and Latif (2010) abundant treated sea sand (ATSS) can be used as an alternative way for replacing the overall use of river sand. This is because it is reliable replacement for river sand in terms of cost, impact on environmental and its sand properties. The higher content of sodium chloride in marine sand can affect durability properties. Khairul and Latif (2010) cited Lee (2002) recommending that the salt content of the sea sand must be eliminated before it is utilized to avoid the potential hazards.

According to Balakrishnan and Batra (2011) the major solid wastes generated from the sugar manufacturing process include sugarcane trash, bagasse, press mud, bagasse fly ash and spent wash. Bagasse is the fibrous residue that remains after the extraction of juice from sugar cane. In sugar processing industries, this bagasse waste is used as a fuel and results in the production of the Sugacane Bagasse Ash. The physical and chemical properties of sugar cane bagasse ash are found to be satisfactory and conform to the requirements for class N pozzolana (ASTM C618, 1978). The major components in bagasse ash being $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $Na_2O$, $K_2O$, $P_2O_5$ and MnO (ASTM C618, 1978).

The use of bagasse ash as pozzolana in sandcrete block has received little attention. As defined in ASTM C618, pozzolanas are siliceous or siliceous and aluminous materials which in itself possesses little or no cementitious value but will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitous properties.With limited information on use of bagasse ash in sandcrete blocks the strength properties of sugarcane bagasse ash (SBA) can be inferred from studies done on concrete. Srinivasan & Sathiya (2010) study shows that the pozzolanic SBA in blended concrete have significantly higher compressive strength, tensile strength, and flexural strength compare to that of the concrete without SBA. It is found that the cement could be advantageously replaced with SBA up to maximum limit of 10%.

### 2.3.2 Properties and performance of dry stack hollow blocks

Compressive strength of a masonry unit is largely used to describe several design properties of masonry wall. Compressive testing on unit blocks is important for both quality control and design. Sornchomkeaw and Duangkeaw (2013) studied Compressive Strength of Interlocking brick by using bottom ash instead of cement. It was found that the maximum compressive strength of 7.2 Mpa is achieved at a cement to sand ratio of 1:6 with 5% of bottom ash used. They opined that this composition is the most appropriate mixture for designing bricks. In this research the density tends to decrease when bottom ash is added because the specific gravity of the bottom ash is less than the specific gravity of cement and the bottom ash is stickier than cement.

Raheem et al., (2012) examined the production and testing of lateritic interlocking blocks. The experiments involved the production of 250 × 130 × 220 mm interlocking blocks with laterite samples obtained within southwestern Nigeria. The blocks were tested for performance based on their compressive strength, water absorption and resistance to abrasion. The results indicated that all of the stabilized blocks satisfied the minimum 28 day wet compressive strength of 1.0 $N/mm^2$ recommended by the Nigeria Building and Road Research Institute.

Ahmad et al. (2014) examined the compressive strength property of interlocking masonry units/blocks and compared it with strength behavior of other masonry units. The research revealed an increase in strength by 20% when compared with the concrete masonry hollow blocks and an increase of 40% in strength as compared with brick. Interlocking prism increases strength by 30% as compared to the prism without interlocking mortar. Further, construction cost was reduced since there was a reduction of the number of high skilled masons required on a construction project.

Vennila et al. (2017) determined the compressive strength on interlocking concrete blocks with acacia nilotica ash and broken tiles. The research reported that the 7 days compressive strength of blocks is 19.36 $N/mm^2$ and 14 days compressive strength of blocks as 25.34 $N/mm^2$. The study concluded that low cost concrete is developed using waste broken tiles and acacia nilotica ash from burning of karuvelammaram thus reducing cement use and the emission of greenhouse gas into the atmosphere.

Akeem et al. (2012) study considered the production and testing of sandcrete hollow blocks and laterite interlocking blocks with a view to comparing their physical characteristics and production cost. The results indicated that the compressive strength of 225mm and 150mm sandcrete hollow blocks varies from 1.59 $N/mm^2$ to 4.25 $N/mm^2$ and 1.48$N/mm^2$ to 3.35 $N/mm^2$ respectively, as the curing age increases from 7 to 28 days. For laterite interlocking blocks, the strength varies from 1.70 $N/mm^2$ at 7 days to 5.03 $N/mm^2$ at 28 days. All the blocks produced satisfied the minimum requirements in terms of compressive strength, by all available codes. The cost per square meter of 225mm and 150mm sandcrete hollow blocks were ₦2,808:00 and ₦2,340:00 respectively, while that of laterite interlocking blocks was ₦2,121:20. It was concluded that laterite interlocking blocks have better strength and are cheaper than sandcrete hollow blocks.

Assiamah et al. (2016) carried out a comparative study of interlocking and sandcrete blocks for building walling systems. The research sought to explore the possibility of adopting the interlocking block wall system as a means of making wall construction of buildings affordable in Ghana. Results showed that, the use of interlocking blocks do not only lead to elimination of a number of non-value adding activities associated with the use of the sandcrete blocks, but also make the wall construction process cheaper and faster. It was also discovered that the absence of mortar jointing in the interlocking system reduced the quantity of materials, like cement and sand, required in the sandcrete wall construction process. Furthermore, there was no statistically difference between the compressive strength of interlocking blocks and conventional sandcrete blocks. However, there were statistically significant differences between construction cost and speed of construction using the two systems of construction.

### 2.3.3 Structural Performance and failure mode of dry stack masonry system.

Anand and Ramamurthy (2003) study focused on laboratory-based productivity of interlocking masonry systems. In this research the productivity of dry stacked masonry systems and conventional mortar jointed masonry construction were compared. The focus of the research was on the output of a mason's crew. These were evaluated by constructing different types of masonry walls .The study concluded that a crew could output approximately 60% more using interlocking dry-stacked blocks than with traditional hollow block masonry.

Uzoegbo and Ngowi (2004) studied on the load capacity of dry-stack masonry walls. In this study hydraform block system developed in South Africa was investigated for load capacity under compression axial test. The test was conducted on 3m wide and 2.5m tall walls the first course of block was laid in mortar in order to provide a level bearing surface. A 3m long steel beam was used to distribute the applied load evenly on top of the wall. Dial gauges were fixed on the wall surface to monitor displacement of the walls due to the applied loading. The walls under tests were built using blocks with varying unit strengths. It was noted that general vertical cracks developed at the mid-section of the wall often accompanied the by loud snap. For wall specimen made with lower unit strength block, the top courses of wall were crushed at failure loads. The study noted that crushing occurred as the ratio of unit strength to overall wall panel strength decreases. Control wall was built using traditional concrete block techniques and tested. The control wall result was used to normalize the testing results of the dry-stack walls. The failure load of the dry-stack walls was divided by the conventional wall's capacity. Results of these tests showed a 65% increase in axial strength when mortar was used in the bed joints. The study attributed the difference in strength to the difference in failure mode. The walls tended to fail in shear and splitting of the head joints. The mortar use resisted the shear, which slightly increased the axial capacity of those walls.

Anand and Ramamurthy (2005) developed and evaluated hollow concrete interlocking block masonry system in India which was named as ITM-HILBLOCK system. The study involved both concentric and eccentric axial testing. Three units were stacked vertically. Testing was conducted on both dry-stacked prisms as well as units stacked with a thin layer of mortar between blocks. A grouted and ungrouted specimens were also tested. The results of the axial strength tests showed that the use of mortar increased the prism strength by 20-30%. During some of the tests samples, the grout column remained intact as the face of the block shells fell away. These results indicate that the amount of grout used directly influences the axial capacity and failure modes of the prisms. Test results from the eccentric load testing showed decreasing capacities associated with increasing eccentricities. The study also indicated that dry stack masonry is advantageous because of the simplicity in block laying, reduction in mortar consumption, and general independence of workmanship variations. The study reported a labor cost reduction of up to 80%.

Anand and Ramamurthy (2005) in their study made a comparison between SILBLOCK systems, a dry stack interlocking block system used primarily in India with traditional mortar bonded masonry. Ten masonry wallettes were constructed and tested under a concentric axial load. The results of the testing showed that "the allowable axial compressive stress for interlocking block masonry is higher than that of conventional masonry." In the study, fifteen masonry walletts were also constructed and tested under an eccentric axial load. Walls were tested with eccentricities of 0, t/3, and t/6, where t was the width of the block. The results of the test showed a significant decrease in strength when the eccentricity was increased. However, this testing showed that the reduction in capacity due to eccentricity was smaller than that for a typical concrete masonry unit (CMU) wall.

At an eccentricity of t/6, the capacity reduction was only around 10% for the SILBLOCK masonry as compared to approximately 30% for the conventional system. The observed increase in strength under eccentric load was attributed mostly to the interlocking features of the SILBLOCK system.

Jaafar et al. (2006) studied the behavior of interlocking mortar less block masonry. In their study, two different tests were performed i.e. "Single Joint" test and "Multiple Joint" test. In the single joint test two blocks were stacked on top of each other. Small mechanical gauge demec points (DPs) were placed near the block interfaces. These DPs were placed near the interface to measure only the deflection caused by the first type of geometric irregularities. The results of the single joint test showed that there was a change in stiffness during testing. The initial stiffness was attributed to settling of the blocks and the closing of block irregularities. As more of the block areas came into contact, the stiffness increased slightly. For the "Multiple Joint" test blocks were placed in a running bond. The test was to simulate both types of irregularities in a dry stack wall. The results of this test showed large differences in displacement between tested walls. These large differences were attributed to the varying block heights which caused small gaps between interfaces.

The size of these gaps varied from wall to wall, thus the differences in deflection.

Hatzinikolas et al. (1986) investigated the structural behavior of an interlocking masonry block. They suggested three important parameters that are required for a successful dry-stack masonry system. This included, superior performance than normal blocks, provision of adequate bending strength in both the vertical and horizontal directions and also provision of adequate resistance to water penetration and good insulation properties. The study involved testing and analyzing of the G.R. dry stacked masonry system laid in a stack bond. Fifteen five course tall by three course wide walls were tested in axial compression. Walls were tested under compression with load applied normal to the bed joints. The load was applied at the top of the walls and distributed by a 130 mm deep steel channel. A layer of compressible fiberboard was used at the top and bottom of the walls in order to ensure that the load was applied evenly on the walls. As ultimate loads were approached, vertical face shell cracking developed. This vertical cracking was attributed to the lateral tensile stresses that develop in the block as the interior grout expands under compression. Numerical values were obtained for the axial capacities of the tested walls. However these values were only applicable to the G.R. system.

Carrasco et al. ( 2013) studied on the performance of walls constructed with interlocking bricks of iron ore by-products and cement under simple compressive loading. Three walls with dimensions of 150 cm width, 240 cm height and 15 cm thickness were built and tested.The study observed that the first fissures arose with a stress of 0.56 MPa, corresponding to only 3.8% of the rupture stress of the brick alone. Horizontal displacement was negligible in all the walls and buckling was not observed. Rupture of  he walls was through crushing; microfissures appeared first and evolved into fissures and then transformation into cracks. After generalized occurrence of cracks, rupture occurred. This behavior was similar to that of the bricks. Compressive load tests were also performed to determine the strength of the brick, of the prism (two overlaid bricks) and of the mortar. Results showed high compressive strength of 14.57 MPa for bricks, 9.82 MPa of the prisms and 25.2 MPa of the mortar. The walls showed good mechanical strength of 2.05 MPa, which represents 14% of the brick strength. Deformations were high, with axial deformation modulus of 420 MPa, which indicates a flexible behavior of the wall. Although the wall was s flexible, the fissuration stress was relatively high, indicating excellent performance of the wall. Another very positive aspect was that this stress was only 13.6 % of the compressive strength of the wall and 1.9% of the brick, which indicated that there was a very large strength reserve.

Ahmad et al. (2014) studied the shear characteristic of interlocking mortarless block masonry joints. In this study modified triplet tests on mortarless interlocking panels with different levels of axial compression were carried out to ascertain the deformation and shear strength characteristics of the system at the joint interface. Failure criterion for the interlocked bed joints under combined normal-shear load was proposed. The experimental tests show that the observed friction behaviour for the interlocking mortarless joints under different axial compression follows the linear Coulomb type failure criterion, and have a coefficient of friction of 0.603 with zero cohesion contribution. The interlocking masonry system provides sufficient shear resistance as required by BS standard. The failure mode was generally that of sliding along the bed joints of the middle course.

Structural performance of concrete masonry was largely dependent upon three key criteria: The engineering rationale incorporated into the design of the structure; the physical characteristics of the materials used in the construction of the structure (i.e., the masonry units, grout, mortar, and reinforcement); and the quality of the construction used in assembling these components (Arya, 2009).

According to Arya (2009) for structural design, the two most important properties of blocks are their size and compressive strength. The most frequently used block has a work face of 440 × 215 mm, width 100 mm and compressive strength 3.6 $N/mm^2$; 2.9 $N/mm^2$ is a popular strength for aircrete blocks, and 7.3 $N/mm^2$ for aggregate concrete blocks as it can be used below ground. Guidance on the selection and specification of concrete blocks in masonry construction can be found in BS 5628-1, (2005) and BS EN 771-3, (2003) respectively.

## 2.4 Summary and research gap

Relevant literature relating to performance of sandcrete blocks and dry stack masonry wall have been reviewed. Empirical studies on non-conventional sand and agro waste materials as replacement of river sand and cement respectively have been reviewed (Oyekan & Kamiyo, 2011; Adewuyi et al., 2013; Wilson et al., 2016; Opeyemi et al, 2014; Ogunbiyi et al, 2014; Swathy & Sugarbramam, 2015; Asiedu & Agbenyega, 2014; Khairul & Latif, 2010; Ata et al., 2007). The performance of this non - conventional materials have been highlighted to demonstrate the feasibility of this research project. Existing studies on dry stack masonry blocks and masonry wall model has also been reviewed. The performance of different block types in terms of compressive strength, flexural strength, durability, water absorption have been discussed (Swathy & Sugarbramam, 2015; Raheem et al., 2012; Ahmad et al., 2014). The literature shows how the properties of sandcrete blocks are dependent on quality of constituent materials, process adopted for manufacturing, duration of curing, block sizes and shapes. This research shall focus on how the materials, and shapes of the dry stack sandcrete blocks affects the engineering properties of sandcrete blocks. Review on the performance of wall models and failure model have also been discussed (Anand & Ramamurthy, 2003; Uzoegbo & Ngowi, 2004; Anand & Ramamurthy, 2005; Jaafar et al., 2006, Hatzinikolas et al., 1986). The literature underscores the need for walls to be of adequate strength, stable, high weather resistance, durable and easy to maintain.

From the literature review it's clear that most dry stack blocks are soil blocks. (Uzoegbo & Ngowi, 2004; Anand & Ramamurthy, 2005; Jaafar et al., 2006). This has primarily been as a result of the less cement content required for its production. While such findings have made contribution to the construction industry, such blocks have comparatively lower strength than similar sandcrete blocks. There is a need for researchers to develop a higher strength building blocks while at the same time cutting down on the cost. Replacing the conventional materials that are commonly used in sandcrete blocks and by modifying of the conventional hollow sandcrete blocks to dry stacked blocks have a potential of producing sandcrete blocks of high strength and comparatively lower cost. Lateritic soils and marine sands have separately been used as fine aggregate (Ogunbiyi et al., 2014; Asiedu & Agbenyega, 2014; Khairul & Latif, 2010). While some studies have recommended up to more than 50% utilization of marine sand with river sand, no studies have shown how marine sand perform when combined with lateritic sand. A blend of coarser lateritic sand and finer marine sand has potential of producing high strength sandcrete block. This allows less cement to be blended with an agro waste pozzolanic materials such as SBA without compromising the recommended sandcrete strength.

Research on Sugarcane bagasse ash has been extensively been done on soil blocks and concrete (Srinivasan & Sathiya, 2010; Onchiri et al, 2014). Utilization of Sugarcane Bagasse Ash (SBA) has proven to enhance the compressive strength of concrete up to an optimum proportion, with some literature citing a utilization of up to 10% (Srinivasan & Sathiya, 2010). Few studies have given a report on performance of bagasse ash in sandcrete blocks even though feasibility of utilization of other agro wastes materials such as rice husk ash (RHA) and bamboo leaf ash (BLA) have been extensively studied (Oyekan & Kamiyo, 2011; Adewuyi et al., 2013).

Load bearing blocks of size 450 × 225 × 225 mm exists as non-dry stack blocks. This research attempt to modify this blocks to dry stack hollow sandcrete blocks. The absence of design guides on mortar less wall system requires that experimental studies should be carried out to provide adequate data to encourage their application. In this research, the performance of sandcrete blocks produced with blended marine sand and lateritic sand, and bagasse ash as partial replacement of cement is investigated. The structural performance of the modified dry stack sandcrete blocks has been established in view of encouraging its use.

## 2.5 Conceptual framework

Figure 2.2 shows the conceptual framework of the study

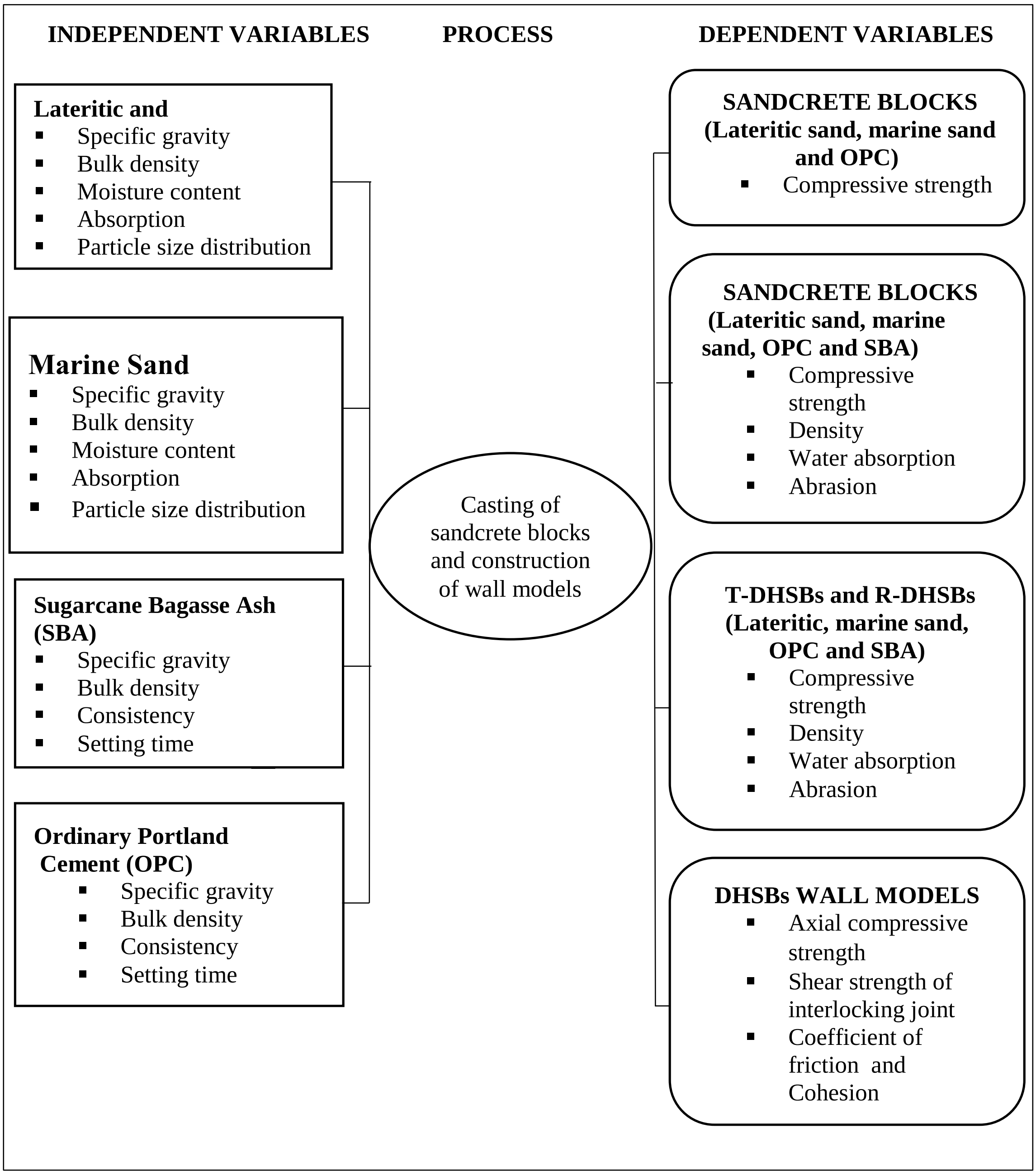



Figure 2.2: Conceptual framework of the study

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Introduction

This chapter describes the materials and methods that were used in the research. Research design, materials, data collection and analysis procedures that were used in achieving each research objective is described. The framework providing a guide to this study is given by the flow chat shown in Figure 3.1.

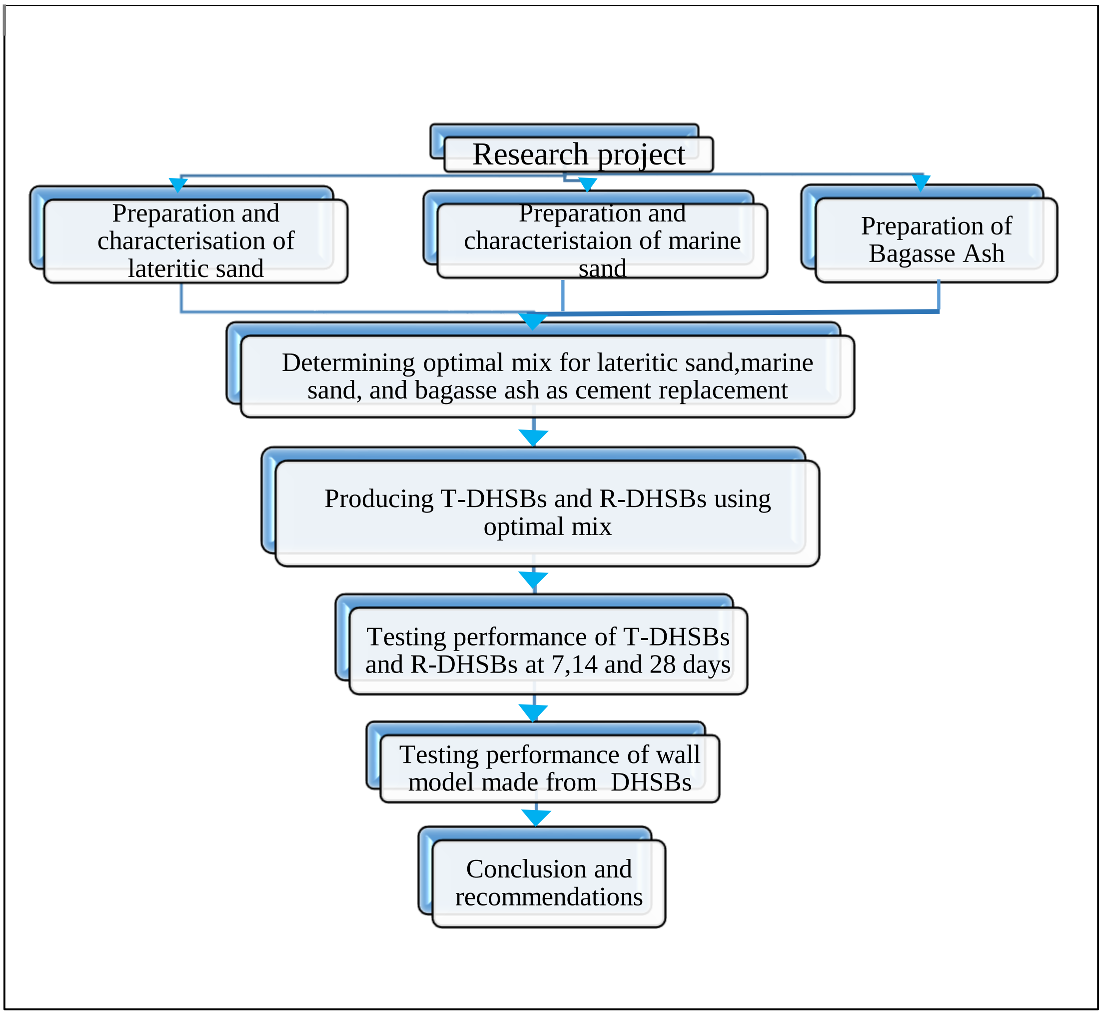



Figure 3.1: Summary of research framework

## 3.2 Performance of lateritic sand, marine sand and bagasse for sandcrete blocks.

### 3.2.1 Research design

The process of determining the performance and the optimal mixture of lateritic sand, marine sand and bagasse ash was conducted systematically through series of laboratory experiments. Lateritic sand was prepared by washing, drying and sieving. Laterites and marine sand were physically characterized by conducting sieve analysis, fineness modulus, specific gravity, silt content tests and bulk densities.

Hollow sandcrete blocks were made by varying the prepared lateritic sand against marine sand from 0% to 100% at intervals of 10% as established from literature review. The blocks were cured and tested for compressive strength in 7, 14, 28 days. Sandcrete strength is 99% at 28 days, it's almost close to its final strength, and thus the research rely upon the results of compressive strength test after 28 days and use this strength as the base.

Using the lateritic sand and marine sand mix ratio that produces higher 28 days compressive strength, pozzolanic sugarcane bagasse ash (SBA) was blended with cement in the ratio of 0%, 5%, 10% 15% 20% and 25% by weight of cement replacement. 90 sandcrete blocks were cast and tested for durability, bulk density, water absorption and compression test. In addition, 9 other sandcrete blocks were cast using river sand to be used as control. The results were analyzed using appropriate charts and graphs and the batches producing strength that satisfy the required minimum strength requirements were identified. The optimal point was determined as the proportion with compressive strength that conforms to the specification given in the NIS 87 (2000) and meets the durability requirement specified in BS 5628-1 (2005).

### 3.2.2 Materials used

The materials used in this investigation were: Ordinary Portland Cement (OPC), Sugarcane Bagasse Ash (SBA), river sand, lateritic sand, marine sand and portable water. The cement used was Ordinary Portland cement (OPC 42.5N) with properties conforming to BS 12. It was obtained from the nearest retail hardware in Thika town in Kenya.

Sugarcane Bagasse Ash (SBA) was obtained from West Kenya Sugar Company, Kakamega County. The company processes only one species of sugarcane which has a bearing on the uniformity in the chemical composition of SBA (Onchiri, et. al, 2014). The SBA was prepared by drying and sieving through a 300µmm sieve and then packed into polythene bags so as to maintain moisture. This was significant in preventing any reaction and thus maintain uniform characteristics of the SBA.

River sand used was sourced from Meru County, Kenya. It was clean, sharp, and free from clay and organic matter and was well graded conformity to BS 882 (1992).

The Lateritic sand used in this experiment was sourced from Kakamega County in Western Kenya between a depths of 1.5 m to 2.0 m using method of disturbed sampling. The lateritic sand was prepared by washing, drying and sieving so as to remove excess clay, silt, debris and organic content. According to Asiedu and Agbenyega (2014) the clay particles in lateritic are hygroscopic and would take up water and subsequently maintain a dynamic equilibrium of water content by absorbing water from the environment or desorb it. The behavior leads to a weakened bond between the aggregate particles and the cement paste resulting in a lower compressive strength.

Marine sand samples where obtained from the offshore strip in Mombasa Kenya. Both river sand, lateritic sand and marine sand used in this investigation passed thought 4.75mm British standard sieve and retained on sieve 150µm.

Pottable tap water was used throughout the research experiments. The water was fit for drinking, free from contaminants either dissolved or in suspension and conformed in totality to the specifications in BS 3148 (1980).

The major equipment that was used in this investigation included an appropriate block making mold and a hydraulic impact compression machine. Other equipment include: Spade which was used for mixing fresh sandcrete to attain the necessary consistency; Wheelbarrow/trolley- for transporting the materials such as cement, lateritic sand, marine sand, blocks etc; Trowel – for mixing sand, laterites and cement ;weighing balance, scale with an accuracy of 0.5kg; weighing pans and buckets; tamping rod- used for tapping the fresh sandcrete to the required stocks in both the slump and cube test; standard test sieve; safety gloves and lab coat- for protecting the body against any physical damage; spanners and screwdrivers used for tightening and stripping the steel molds other miscellaneous items.

### 3.2.3 Mix proportioning

In this study, a nominal mix proportions of 1:6 (one volume of cement to six volume of sand) as specified in NIS 87 (2000) was used. The proportioning was by weight. Trial test were conducted for all batches using water-cement ratio of 0.4, 0.5, and 0.6 and it was found that a water-cement ratio of 0.5 was suitable for all the batches. This value is similar with the water to cement ratio adopted by Asiedu and Agbenyega (2014) and Nwofor (2012). Marine sand was blended with the prepared sample of lateritic sand in the ratio of 0%, 10%, 20%, 30%, 40%, 50%, 60%, 80% and 100%. The proportioning was by weight. Cement content was held constant at 16.05% of the total weight of the mix while marine sand was varied against lateritic sand at an interval of 10%. Due to the difference in water absorption values and the natural moisture content of marine sand and lateritic sand, adjustment on the proportioning was done appropriately to achieve the 0.5 free water to cement ratio (see Appendix B). Table 3.1 below summarizes the mix proportioning of the materials at saturated surface dry (SDD) condition.

For the mix producing maximum strength, SBA was partially used to replace cement in the ratio of 0%, 5%, and 10% 15%, 20% and 25% by weight of cement. The percentage of marine sand and lateritic sand were held constant at each batch (See appendix B). Table 3.2 summarizes the mix proportioning when SBA was used to partially replace cement for the various percentages.

Table 3.1: Mix proportioning for cement and blended sand mixes

| Marine sand % | Cement Kg/m³ | Cement % | Lateritic sand Kg/m³ | Marine sand Kg/m³ | Water Kg/m³ | Water/cement ratio |
|---|---|---|---|---|---|---|
| 0 | 233.82 | 16.05 | 1222.86 | 0 | 116.91 | 0.5 |
| 10 | 234.79 | 16.05 | 1105.14 | 122.76 | 117.39 | 0.5 |
| 20 | 235.76 | 16.05 | 986.41 | 246.60 | 117.88 | 0.5 |
| 30 | 236.73 | 16.05 | 866.66 | 371.42 | 118.36 | 0.5 |
| 40 | 237.70 | 16.05 | 745.94 | 497.26 | 118.85 | 0.5 |
| 50 | 238.67 | 16.05 | 624.11 | 624.11 | 119.33 | 0.5 |
| 60 | 239.64 | 16.05 | 501.32 | 751.98 | 119.82 | 0.5 |
| 80 | 241.58 | 16.05 | 252.69 | 1010.76 | 120.39 | 0.5 |
| 100 | 243.52 | 16.05 | 0 | 1273.6 | 121.8 | 0.5 |
| | | | | | | |
| **Control** | **Cement Kg/m³** | | **River sand Kg/m³** | | **Water Kg/m³** | **Water/cement Ratio** |
| 100% river sand | 227 | 16.05 | 1187.23 | | 113.50 | 0.5 |

Table 3.2: Mix proportioning for various SBA % replacement of cement.

| % SBA | SBA Kg/m³ | Cement Kg/m³ | Lateritic sand Kg/m³ | Marine sand Kg/m³ | Water Kg/m³ |
|---|---|---|---|---|---|
| 0 | 0 | 236.73 | 866.66 | 371.42 | 118.36 |
| 5 | 11.79 | 224.01 | 863.25 | 369.96 | 117.90 |
| 10 | 23.49 | 211.38 | 859.84 | 368.50 | 117.43 |
| 15 | 35.09 | 198.85 | 856.44 | 367.04 | 116.97 |
| 20 | 46.60 | 186.40 | 853.03 | 365.58 | 116.50 |
| 25 | 58.02 | 174.06 | 849.62 | 364.12 | 116.04 |

In this study, the hand mixing was used. Goncalves and Bergmann (2007) recommends that in hand mixing the materials are turned over a number of times until an even color and consistency are attained. The blocks produced manually and compacted manually with the aid of a wooden rod as explained by Nunnally (2007) for small scale production. The binder/s and blended sand were mixed in a dry form and water was then added.

### 3.2.4 Experimental program and result analysis

Lateritic sand, marine sand and river sand (control) used in this study were physically characterized by conducting sieve analysis, fineness modulus, specific gravity test, water absorption and natural moisture content tests. The specific gravity, bulk density and consistency of sugarcane bagasse ash was determined. Chemical analysis of the SBA was determined to in order to ascertain the pozzollanic characteristic of the SBA.

The sieve analysis tests and fineness modulus were carried out in accordance to the specifications provided in BS 1377 (1975) with specific references to the ASTM standards. Specific gravity was determined by standard pycnometer method described in ASTM D854-14. The silt content was determined in accordance to BS 812-1, (1995) and the bulk densities were determined in accordance to BS 812-2, (1995).

The standard cement sand mix ratio of 1:6 (cement: sand) for sandcrete with a water cement ratio of 0.5 was used in casting hollow sandcretes $450 \times 225 \times 225$ mm blocks (See plate 3.1) with laterite content varying against marine sand. Batching was by weight. For each batch 9 blocks were casted. In total 99 blocks were cast in this study. Using River sand, 9 blocks were cast to be used as control.

Plate 3.1: Sandcrete blocks made by blending clean lateritic and marine sand

Experiences from the rule of thumb have revealed that different batches of the same mix will experience little or no significant variation in compressive strength (Osunade, 2002). This practice is being used in commercial production blocks (Ata et al., 2007). Curing was done by sprinkling the blocks with water twice a day for one week and covering the blocks with polythene sheet to prevent rapid drying out of the blocks which could lead to shrinkage cracking (NIS 87, 2000). Crushing test were performed on the samples to determine their compressive strengths on the required number of days.

Table 3.3, Table 3.4 and Table 3.5 below show the labels that were used for the different curing periods. The 7, 14 and 28 curing days were arbitrary represented by numbers 1, 2, and 3 respectively. Samples A, B and C represented the different casting of the same batch. A label of 1A10 refers to the sample tested after 7 days in which 10% of lateritic sand is mixed with 90% marine sand. River sand was used as control and was labeled as C1, C2 and C3 for 7, 14 and 28 curing days.

Table 3.3: Sample labels for 7 day test.

| **Sample No** | **Percentage of lateritic sand against marine sand** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | **20%** | **30%** | **40%** | **50%** | **60%** | **70%** | **80%** | **100%** |
| **Sample A** | 1A0 | 1A10 | 1A20 | 1A30 | 1A40 | 1A50 | 1A60 | 1A70 | 1A80 | 1A100 |
| **Sample B** | 1B0 | 1B10 | 1B20 | 1B30 | 1B40 | 1B50 | 1B60 | 1B70 | 1B80 | 1B100 |
| **Sample C** | 1C0 | 1C10 | 1C20 | 1C30 | 1C40 | 1C50 | 1C60 | 1C70 | 1C80 | 1C100 |

Table 3.4: Sample labels for 14 days test

| **Sample No** | **Percentage of lateritic sand against marine sand** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | **20%** | **30%** | **40%** | **50%** | **60%** | **70%** | **80%** | **100%** |
| **Sample A** | 2A0 | 2A10 | 2A20 | 2A30 | 2A40 | 2A50 | 2A60 | 2A70 | 2A80 | 2A100 |
| **Sample B** | 2B0 | 2B10 | 2B20 | 2B30 | 2B40 | 2B50 | 2B60 | 2B70 | 2B80 | 2B100 |
| **Sample C** | 2C0 | 2C10 | 2C20 | 2C30 | 2C40 | 2C50 | 2C60 | 2C70 | 2C80 | 2C100 |

Table 3.5: Sample labels for 28 days test

| Sample No | Percentage of lateritic sand against marine sand | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0%** | **10%** | **20%** | **30%** | **40%** | **50%** | **60%** | **70%** | **80%** | **100%** |
| **Sample A** | 3A0 | 3A10 | 3A20 | 3A30 | 3A40 | 3A50 | 3A60 | 3A70 | 3A80 | 3A100 |
| **Sample B** | 3B0 | 3B10 | 3B20 | 3B30 | 3B40 | 2B50 | 3B60 | 3B70 | 3B80 | 3B100 |
| **Sample C** | 3C0 | 3C10 | 3C20 | 3C30 | 3C40 | 3C50 | 3C60 | 3C70 | 3C80 | 3C100 |

The lateritic sand and marine sand mix ratio that produced higher compressive strength in 28 days was established as the optimal value. Using this optimal lateritic and marine sand mixture, SBA was used to partially replace cement in the ratio of 0%, 5%, and 10% 15%, 20% and 25% by weight of cement. 15 sandcrete blocks were casted in each batch to be tested for compressive strength after 7, 14 and 28 days. Abrasion tests and water absorption tests were conducted after 28 days. In total, 75 sandcrete blocks were casted and tested for durability, bulk density, water absorption and compression test.

The average compressive strength for each number of curing days was determined as an average of three blocks and tabulated accordingly. Compressive strength was computed by diving the compression load by the bearing area. Graphs showing variations in compressive strength with the introduction of the lateritic sand in marine sand were drawn. The results were compared with specification for sandcrete strength provide in NIS 87 (2000) which provides a minimum 28 day strength of 3.45 $N/mm^2$ for load bearing walls. The 28 days results for dry density and water absorption when sugarcane bagasse ash have been introduced, was tabulated and analyzed using chats. The values were checked to confirm if they are within the acceptable limit.

According to BS 2028 recommendation, the average density of three (3) blocks is 1500 $kg/m^3$ for a load bearing sandcrete masonry unit. Water absorption for the sandcrete blocks were checked not to exceed the maximum allowed water absorption of 12% as specified by BS 5628-1 (2005).

The optimal proportion of SBA to be used in the lateritic and marine sand blend was established from the mix proportion that produced sandcrete blocks which satisfies the compressive and durability requirements specified in NIS 87 (2000) and BS 5628-1 (2005) respectively. The optimal mix was the one with the compressive strength exceeding 3.45 N/mm$^2$ and at the same time conform to the durability requirement given in the standards. This was identified from the various batches discussed earlier. This optimal mix was used to develop the dry stack hollow sandcrete blocks identified as T-DHSBs and R-DHSBs in this research.

## 3.3 Performance of dry stacked hollow sandcrete blocks (DHSBs)

### 3.3.1 Research design

In determining the performance of selected dry stack hollow sandcrete blocks (DHSBs) units, two types of dry stack hollow sandcrete blocks were made using the optimal mix of lateritic sand marine sand and bagasse ash obtained in Section 3.2. The two types of DHSBs were identified as T-DHSBs and R-DHSBs (shown in plate 3.2). The performance of the blocks in terms of durability, bulk density and water absorption was tested in 28 days. The compressive strength of the blocks were tested in 7, 14 and 28 days. The performance of the dry stack hollow sandcrete blocks (DHSBs) was compared to conventional sandcrete blocks by considering the strength and durability requirements.

### 3.3.2 Preparation of materials samples

The marine sand sample to be used was dried and sieved so as to remove debris and organic materials. Lateritic sand was washed, dried and sieved. Sieving was done using a wire mesh screen with aperture of about 5 mm in diameter as recommended by Oshodi (2004). This is done to remove unnecessary and oversized materials. Fine materials passing through the sieve were collected for use while those retained were discarded. The SBA was prepared by drying and sieving through a 300µmm sieve.

### 3.3.3 Experimental program and result analysis for testing dry stack hollow sandcrete blocks (DHSBs).

Using the appropriate molds, 15 DHSBs of each type $450\,\text{mm} \times 225\,\text{mm} \times 225\,\text{mm}$ shown in Plate 3.2 were produced using the optimal lateritic fines, marine sand and bagasse ash in a ratio of 1:6 (cement: fine aggregate ratio). Conventional hollow sandcrete blocks of similar dimension were used as control. The process involved batching, mixing, casting and compaction of the blocks. Compaction was done using a wooden rammer. The blocks were cured for 7, 14 and 28 days and tested. For each testing days the dry-stack hollow sandcrete blocks (DHSBs) was tested for density and compressive strength. Durability and water absorption test were conducted after 28 days.

The sandcrete blocks were first allowed to air dry under a shade made with polythene sheet for 24 hours. Thereafter, Curing was done by sprinkling the blocks with water twice a day for one week and covering the blocks with polythene sheet to prevent rapid drying out of the blocks which could lead to shrinkage cracking (NIS 87, 2000). The blocks were stacked in rows and columns with maximum of four blocks in a column until they were ready for testing.

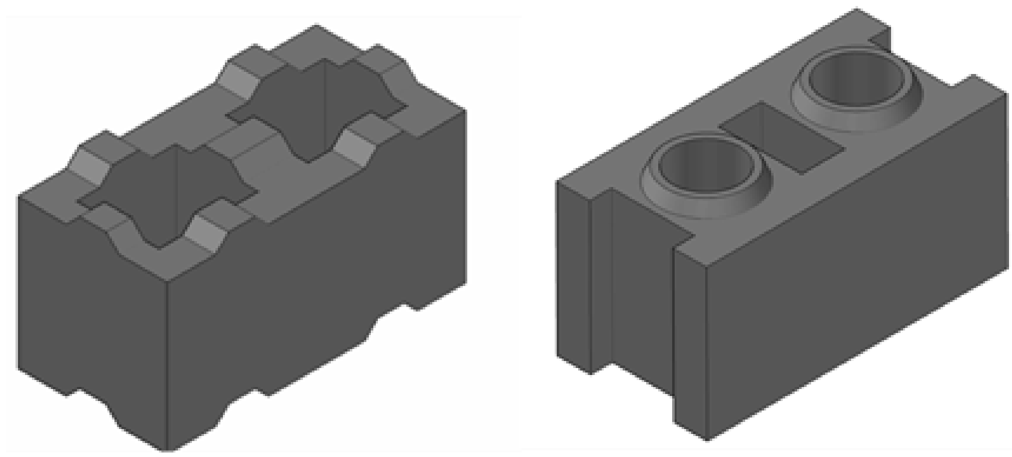



Plate 3.2: Shapes of T-DHSBs and R-DHSBs

Compressive strength was carried out to determine the load bearing capacity of each blocks. Dry compressive strengths was determined. The blocks that had attained the ripe ages for strength test of 7, 14, and 28 days were be taken from the stacking area to the laboratory, two hours before the test was conducted to normalize the temperature and to make the block relatively dry or free from moisture. The weight of the each block was taken before being placed on the compression testing machine. The placing was such that the top and bottom were as molded and lie horizontally on a flat metal plate. The recessions were filled with wooden plate of the exact size to prevent sheaving of the block during testing. The block was then crushed and the corresponding failure load recorded. The crushing force was divided by the sectional area of the block to arrive at the compressive strength.

The durability of the blocks was determined through abrasion test as described by Akeem, et al. (2012). After the DHSBs had attained the 28 day curing age, three blocks of each type were selected at random and weighed in the laboratory and their weight recorded. The blocks were placed on a smooth and firm surface and then wire-brushed to and fro on all the surfaces for 50 times, to and fro making a stroke. After brushing, the blocks was weighed again to determine the amount of material or particles abraded. This procedure was repeated for all blocks.

The water absorption was performed by randomly selecting three blocks from each group, and oven dried for 24 hours then weighing them on a balance of 0.001kg accuracy. These blocks were then completely immersed in water for 24 hours, after which they were removed and weighed again. The percentages of water absorbed by the blocks were estimated as follows (NIS 87, 2000).

$$Wa = \frac{Ws - Wd}{Wd} \times 100 \qquad \text{Equation 3.1}$$

Where:

Wa =Percentage moisture absorption

Ws =Weight of soaked block

Wd = Weight of oven dried block

The compressive strength was determined by dividing the compression load by the bearing area. The average compressive strength for each age were determined and compared. Graphs showing variations in compressive strength with curing duration was drawn for each type of the dry stack hollow sandcrete blocks. The results was compared with the conventional hollow sandcrete block. NIS 87 (2000) recommends that the compressive strength of three (3) blocks shall not be less than 3.45 $N/mm^2$. The water absorption capacities for the two blocks were tabulated for all the dry stack hollow sandcrete blocks and the values were compared with the maximum limit of 12% recommended in the standards by BS 5628-1 (2005). The dry density for each testing period was tabulated and the results compared with 1500$kg/m^3$ specified by BS

6073-1 (1981) recommendation for an average of three (3) blocks and 1600kg/m$^3$ recommended by Duggal (2009).

## 3.4 Structural behavior and failure mode of T-DHSBs and R-DHSBs wall models.

### 3.4.1 Research Design

Structural behavior and failure mode of wall models made from T-DHSBs and R-DHSBs were investigated. To achieve this objective, unreinforced masonry walls specimen made from the T-DHSBs and R-DHSBs were constructed. In this masonry unit, no mortar was used. The connection between the block units were provided by the interlocking of the dry stack hollow sandcrete blocks. Two walls were constructed, and each wall was tested for ultimate load capacity, lateral displacement, vertical displacement, compressive strength, stress strain relationship and crack patterns. Six triplet test specimen for each of the DHSBs specimens were made for shear tests to determine the shear properties of the interlocking joints. The shear strength and the mechanical parameters of the interlocking joints were established.

### 3.4.2 Experimental program and result analysis

**Walls under axial compression**

Four course tall by three course wide walls (1350 × 900 × 225 mm) of each type were constructed and tested in axial compression as shown in Figure 3.2. The walls were tested under compression with load applied normal to the bed joints. The load was applied at the top of the walls and distributed by a 130 mm deep steel channel. A layer of compressible board was used at the top and bottom of the walls in order to ensure that the load is applied evenly on the walls.

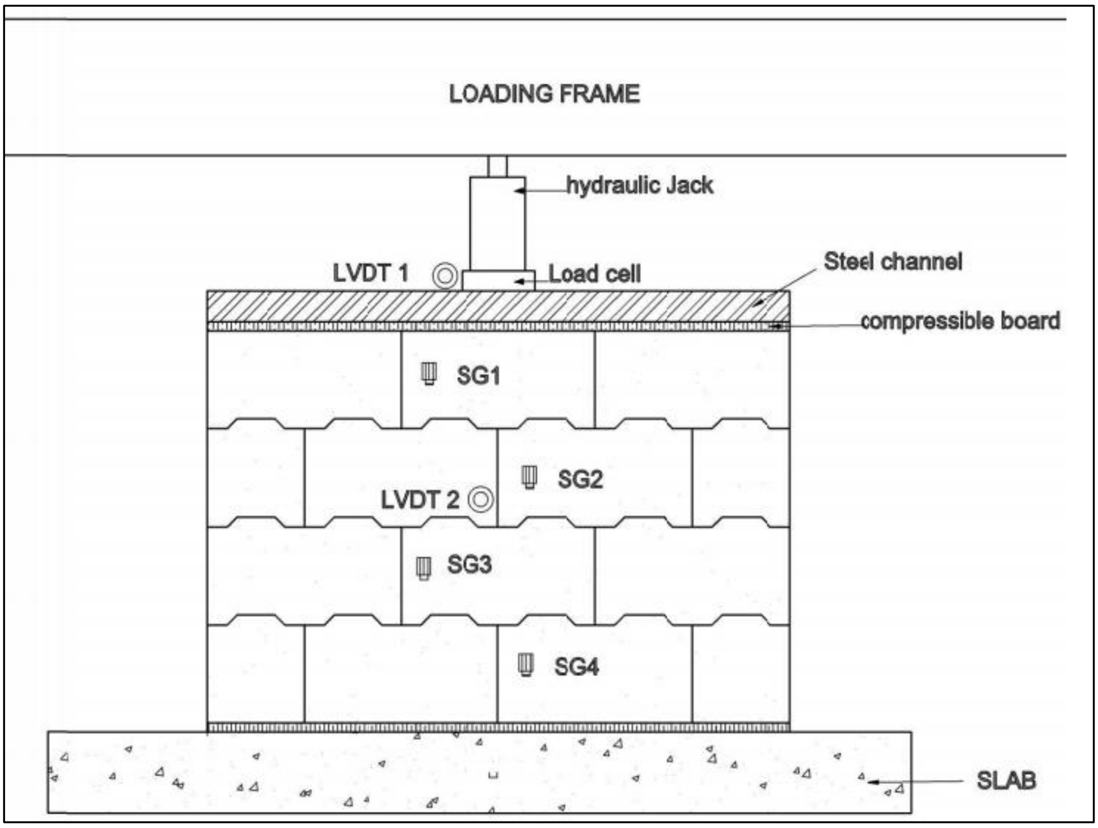



Figure 3.2: Set up and instrumentation of the wall specimens

Four types of data were collected during the testing; applied vertical load, vertical deflection of the specimen, horizontal deflection and strains at top, middle and bottom of the specimen height. The applied load and stress were obtained from loads cells which were mounted between the hydraulic jacks and the loading frame. The vertical wall deflection was measured using Linear Variable Displacement Transformers LVDT1 (see Figure 3.2). The LVDT 1 was attached to the top of the steel beam. The horizontal deflection at mid-height of the wall was measured using one Linear Variable Displacement Transformers (LVDT 2). The LVDT 2 was placed in perpendicular manner to the direction of the load. Strains in the specimen was detected by the strain gauges which were mounted at the positions shown in Figure 3.2. The strain gages (SG) were named as SG1, SG2, SG3 and SG4. All the instrumentation were connected to the data logger data for purposes of recording the necessary data. The failure mode of the walls was observed as soon as the failure load was attained and formation of cracks pattern begins.

The axial capacities of the masonry walls tested was tabulated. The compressive stress of each wall model was determined by dividing the axial load capacity with the total net bearing area. A calibration procedure was done by linear regression to establish the relationship between the readings provided by the data logger and the actual force and displacement values (see appendix I and appendix J). The maximum value of stresses for each wall type was compared with other researches work on dry stack masonry. The vertical displacement, lateral displacements, stresses and crack patterns of the walls specimens were compared. Typical load displacement curves for the wall specimens were drawn and results compared. Stress-strain relationship curves for each wall specimen was plotted and results compared. The failed wall specimens was investigated in terms of cracks formation. Direction and pattern of cracks were used to analyze the results.

**Triplet test**

Shear strength properties of the interlocking masonry was determined by triplet shear test set-up to simulate the interlocking features of the dry stack hollow sandcrete blocks. To construct the triplet test specimen, three DHSBs were dry-stacked on top of each other without using mortar and setup arranged as shown in Figure 3.3. The two outer blocks were restrained to move horizontally and were supported at the bottom whereas the middle course was allowed to move under applied vertical load. Block boards was used at the outer blocks of the panel to ensure the evenness of the end surface. The outer two bricks were also supported. The block boards were held together by means of bidding wire to provide the stability of the test setup.

In line with the provision of EN 1052-3 standard (BS EN, 2002), all specimens was subjected to a horizontal pre-compression load. Three different horizontal stress levels were adopted (0.2 MPa, 0.6 MPa and 1 MPa) and were kept constant, as much as possible, during the complete test. Vertical and horizontal loads were applied using two hydraulic jacks with maximum loading capacity of 50 MPa each. Firstly, the pre-compression was applied by a horizontal hydraulic jack and a manually operated pump to the required level. Then, the shear vertical load was applied using vertical hydraulic jack till the specimen’s collapse. The vertical load was indirectly applied to the specimen through using a spreader plate of 3 mm. In all tests, the horizontal load was kept (approximately) constant. The displacements of the specimens was recorded with LVDT 1 placed on metal plate at the middle block of the specimen. When the applied shear load was greater than the shear resistance of the interlocking joints, the middle course will slide providing the value of the shear strength of the two joints simultaneously.

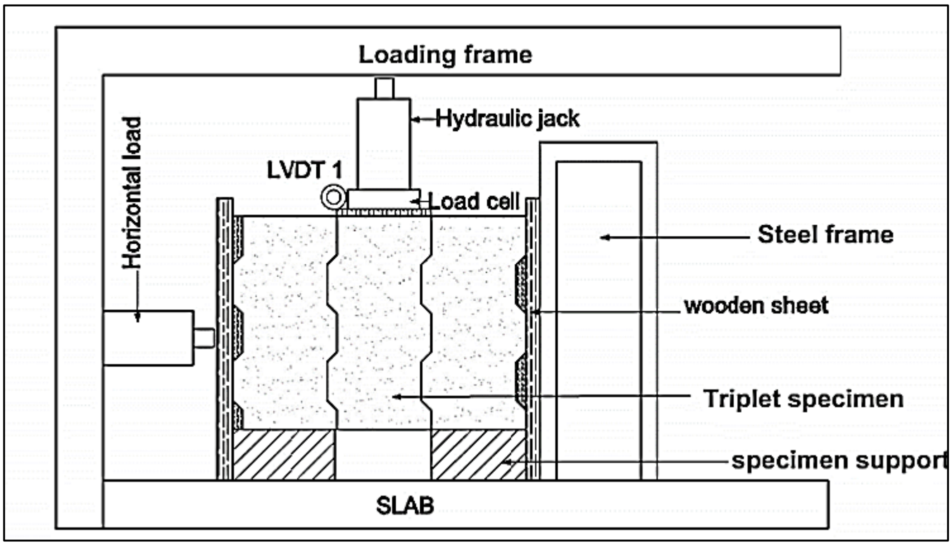



Figure 3.3: Set up and instrumentation for Triplet test

For the triplet tests, a graph was plotted to show the relationship between vertical force and vertical displacement for all specimens. Graphs for all the three levels of pre compression were drawn for comparison purposes. The maximum shear stress attained at each horizontal pre-compression stress was determined by dividing the maximum shear force at each test by the shearing area. A linear graph was drawn with shear stress ($\tau$) on the y-axis and the corresponding pre-compression stress ($\sigma$) on the x- axis. The shear strength $\tau$ of masonry under moderate normal stresses was given by the Coulomb criterion

$$\tau = \tau_o + \mu \times \sigma \quad \text{Equation 3.2}$$

Where $\mu$ and $\sigma$ stand for coefficient of friction and horizontal stress, respectively. The results of the triplet tests performed with different $\sigma$ values were used to define $\tau_o$ and $\mu$ by means of linear regression. Coefficient of friction, $\mu$, was established from the slope of the correlation, whereas the extrapolated intercept was the cohesion ($C_O$).

# CHAPTER FOUR

# RESULTS ANALYSIS AND DISCUSSION

## 4.1 Introduction

This chapter highlights the results and then describes trends observed on the results obtained for each specific objective. Inference to similar or contrasting results derived from literature is made in an attempt to support the discussion. Unusual observations are noted and explanation given for their cause. Relevant deductions are also made.

## 4.2 Performance of non-conventional materials for sandcrete blocks production

### 4.2.1 Material properties

**River sand**

Clean river sand free of clay, loam, dirt and any organic or chemical matter was sourced from Meru County, Kenya and sieved though 4.75 mm zone of British standard (BS) test sieves. The physical properties of the river sand is are given in Table 4.1 below.

Table 4.1: Physical properties of the river sand

| PROPERTY | TEST RESULT |
|---|---|
| Specific gravity (SSD) | 2.5 |
| Fineness modulus | 2.3 |
| Bulk density ; Loose<br>Compacted | 1403 Kg/m$^3$<br>1603 Kg/m$^3$ |
| Moisture content % | 3.6 |
| Absorption % | 6.1 |
| Silt content % | 4.7 |
| Grading | Complies with C:BS 882:1992 |

Dry sieving analysis was done in accordance with BS 1377 (1975). The river sand complied with C of (BS 882, 1992). The silt content is less than 5% maximum limit recommended in BS 812-1, (1995). The river sand was therefore good for construction purpose. The particle size distribution curve of the sand used in this study is shown in Figure 4.1.

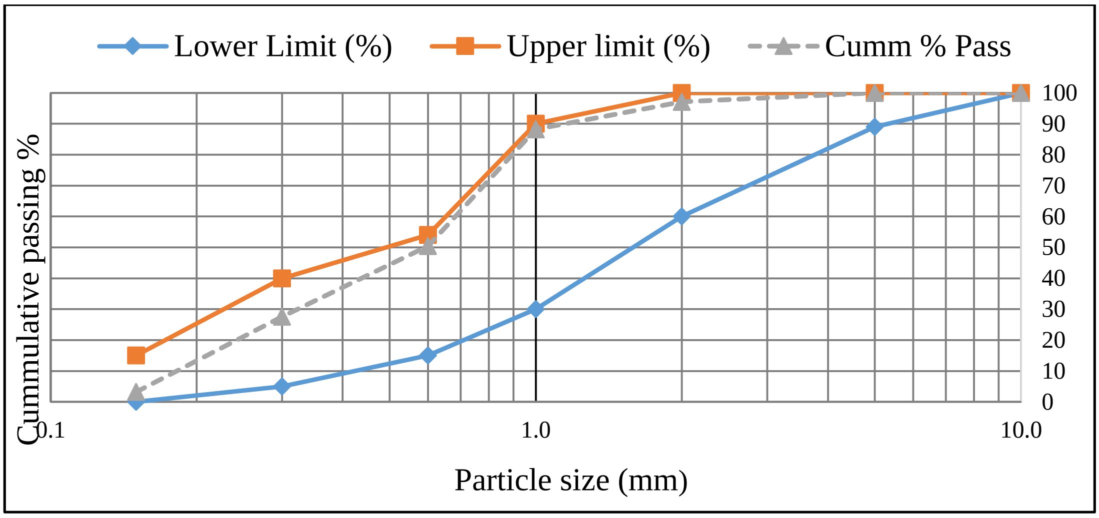



Figure 4.1: Sieve analysis results for river sand

The grading curve shows that river sand used in this study is fine sand having a lower finer modulus. Up to 90% of the river sand passes the 1.00 mm B.S. test sieve. Such fine aggregate would have more water demand and would produce comparatively lower strength sandcrete blocks as compared to the coarser fine aggregate.

**The Lateritic sand**

The physical properties of the prepared lateritic sand are as shown in Table 4.2.

Table 4.2: Physical properties of lateritic sand

| **PROPERTY** | **TEST RESULT** |
|---|---|
| Specific gravity (SSD) | 2.8 |
| Fineness modulus | 3.5 |
| Bulk density ; Loose<br>Compacted | 1519 $Kg/m^3$<br>1662 $Kg/m^3$ |
| Natural moisture content % | 2.3 |
| Absorption % | 5.3 |
| Silt content % | 4.0 |
| Grading | Complies with C:BS 882:1992 |

The lateritic sand used in this investigation was brownish sand obtained after washing, drying and sieving through the 4.75mm BS sieves. The sand was clean free from clay, loam, dirt and any organic matter.

The specific gravity of 2.88 for the lateritic sand is slightly higher than that obtained by Srinivasan and Sathiya (2010) and 2.78 obtained by Dongapure and Shivaraj (2014). The loose and bulk densities are close to 1490Kg/m$^3$ and 1660Kg/m$^3$ obtained by Dongapure & Shivaraj (2014).This clearly shows that the inherent physical properties of lateritic sand is location dependent. The silt content is less than 5% maximum limit recommended in BS 812-1 (1995).

Figure 4.2 shows the grading curve for the lateritic sand used in this study. The particle size distribution curve complies with curve C of table 4 in BS 812-1, (1995). The lateritic sand is thus good for construction purpose.

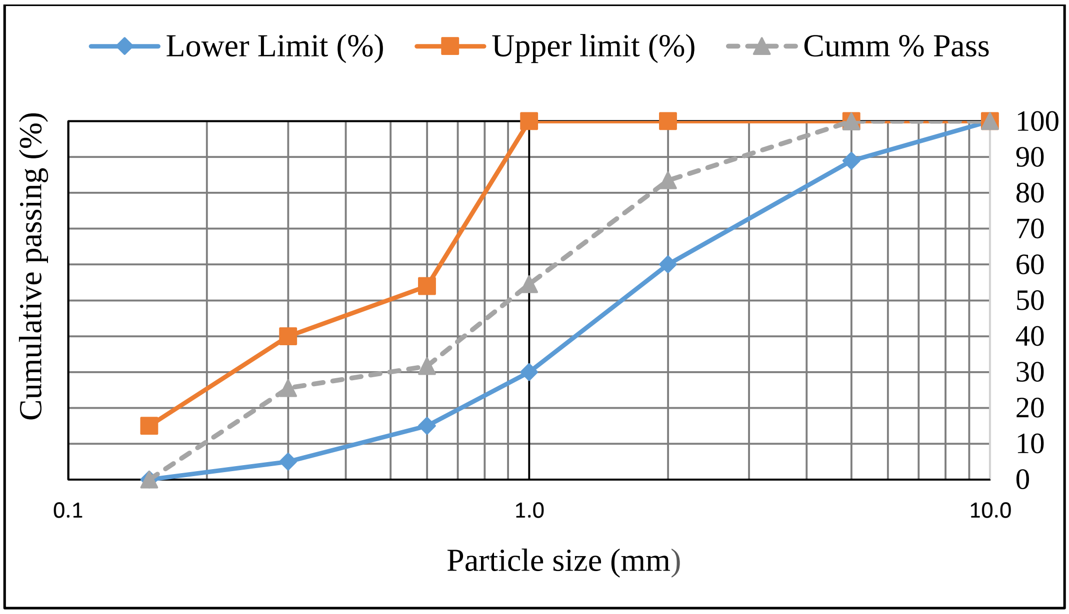



Figure 4.2: Sieve analysis results for the lateritic sand

The grading curve depicts a coarse sand with a high finer modulus. Only 55% of the lateritic sand passes the 1.00 mm B.S. test sieve. When used in sandcrete blocks lateritic sand will require less water to achieve the same consistency as the river sand used in this study. Other factors remaining constant, sandcrete blocks produced with lateritic sand has a higher strength than the river sand used in this study (see Figure 4.9).

**Marine sand**

The specific gravity of the marine sand used in this study is 2.3 this value is slightly lower than 2.66 obtained by Ravindra & Buraka (2016). A fineness modulus of 0.97 is an indication than the marine sand is finer than river sand with majority of the particles being retained on sieve number 1. A summary of the physical properties of the marine sand is tabulated in Table 4.3

Table 4.3: Physical properties of marine sand.

| PROPERTY | TEST RESULT |
|---|---|
| Specific gravity SSD | 2.3 |
| Fineness modulus | 0.97 |
| Bulk density ; Loose<br>Compacted | 1573 Kg/m$^3$<br>1746 Kg/m$^3$ |
| Moisture content % | 3.2 |
| Absorption % | 13.8 |
| Silt content % | 2.8 |
| Grading | Close to F, BS 882:1992 |

The marine sand is uniformly graded and does not comply with C, M and F of BS 882. The grading is however close to curve F. When the marine sand was blended with the lateritic sand used in this study, it was discovered that the 0%, 10%, 20% and 30% replacement of the marine sand replacements in lateritic sand conformed to the requirements of grading C BS 882 (1992). The 40%, 50% and 60% replacement conformed to M while 70% and 80% replacement conformed to F. Figure 4.3 to Figure 4.5 shows a typical grading curve for 30%, 40% and 60% marine sand in lateritic sand.

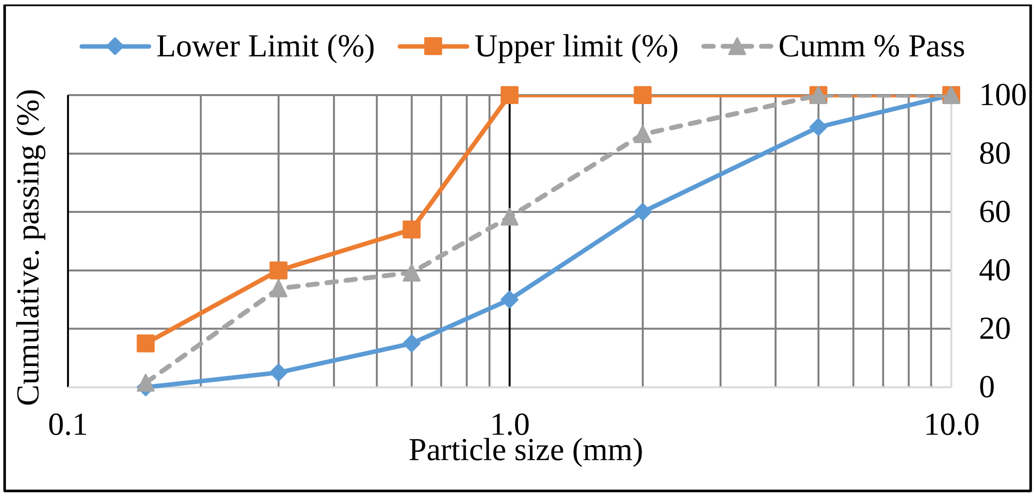



Figure 4.3: Sieve analysis results for 30:70 marine sand to lateritic sand mix

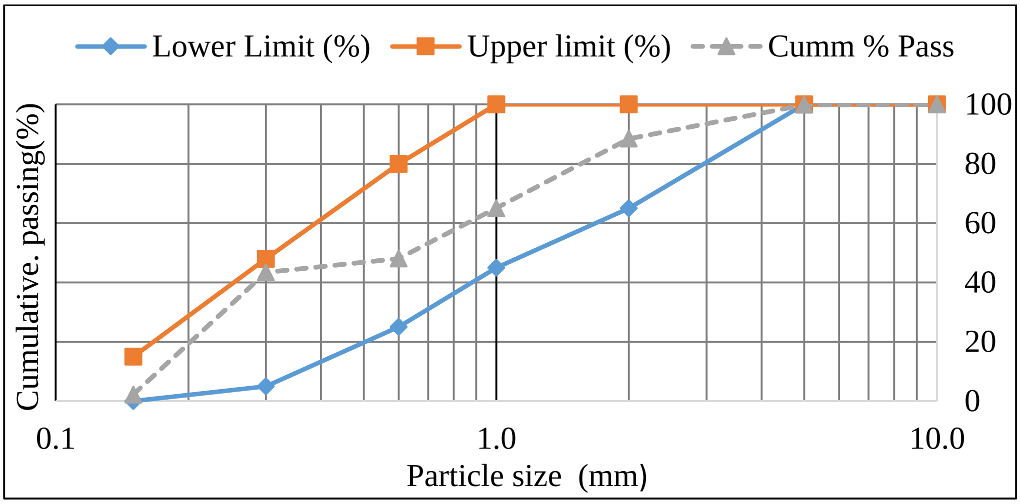



Figure 4.4: Sieve analysis results for 40:60 marine sand to lateritic sand mix

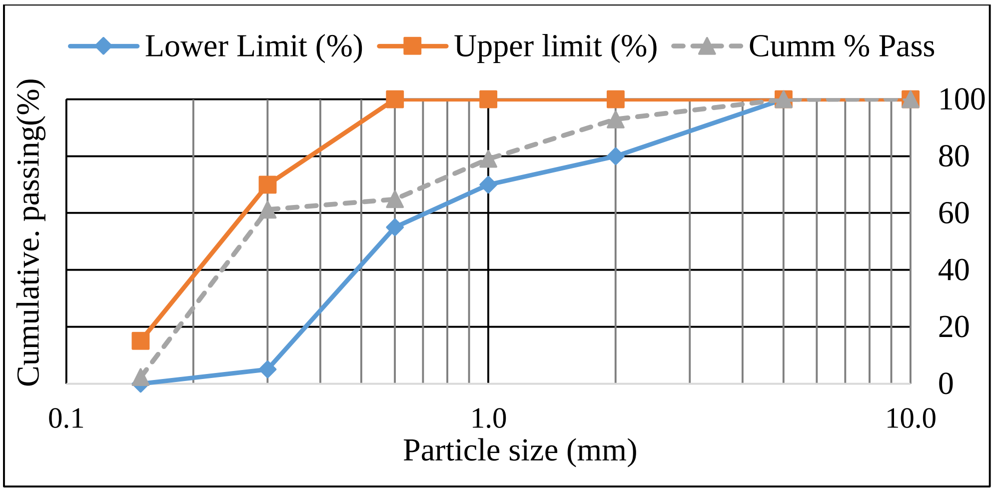



Figure 4.5: Sieve analysis results for 60:40 marine sand to lateritic sand mix

The marine sand used in this study was finer than sand. Majority of the particles were retained by B.S test sieve 150 mm. This sand have a high surface area and would require more water than river sand to achieve the same consistency. Subsequently, sandcrete blocks produced by 100% marine sand will fail at low compression force. Such a sand is not suitable for general construction. Blending of the marine sand with lateritic sand was therefore necessary in producing a marine-lateritic sand mixture that meets the requirement of BS 882 (1992). When 30, 40 and 60% of the marine sand is blended with the lateritic sand, 58, 65 and 79% of the blend passes the 1.00 mm B.S. test sieve. This means increasing the percentage of marine sand in the mix jeopardizes the chances of the blend to produce a higher strength sandcrete blocks

**Ordinary Portland cement**

Ordinary Portland cement (OPC 42.5N) was used in this study. The properties of the OPC are summarized in Table 4.4.

Table 4.4: Properties of Ordinary Portland cement

| **PROPERTY** | **TEST RESULT** |
|---|---|
| Cement :OPC 42.5N | |
| Specific gravity | 3.11 |
| Bulk Density :Loose<br>Compacted | 1162Kg/m$^3$<br>1398Kg/m$^3$ |
| Setting time; Initial setting time<br>Final setting time | 160 minutes<br>252 minutes |
| Water demand | 25.65% |

The specific gravity of the OPC is close to 3.1 that was obtained by Swathy and Sugarbramam (2015) and specific gravity of 3.12 obtained by Dongapure and Shivaraj (2014). Cement blended with SBA at 5, 10, 15, 20 and 25% level of replacement has a standard consistency of 36, 40, 44, 50 and 54 percentages respectively.

**Sugarcane Bagasse Ash (SBA)**

Table 4.5 shows the result of the chemical analysis of the SBA and the Ordinary Portland cement. The result has been compared with that of Fly Ash (artificial pozzolana) whose chemical composition is provided in ASTM C618. Results obtained by Barasa et al. (2016) and Ahmed and Kamau (2017) for different agro waste pozzolanic materials have been provided for comparison purposes.

Table 4.5: Chemical analysis of the sugarcane bagasse ash.

| **Parameter** | **Sugarcane Bagasse Ash (%)** | **Fly Ash class F ASTM 618 (%)** | **Bagasse Ash from Nzoia sugar (Barasa et al., 2016)** | **Rice Husk Ash (Ahmed and Kamau, 2017)** | **Ordinary Portland Cement (OPC) (%)** |
|---|---|---|---|---|---|
| Silica ($SiO_2$) | 62.3 | 40-63 | 66.23 | 87.8 | 22.0 |
| Aluminium Oxide($Al_2O_3$) | 4.25 | 17-28 | 1.90 | 0.4 | 4.80 |
| Ferrous Oxide ($Fe_2O_3$) | 3.69 | 3-12 | 3.09 | 0.3 | 2.44 |
| Calcium Oxide (CaO) | 1.02 | 2-8 | 2.81 | 0.7 | 59.0 |
| Magnesium Oxide (MgO) | 0.43 | 0.6-2 | 1.54 | 0.6 | 0.75 |
| Sodium Oxide ($Na_2O$) | 0.38 | - | 0.26 | 0.5 | 0.28 |
| Potassium Oxide ($K_2O$) | 2.7 | - | 6.44 | 2.2 | 0.60 |
| Titanium Oxide ($TiO_2$) | 0.32 | - | 0.07 | 2.2 | 0.20 |
| Manganese Oxide (MnO) | 0.23 | - | 1.54 | - | 0.04 |
| LOI | 15.28 | 0-5 | 16.36 | 2.2 | 6.30 |

The result for the chemical analysis was as recorded in column 1 of table 4.5 above. In this chemical analysis of SBA, the sum of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ is more than 70% thus satisfies the minimum percentage requirement for pozzolana, class F, according to ASTM C618. The sum of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ is slightly lower than obtained by Barasa et al., (2015). The specific gravity of the SBA is 1.94 and its compacted bulk density is 555 Kg/$m^3$. Low specific gravity (1.8–2.1) of the bagasse ash may be due to large amount of lightweight unburnt particles (Cordeiro et al., 2009). This factor will significantly affect the density of blocks when Sugarcane bagasse ash is used as part of the bonding material. To reduce this unburned materials bagasse ash should be sieved properly through BS standard sieve of less than 300mm.

### 4.2.2 Properties of sandcrete blocks made by blending marine and lateritic sand.

**Dry Density**

The values of density at various percentage proportion of marine sand for 7, 14 and 28 days curing days are shown in Table F1 Appendix F. For all curing periods, and up to 100% replacement of the marine sand, the values exceeded the BS 2028 minimum limit of 1500 $Kg/m^3$ for individual block. The average density for three blocks varies from 1986.93 $Kg/m^3$ to 1835.88 $Kg/m^3$ in 7 days, 1989.25 $Kg/m^3$ to 1780.90 $Kg/m^3$ in 14 days and 1970.66 $Kg/m^3$ to 1749.89 $Kg/m^3$ in 28 days.

The Figures 4.6, 4.7 & 4.8 illustrates the variation of the density of sandcrete blocks with different percentage of marine sand and laterite sand for 7 days, 14 days and 28 days curing respectively.

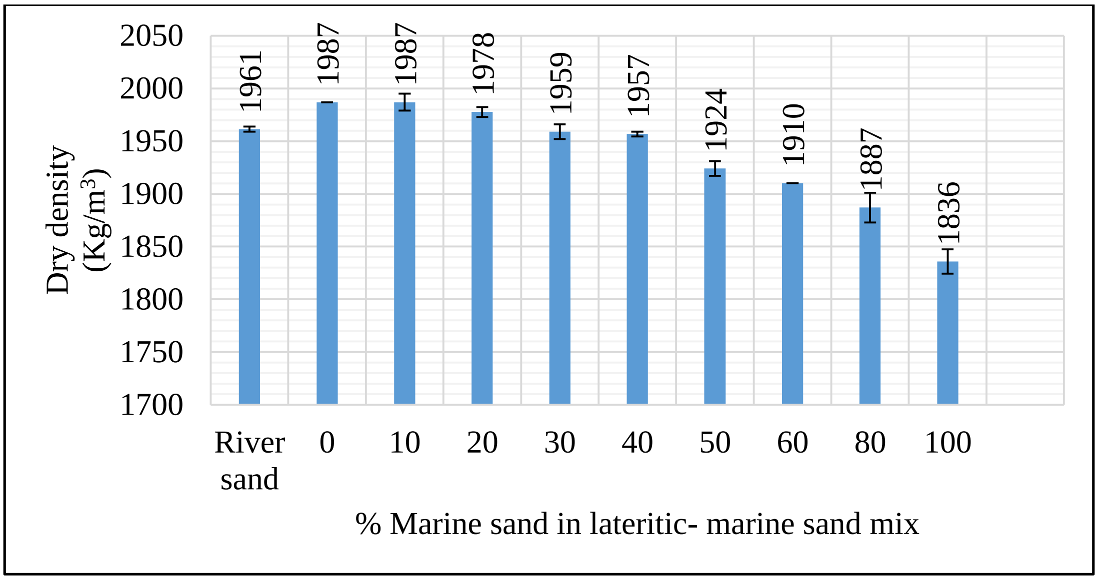



Figure 4.6: 7 days density of blocks made by blending marine and lateritic sand

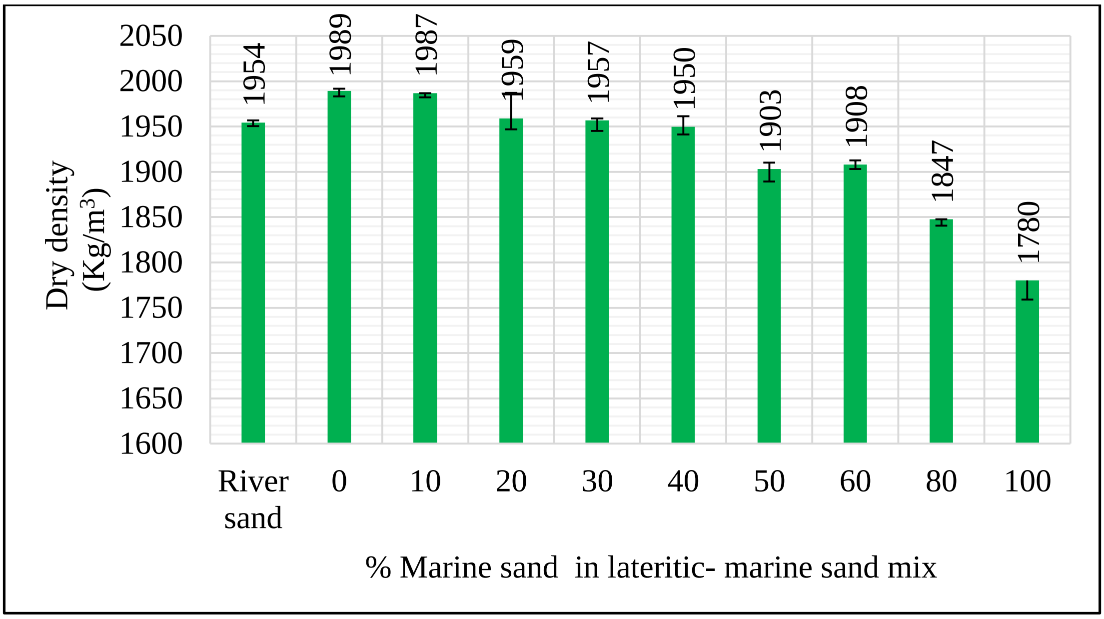



Figure 4.7: 14 days density of blocks made by blending marine and lateritic sand.

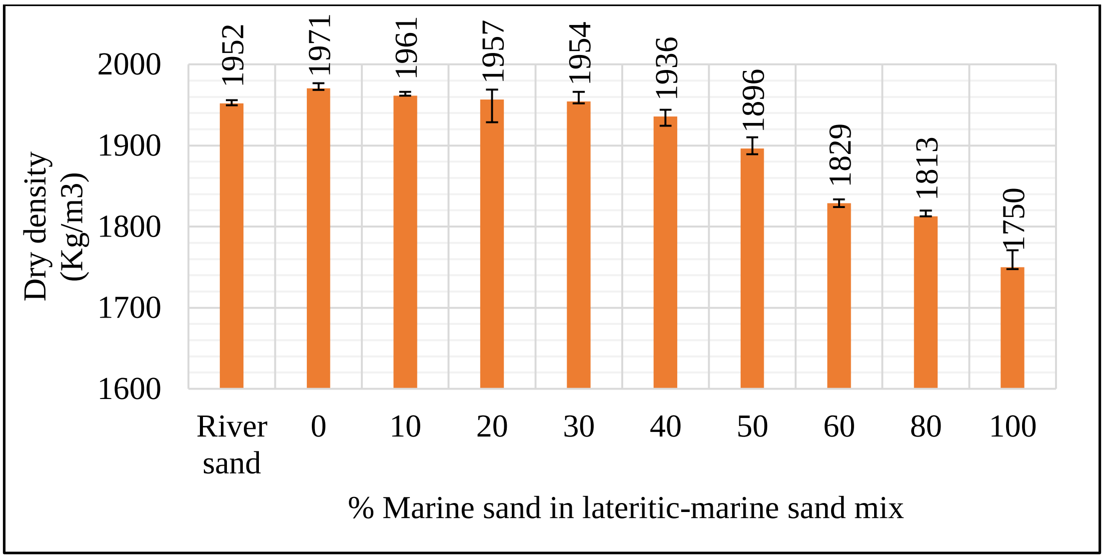



Figure 4.8: 28 days density of blocks made by blending marine and lateritic sand

From results shown in Figure 4.6, 4.7 and 4.8, all the values for density exceed the 1500 kg/m$^3$ BS 2028 recommendation for an average of three (3) blocks and all the blocks had densities more than the minimum of 1600kg/m$^3$ recommended by Duggal (2009) for a masonry units. The values of dry density in this study were lower than those obtained by Raheem et al. (2012) which ranged from 2002.21 kg/m$^3$ to 2203.03 kg/m$^3$. The lower bulk density is attributed to the manual production and compaction as opposed to the use of block molding machine employed by Raheem et al. (2012).

For the 7, 14 and 28 curing days, a general decline of the density as the percentage of the marine sand increases in the lateritic marine mixture is observed. This decline can be attributed to the lower value (2.3) of specific density of marine sand compared to 2.8 of lateritic sand. Subsequently the density of the blocks decrease as the percentage of marine sand in the mix increases. A similar trend was observed by Adebakin et al. (2012) when sawdust (a lighter material) was used to replace sand in hollow sandcrete blocks.

The control block have a slightly lower density than that of 100% lateritic sand. This is because the control block is composed of a finer sand than the lateritic sand and therefore has a high water demand. Sandcrete containing fine sand requires more water for the same consistency, than an equivalent amount of coarse sand. For this reason full compaction is not attained.

**Compressive strength**

The compressive strength results of the sandcrete blocks with different blend of lateritic sand and marine is shown in Table F2 in appendix F. Figure 4.9 shows Compressive strength of sandcrete blocks made by blending marine and lateritic sand for the 7, 14 and 28 curing days.

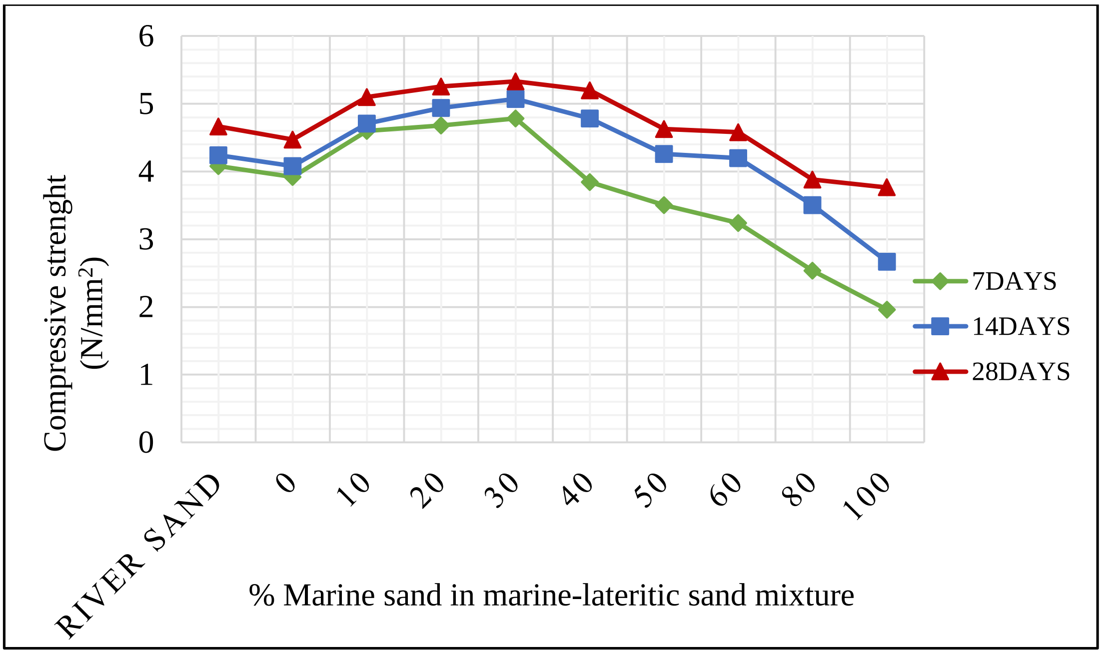



Figure 4.9: Compressive strength of blocks made by marine and lateritic sand blends

The results in Figure 4.9 above, shows that the compressive strength ranges from 1.96 $N/mm^2$ to 4.78 $N/mm^2$, 2.67 $N/mm^2$ to 5.07 $N/mm^2$ and 3.76 $N/mm^2$ to 5.33 $N/mm^2$ at 7, 14 and 28 curing ages respectively. The compressive strength for the control block made from 100% river sand is 4.08 $N/mm^2$, 4.24 $N/mm^2$ and 4.67 $N/mm^2$ for 7, 14 and 28 curing days respectively. The 28 days strength obtained for both the percentages blends of sands exceeds the minimum strength value of 3.45$N/mm^2$ specified by Nigerian Industrial Standard NIS 87 (2000) for load bearing walls. These results obtained in this study are higher than those obtained by Raheem et al. (2012) where the result indicated that the compressive strength of 225mm sandcrete hollow blocks varies from 1.59 $N/mm^2$ at 7 days and 4.25 $N/mm^2$ at 28 days. The higher compressive strength recorded in this study are due to the stronger mix ratio of 1:6 (cement: sand) used.

From Figure 4.9, it is also observed that, as the percentage of marine sand is increased in the marine-lateritic sand blended mix, the compressive strength of sandcrete blocks at 7 days, 14 days and 28 days are increased up to 30% replacement level and then declines. At 40% replacement level, compressive strength is less than the strength at 30% replacement level but become greater than the strength of control sandcrete block. At replacement level greater than 40%, the strength reduces to values less than the control sandcrete block. At replacement levels less than 30%, the smaller sized particles of marine sand fills the spaces between the bigger lateritic ones, this creates a more compact sandcrete block and increases the strength. Beyond 30% marine sand replacement, the strength reduces as finer materials introduced increases the overall surface area of the sandcrete increasing the water demand.

The results conforms to an earlier studies Memon and Channa (2015) conducted on fine sand-local sand blend for masonry concrete unit (MCU) where the strength of the blocks increased up to 40% replacement of fine sand with local sand, and dropped at replacement level above 40%. A similar trend was also obtained by Singh et al. (2015) in which the strength of concrete increased with replacement level of fine aggregate with stone dust up to 60% then dropped.

### 4.2.3 Effect of Sugarcane Bagasse Ash on marine/lateritic hollow sandcrete blocks

**Effect on Density**

The Table G1 in appendix G shows the values of density of sandcrete blocks at various replacement of cement with sugarcane bagasse ash (SBA). The density for the three blocks for each batch at 7, 14 and 28 days is shown in Figure 4.10.

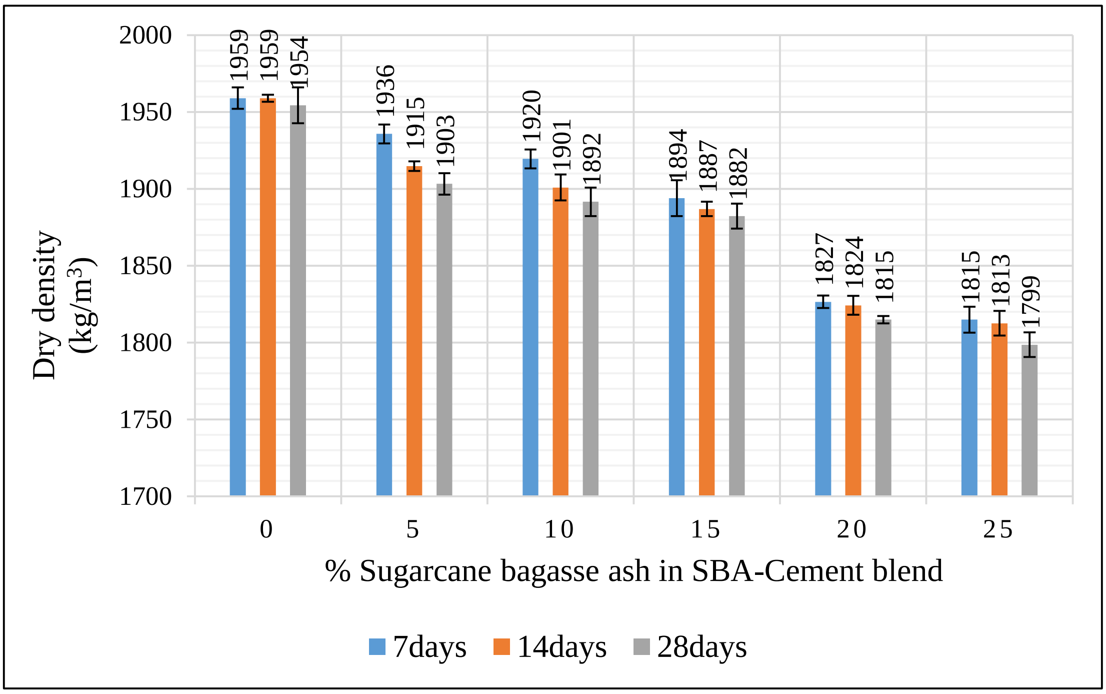



Figure 4.10: Density of sandcrete block made by blending SBA and cement

The result in Figure 4.10 shows the for density varies from 1814.96 Kg/m$^3$ to 1959.39 Kg/m$^3$ at 7 days, 1812.64 Kg/m$^3$ to 1959.04 Kg/m$^3$ at 14 days and 1798.69 to1954.39 Kg/m$^3$ at 28 days tests. Both the lowest and highest values of density are higher than 1500 kg/m$^3$ which are the minimum values of density required for load bearing blocks as recommended in the standards (NIS 87, 2000). A decrease in density with percentage increase in SBA substitution is observed. This was contributed by the lower specific gravity of SBA 1.94 compared to that one of cement 3.11 consequently partially substituting cement with SBA produces lighter sandcrete blocks. Also, as the SBA content increases, cement content reduces leading to a reduction in cement- sand bonding. This leads to a less compact sandcrete blocks. A similar trend was also obtained by Adewuyi et al. (2013) where the density of sandcrete decreased with replacement level of cement with bamboo leaf ash (BLA). The data also indicates a decreases in density with increased curing age, a trend which conforms to Oyekan and Kamiyo (2011).

**Compressive strength**

The compressive strengths of the SBA sandcrete blocks with varying replacement levels are shown in Figure 4.11 below for 7 days, 14 days, and 28 days of curing. The compressive strength were determined as an average of 3 blocks (NIS 87, 2000).

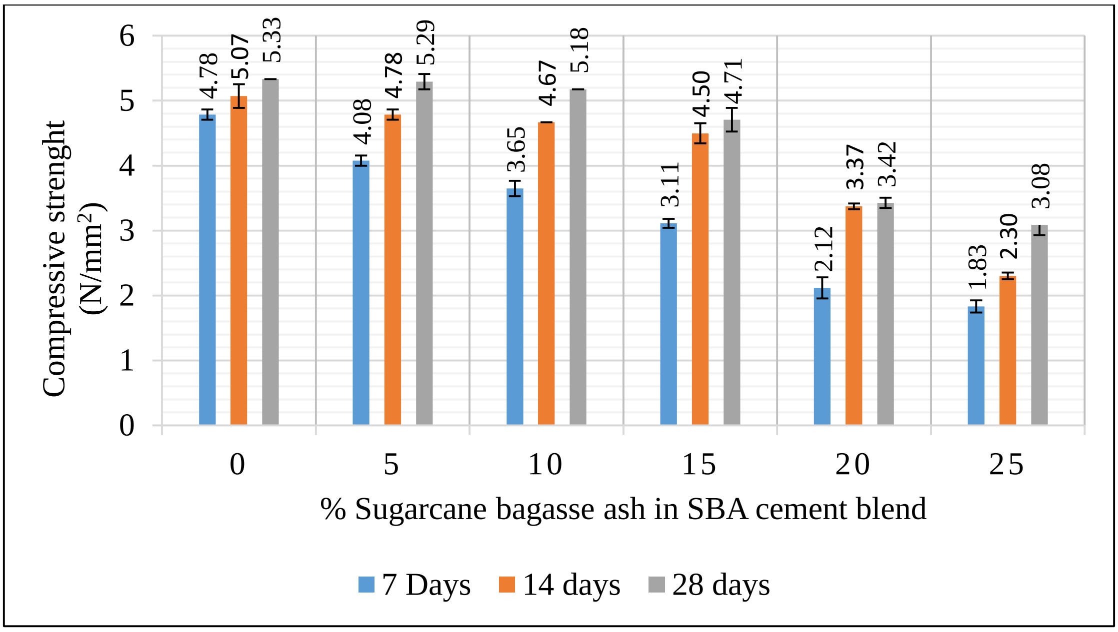



Figure 4.11: Compressive strength of sandcrete blocks made by SBA and cement blend

The compressive strength of sandcrete blocks made with increasing SBA percentages varies from 4.78 N/mm$^2$ to 1.83 N/mm$^2$, 5.07 N/mm$^2$ to 2.30 N/mm$^2$ and 5.33 N/mm$^2$ to 3.08 N/mm$^2$ for 7 days, 14 days and 28 days curing age respectively. The compressive strength obtained at 14 days is higher than those obtained by Raheem (2006) of sandcrete blocks produced with partial replacement of cement with saw dust ash (SDA) which were 2.16 N/mm$^2$, 1.94 N/mm$^2$, 1.64 N/mm$^2$, 1.59 N/mm$^2$, 1.39 N/mm$^2$, and 1.25 N/mm$^2$ for 0%, 5%, 10%, 15%, 20% and 25% SDA contents respectively. At 7 days curing age up to 10% replacement level produces sandcrete blocks meeting the requirement of 3.45 N/mm$^2$ specified by Nigerian Industrial Standard (NIS 87, 2000). At 14 days and 28 days, up to the 15% replacement levels satisfy the recommended standards.

A decrease in compressive strength as the SBA percentage content in the mix increases is noted from Figure 4.11. This can be attributed to the decrease of cement content as the percentage of SBA was increased. The main constituent of SBA is silica ($SiO_2$) while that of cement is calcium (CaO). When cement is replaced by sugarcane bagasse ash, the proportion of cement reduces and subsequently the quantity of cement in the mix available for the hydration process. Also, increase of sugarcane bagasse ash (SBA) increases the quantity of silica, at lower percentage replacement, silica contributes to the pozzolanic reaction. At higher SBA replacement, the excess silica does not contributes significantly to hydration of cement and consequently resulting to reduction in compressive strength (Oyetola & Abdullahi, 2006). A similar pattern was observed an earlier study by Anowal and Afunanya (2017) which showed that compressive strength decreases with increase in millet husk ash (MHA) content for all ages of curing. At 28 days, the compressive strength of mixes with 0, 10, 20, 30 and 40% replacements of cement with MHA were 4.50 $N/mm^2$, 4.00 $N/mm^2$, 3.15 $N/mm^2$, 2.00 $N/mm^2$, and 1.15 $N/mm^2$ respectively. On using coconut husk ash to replace cement, Oyelade (2011) also observed that the compressive strength of the Ordinary Portland Cement -coconut husk ash sandcrete blocks generally decreases as the percentage of coconut husk ash content increases**.**

**Water absorption**

Table G2 in appendix G shows the values obtained for water absorption at 28 days. The water absorption for each batch is summarized in Figure 4.12. The water absorption of the blocks for SBA replacement of 0%, 5%, 10%, 15%, 20% and 25% are 5.01%, 5.39%, 6.02%, 6.52%, 7.01% and 7.23 % respectively. It was observed that the water absorption increases as the percentage replacement of SBA increases with the highest value of absorption of 7.23% recorded at 25% SBA replacement. This may be attributed to increase in pores spaces in the blocks as SBA percentage increases owing to the fact that the cement binder is stickier than SBA. This may have resulted to less compaction. This values are close to those obtained by Anowal and Afunanya (2017) which were 5.25%, 5.00%, 5.85%, 6.75% and 8.25 % for 0%, 10%, 20%, 30% and 40% MHA replacement respectively. Water absorption for all replacement levels does not exceed the maximum allowed water absorption of 12% as specified by BS 5628-1 (2005).

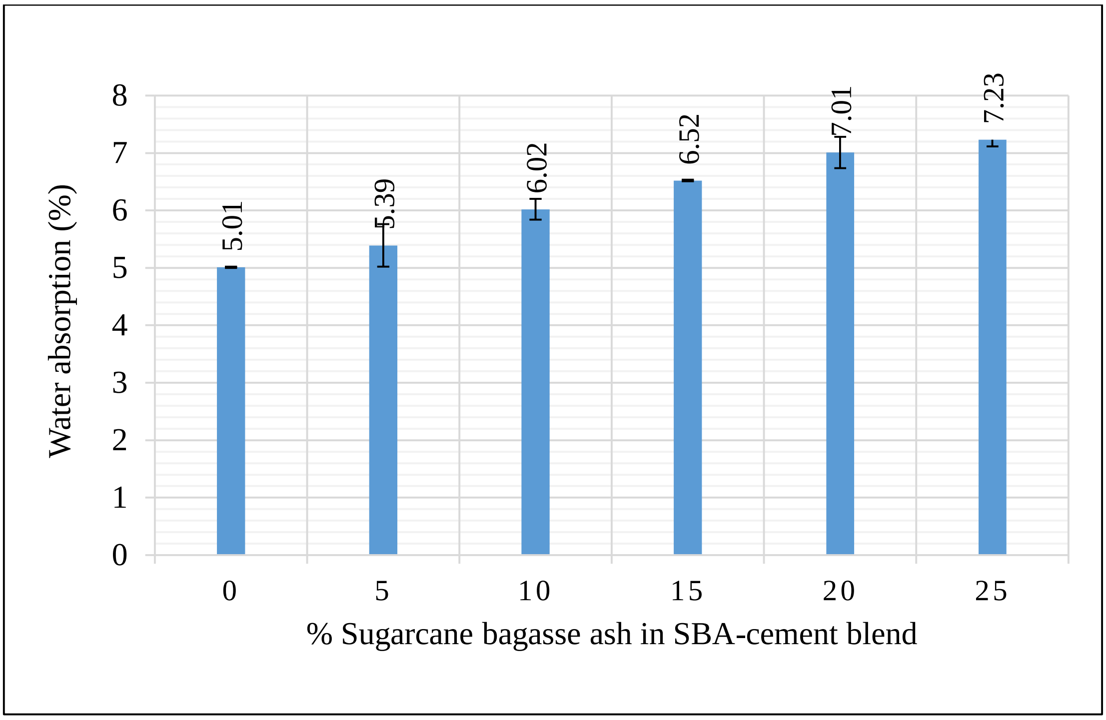



Figure 4.12: Water absorption of sandcrete blocks made by blending SBA and cement.

**Abrasion test:**

Figure 4.13 shows the results of the abrasion tests. The loss of weight due to abrasion for 28 days blocks increases as the percentage of SBA is increased. This implies that the block becomes weaker as the cement content in the mix reduces. The percentage of the materials abraded away from the blocks is 0.004%, 0.010%, 0.018%, 0.036%, 0.056% and 0.066% for 0%, 5%, 10%, 15%, 20% and, 25% SBA replacement . Adewuyi et al. (2013) obtained a similar trend, however, the materials abraded away in there study were slightly higher. The lower values obtained in this study ascertained the suitability of the mix to produce a more durable sandcrete blocks.

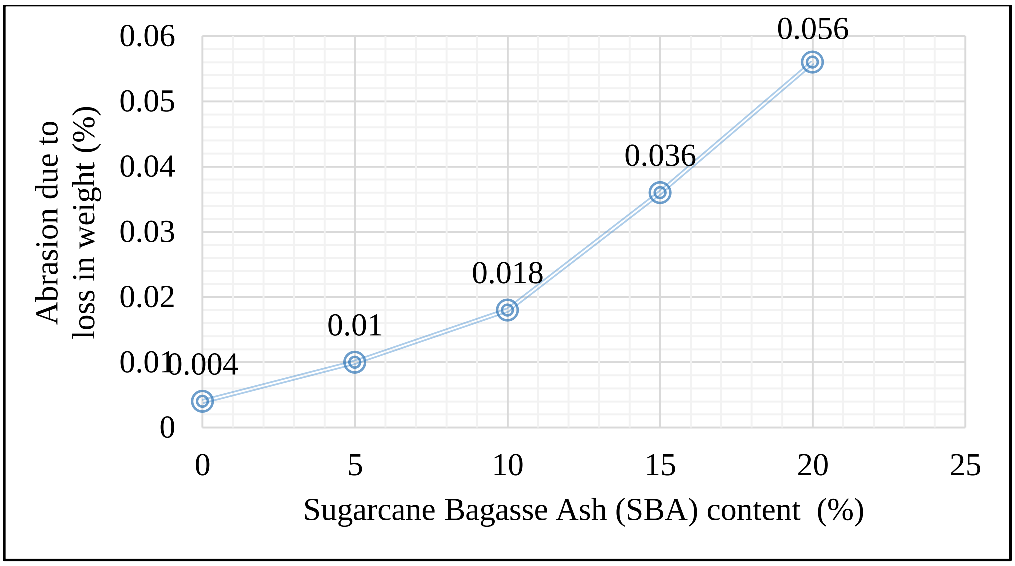



Figure 4.13: Abrasion test results

## 4.3 Performance of dry stack hollow sandcrete blocks

**Dry density**

Table HI in appendix H shows the dry densities of T-DHSBs and R-DHSBS, determined in accordance with BS 2028 (1996).The average dry density for T-DHSB is 1659.26Kg/m$^{3,}$ 1656.94Kg/m$^3$ and 1654.61 Kg/m$^3$ at 7, 14 and 28 days respectively while that of R-DHSB blocks is 1671.90 Kg/m$^{3,}$ 1666.27 Kg/m$^3$ and 1662.51 Kg/m$^3$ at 7, 14 and 28 days curing respectively. These values meets the 1500kg/m$^3$ BS 2028 recommendation for an average of three blocks as well as the minimum density of 1600kg/m$^3$ recommended by Duggal (2009) for load bearing sandcrete blocks. For all the block types the individual blocks dry density values meets the 1500Kg/m$^3$ for individual block for a masonry unit as stated in the BS 2028.The density of dry stack blocks of 230 × 230 ×115 mm size tested by Raheem et al. (2012) had density ranging from 6184.21kg/m$^3$ to 6784.54kg/m$^3$. The values are high due to the fact that the laterite interlocking blocks have high solid blocks.

Figure 4.14 compares the densities of the two types DHSBs produced in this study with non-dry stacked hollow sandcrete block produced in section 4.2. T-DHSBs has a comparatively lower density compared to the R-DHSBs. This difference is due to the different void volumes in the blocks. T-DHSBs have a high void volume compared to R-DHSBs hence less dry density. The design of the molds were done in such a manner as to facilitate the manual production of blocks while at the same time achieve approximately a third void volume.

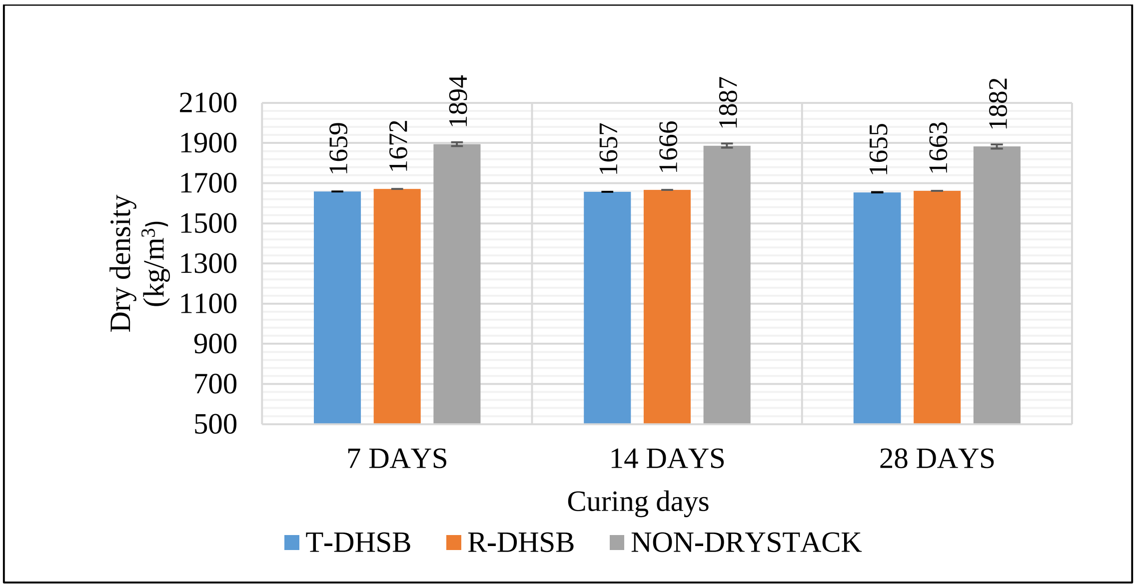



Figure 4.14: Densities of the T-DHSBs and R-DHSBs

**Compressive strength**

The compressive strength characteristics of the R-DHSBs and T-DHSBs are shown own in Table H2 of Appendix H. The average compressive strength for T-DHSBs is 2.17 N/mm$^2$, 2.82 N/mm$^2$ and 3.58 N/mm$^2$ while R-DHSBs is 2.24 N/mm$^2$, 2.92 N/mm$^2$ and 4.04 N/mm$^2$ at 7, 14 and 28 curing age respectively. The 28 days strength obtained for both block types exceeds the minimum strength value of 3.45 N/mm$^2$ specified by Nigerian Industrial Standard NIS 87 (2000) for load bearing walls. Figure 4.15 shows strength development of the two types of blocks in comparison with the non-dry stacked hollow sandcrete block made from the same mix.

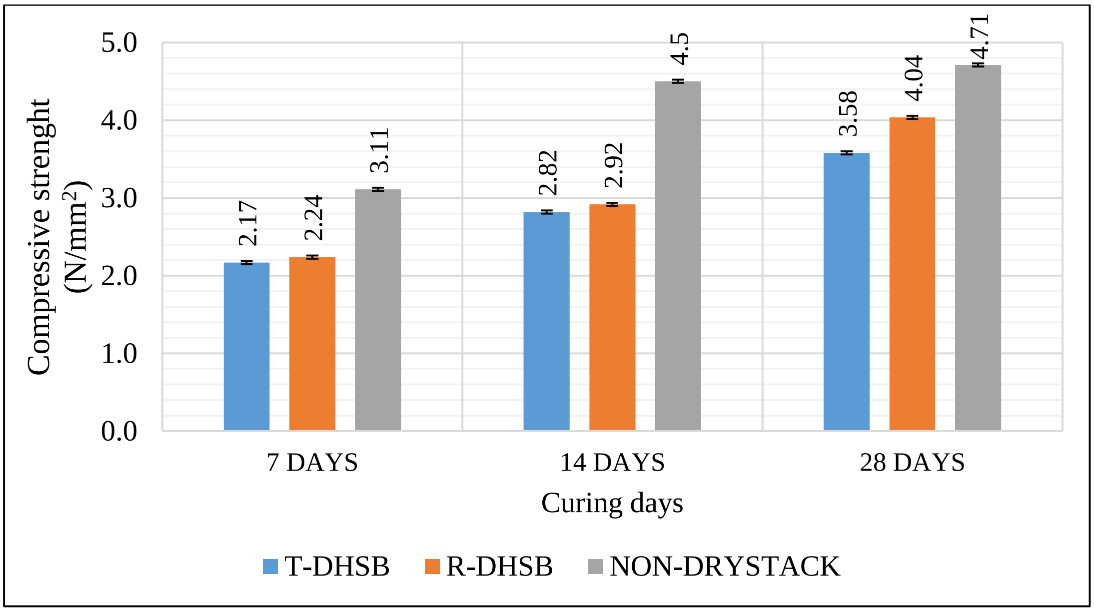



Figure 4.15: Compressive strength for R-DHSBs and R-DHSBs

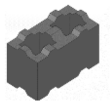
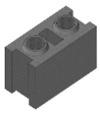
Figure 4.15 reveals that, the non-dry stacked hollow sandcrete blocks made from the same materials show comparative higher compressive strength. These varying compressive strength values indicates that shape of the blocks influences the strength of the blocks. For instance T-DHSBs have less strength than R-DHSBs due to difference in web thickness and cavity size.

Ezeokonkwo (2012) established that the strength of hollow sandcrete blocks decreases as the cavity volume increases. He attributes this to the fact that a greater volume of specimen (solid volume) leads to a more uniform stress distribution and therefore a lesser likelihood of premature failure. The blocks with higher cavity would consequently have comparatively low compressive strength.

**Water absorption**

Table 4.6 presents the results obtained for water absorption at 28 days for the two types of DHSBs.

Table 4.6: Water absorption test result for T-DHSBs and R-DHSBs

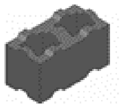
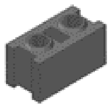
| **Blocks types** | **S.N** | **Weight of oven dried block (Kg)** | **Weight of soaked block (Kg** | **Weight of water absorbed (kg)** | **Water absorption (%)** | **Average water absorption (%)** |
|---|---|---|---|---|---|---|
| T-DHSBs | 1 | 23.80 | 26.00 | 2.20 | 9.24 | |
|  | 2 | 23.80 | 25.90 | 2.10 | 8.82 | |
| | 3 | 23.70 | 25.80 | 2.10 | 8.86 | 8.98 |
| R-DHSBs | 1 | 29.40 | 32.20 | 2.80 | 9.52 | |
|  | 2 | 29.50 | 32.20 | 2.70 | 9.15 | 9.39 |
| | 3 | 29.50 | 32.30 | 2.80 | 9.49 | |

The water absorption of the blocks for T-DHSBs and R-DHSBs are 8.98 and 9.39 % respectively. This values are close to those obtained by Anowal and Afunanya (2017) which recorded the highest water absorption rate as 8.25% for sandcrete blocks contain millet husk ash. There isn't a notable variation in the water absorption values obtained earlier for conventional sandcrete blocks made from the same material. The water absorption for block R-DHSB is higher than that of T-DHSB. This may be attributed to pores spaces in the blocks which are more for blocks with highest volume. Water absorption for both T-DHSBs and R-DHSBs does not exceed the maximum allowed water absorption of 12% as specified by BS 5628-1 (2005). Nwaigwe et al. (2015) explains that poor quality sandcrete block is as result of poor mix ratio, inadequate curing and compaction of the sandcrete blocks. In the event of persistence flooding, a highly porous block could absorb water, consequently become weakened and eventually fail.

**Abrasion test**

Table 4.7 shows the results of the abrasion tests for the DHSBs.

Table 4.7: Abrasion test results for DHSBs

| Blocks Types | Test number | Weight block (Kg) | Weight after abrasion | weight abraded away | Abrasion (%) | Average abrasion (%) |
|---|---|---|---|---|---|---|
| T-DHSBs | 1 | 23.800 | 23.785 | 0.015 | 0.06 | 0.056 |
|  | 2 | 23.700 | 23.690 | 0.010 | 0.04 | |
| | 3 | 23.785 | 23.770 | 0.015 | 0.06 | |
| R-DHSBs | 1 | 29.400 | 29.385 | 0.015 | 0.05 | 0.051 |
|  | 2 | 29.390 | 29.375 | 0.015 | 0.05 | |
| | 3 | 29.395 | 29.380 | 0.015 | 0.05 | |

From the Table 4.7 above, the percentage of the materials abraded away from the blocks is 0.056% and 0.051% for T-DHSBs and R-DHSBs respectively. This is slightly higher than 0.036% obtained for non-dry stack sandcrete block reported in the previous section. This implies that there is no significant variation in the durability of the blocks with varying geometrical orientation. The values obtained in this study compares favorably with those of Raheem et al. (2012) which recorded a high abrasion value of 0.34% for laterite interlocking blocks. The materials abraded away in there study were slightly higher. The lower values obtained in this study ascertained the suitability of the mix to produce a durable dry stack hollow sandcrete block.

## 4.4 Structural behavior and failure mode of DHSBs wall models

### 4.4.1 Performance of DHSBs wall models under axial compression.

**Vertical load versus deflection graphs**

The DHSBs wall models were experimentally tested under axial compression loading. Load versus deflection graphs provide a means of evaluating the performance of the DHSBs wall models .The graphs of load-vertical displacement curves of T-DHSBs and of R-DHSBs wall models are presented in Figure 4.16.

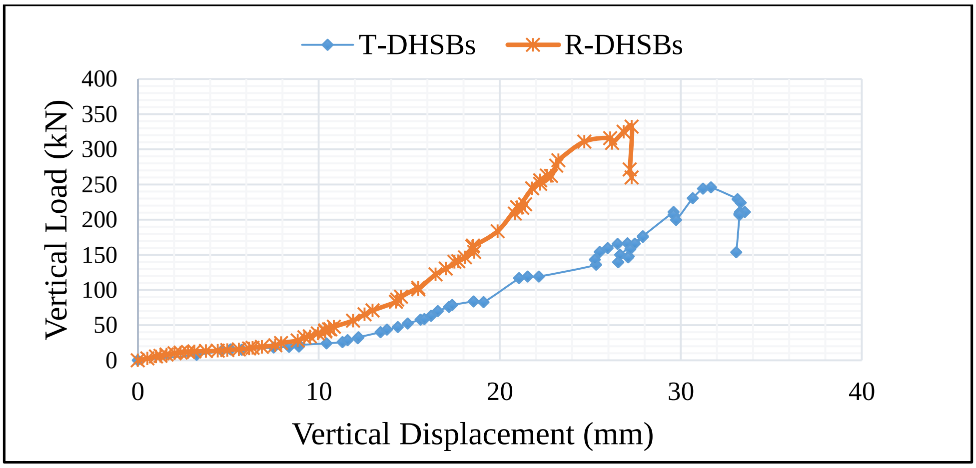



Figure 4.16: Load vs vertical displacement curves of DHSBs wall models

The curves in Figure 4.16 compares the behavior of the wall models during the tests. As the load was gradually applied the corresponding deflection increased. At 166 kN and 316 kN the first crack was observed for T-DHSBs and R-DHSBs wall models respectively. The ultimate failure occurs when the load reaches at 245.8 kN for T-DHSB and 332.5 kN for T-DHSBs wall models. The failure of the wall models was gradual and several micro and macro cracks are formed before the ultimate failure .At ultimate failure, the load is dropped with cracking and spalling of the sandcrete block. A similar trend of the load –displacement curve was also observed by Ahmad et al. (2014) on masonry wall constructed using interlocking soil cement bricks.

**The vertical load versus horizontal deflection curves**

The vertical load horizontal vs. deflection curves for T-DHSBs and R-DHSBs of the walls is presented in Figure 4.17.

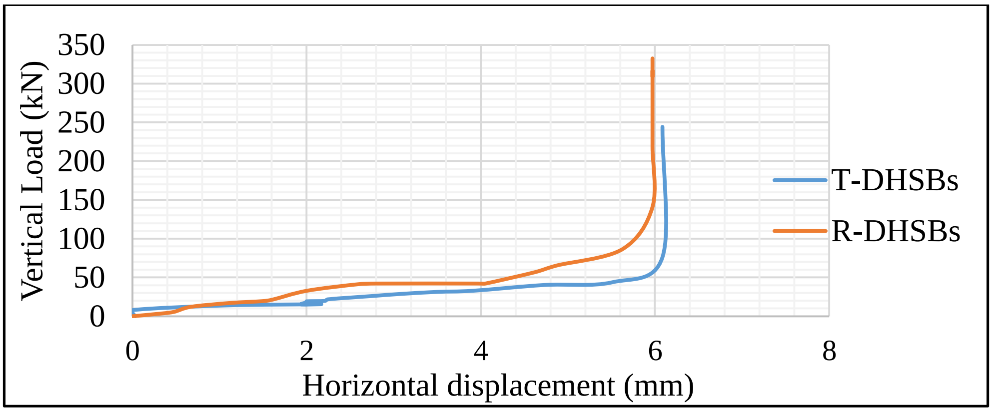



Figure 4.17: Load vs horizontal deflection curves of DHSBs wall models

Figure 4.17 reveals that minimal horizontal deflection were recorded. This is an indication that there was no buckling as the wall is stable due to its low slenderness ratio. At about 50 kN load the maximum horizontal deflection is of 6.1mm and 6.0 mm for T-DHSB and R-DHSBs wall models respectively were achieved. This minimal horizontal displacement is as a result of the effect of poisson's ratio. This trend conforms to Carrasco et al. (2013) results which indicated that horizontal displacement on walls of interlocking bricks made of iron ore by products and cement was practically negligible with approximately 5mm maximum horizontal deflection achieved at about 45 kN load. The research revealed that there was no progressive increase in horizontal displacement as load increased.

**Stress strain relationship**

The Stress and corresponding strain at the different location of wall panel are presented in Figure 4.18 and Figure 4.19.

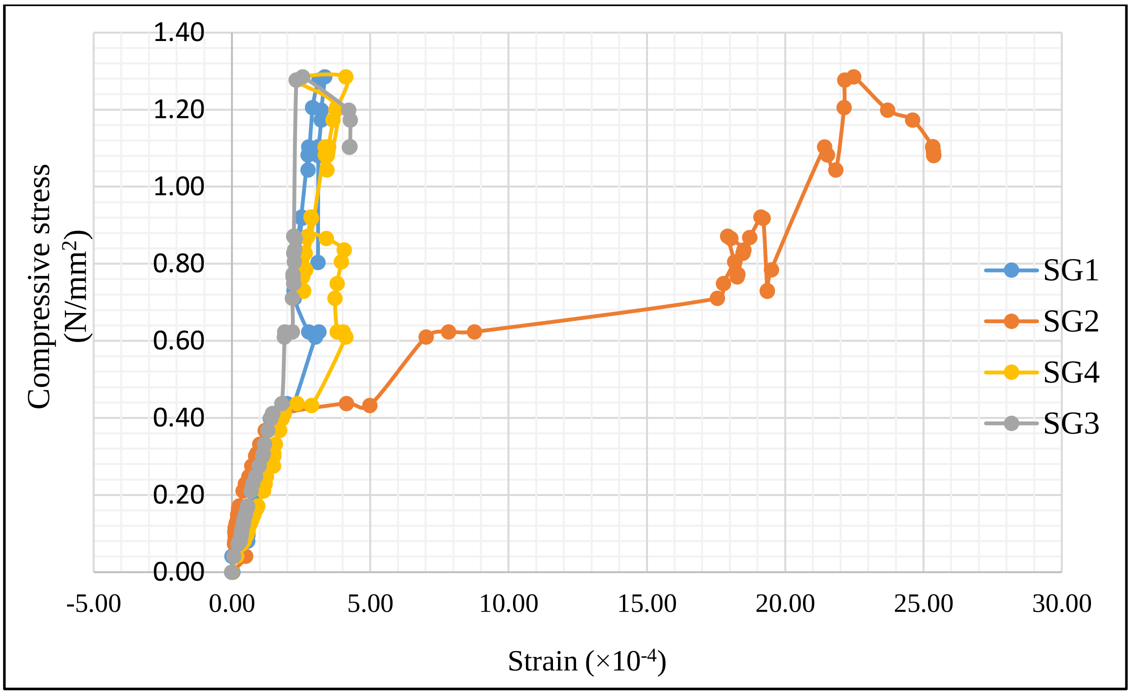



Figure 4.18: Stress versus strain at different location on the wall model of T-DHSBs

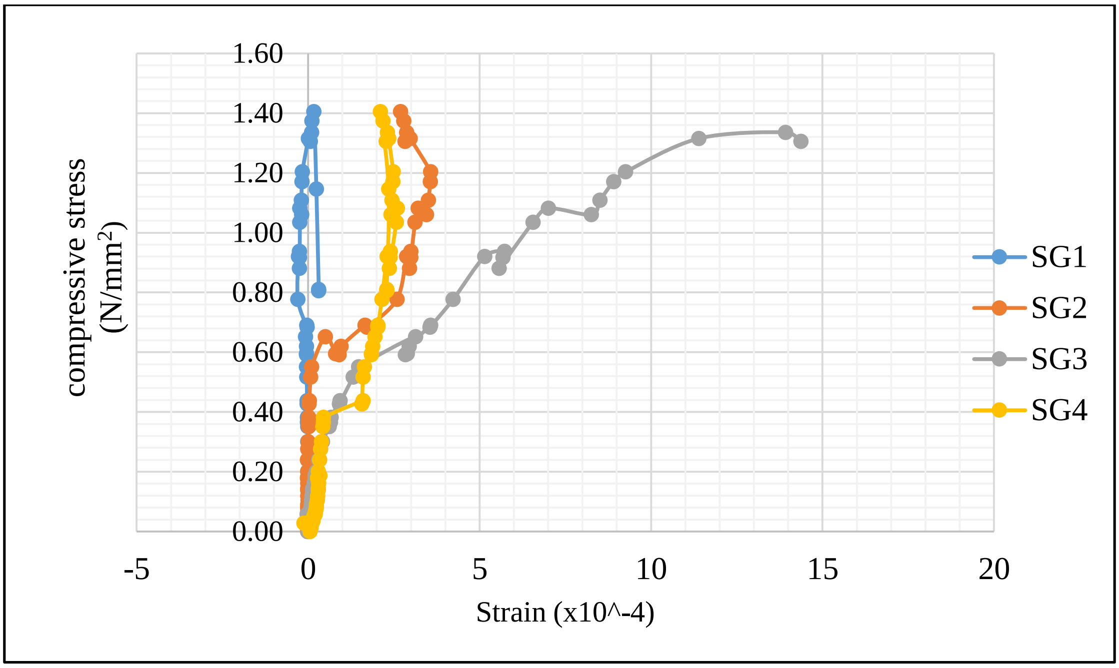



Figure 4.19: Stress versus strain at different location on the wall panel of R-DHSBs

The stress-strain relationships for both blocks tend to be proportionally similar at low stress values, however as more stress is applied to the specimens a varying trend with regard to the position of strain measurement is observed. Extreme strain values were noted on positions SG2 for T-DHSB and SG3 for block R-DHSB. This extreme values may be as a results of early fissures and micro fissures development on the mid layer section of the wall specimens. These may have developed as a results of non-uniform stresses in each masonry course. Dry stacked masonry are known for the gaps forming on the inter-surface. Murray (2007) asserted there is no economical method of producing concrete masonry blocks with little or no variation in height. Dry-stack masonry contractors have come up with several methods of address this issue including using metal shims between blocks, using small amounts of mortar where required, or placing the blocks in a stack bond. He suggest the use of mortar between the courses of blocks so that the gaps created by non-uniform heights blocks are filled.

Where such a fill is not implemented, as is in the case in this study, there would be a possibility of uneven development of micro and macro cracks, this would course some unit blocks to develop cracks earlier than others and subsequently show a varying stress-strain relationship such as those in SG2 for T-DHSBs, and SG2 and SG3 for block R-DHSB. At maximum compression stress the walls fails by development of cracks and spalling of sandcrete face . This courses the stress to drop significantly without a significant changes in strain. This is seen in SG1, SG2 and SG4 for T-DHSBs ,and SG1 in R-DHSBs. SG1 in R-DHSBs recorded less strains values. High values of strains were recorded by SG2 and SG3 in the R-DHSBs wall model. This shows that strain is high at the mid course layers of the wall models. Spalling of the sandcrete face was prominently seen in these two middle course.To prevents the damage of the load cell and LVDT, the experiment was stopped immediately after the wall failed and compression stress had began to drop.

Marzahn (1999) performed short term and long term tests on dry stacked masonry walls built using varying individual block strengths and compared the results with a thin mortar layer. The study revealed that the walls built using mortar tended to have a nearly linear relationship between stress and strain from the beginning of the test up to failure. However, the stress-strain behavior of dry masonry was somewhat bi-linear. The linear curve extending up to approximately one third of the failure load. This resulted was attributed to the initial settlement of uneven surfaces and block irregularities due to difference in block height.

**Compressive strength**

Wall model of R- DHSBs recorded high ultimate compressive strength values than that of T-DHSB models .This may be as a result of high unit strength for R-DHSBs as compared to T- DHSBs. The compressive strength were 1.28 N/mm$^2$ and 1.41 N/mm$^2$ for T-DHSBs and of R-DHSBs respectively as tabulated in Table 4.8.

Test results indicate that the DHSBs wall models have lower compressive strength compared to their corresponding unit blocks. This may be as a result of slenderness effects as well as the irregular interface joints which causes instability. In testing mortared conventional masonry, Vanderwerf (1999) attributed this behavior to the presence of a mortar used to join the block units.

Table 4.8: Compressive strength properties of DHSBs wall model

| Block type | Block unit compressive strength (Mpa) | Ultimate compressive load`(kN) | Bearin-g area ($m^2$) | Masonry compressive strength (MPa) | Masonry/ unit strength ratio | Maximum lateral displacement (mm) |
|---|---|---|---|---|---|---|
| T-DHSBs | 3.58 | 245.76 | 0.19 | 1.28 | 0.36 | 6.0 |
| R-DHSBs | 4.04 | 332.47 | 0.24 | 1.41 | 0.35 | 6.1 |

Characteristic compressive strength of masonry is an important parameter for design of masonry walls. In BS 5628-1 (2005) the characteristic compressive strength of masonry is outline in Table 2, further experimental procedure for determination of characteristic compressive strength of masonry has been outlined. There is however, no laboratory testing method or standard values of characteristic compressive strength for dry stacked masonry. Laboratory tested data dry-stack masonry panel can therefore be used for comparison purposes. For example Pave and Uzoegbo (2007) research on four dry-stack wall panels with block units .The blocks having the mean compressive strengths of 5, 9, 12 and 23 MPa, were established to have had masonry compressive strength of 1.98,2.40,3.13 and 4.53 MPa respectively. This values reveals a similar trend to the results obtained in this research.

### Failure mode under axial loading

The failure of the DHSBs wall models were preceded by formation of several cracks and micro cracks before the wall panels would reach ultimate failure. At initial stages cracks would form at the top course and gradually form to the remaining course. The general failure mode of the DHSBs walls model was by formation of vertical cracks parallel to the axis of loading at approximately center of the block units as illustrated in Plate 4.1 and plate 4.2 .This vertical crack may be attributed to stress concentration within the region.


Plate 4.1: Vertical cracks parallel to the axis of loading for T-DHSBs wall model

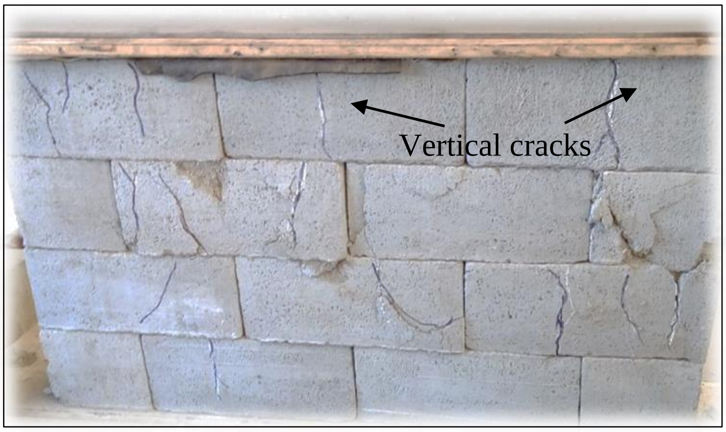



Plate 4.2: Vertical cracks parallel to the axis of loading for R-DHSBs wall model

T-DHSBs wall models experienced more cracks and micro fissures since extra cracks were propagated from the interlocking joints of the blocks as shown in Plate 4.3 Uneven distribution of bed stress due to variability in interlocking surface caused by small difference of the interlocking joints may be the reason behind the formation of the shear cracks. The face shell would disintegrates as the load approaches the ultimate limit. This disintegration is gradual as revealed by the formation of cracks along the web-shell interface from end face (see Plate 4.4). Jonaitis and Zavalis (2013) agrees with analogy. Their research revealed that failure of the hollow block masonry specimens started from the failure of the bed joints. Big transverse block deformations of the wall flat were observed during the test, stumble of the shell was also noticed.

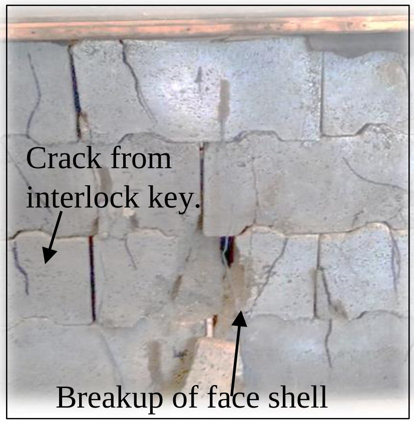



Plate 4.3: Crack propagation and face-shell disintegration of T-DHSBs

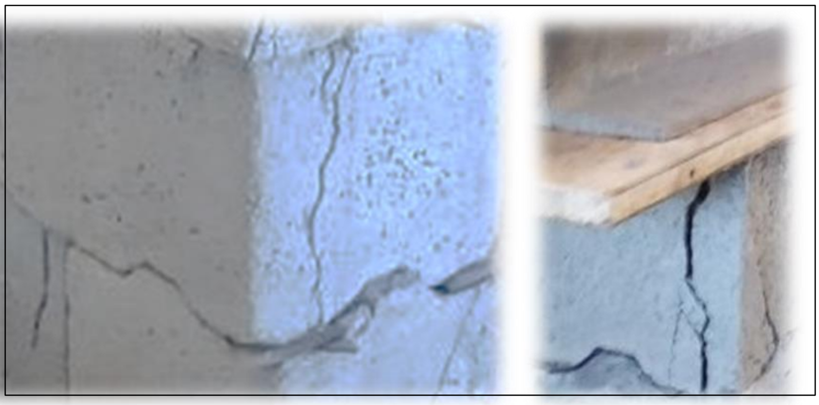


Plate 4.4: Cracks along the face interface from end view of T-DHSBs

The R-DHSB had a better load carrying capacity compared to the T-DHSB. At ultimate load R-DHSBs wall model exhibited spalling of the face shell majorly at the mid-course layers. A loud snap would be heard as the vertical crack formed at the edges of the specimen expands abruptly .Vertical cracking are seen to develop at the end face of the specimen, unlike T-DHSBs specimen this cracks are more prominently and develop at approximately near the mid center of the end view as shown in Plate 4.5. This phenomenon occurs due to effect of load concentration which leads to flexural failure. The cracks are formed from the top block downwards. Pave and Uzoegbo (2007) provided the reason for shear failure mode, they considered the top block loaded at center. When the top block collapses by shear or flexure, it constitutes a center loading to the next block unit which also fails by shear, hence loading the third block at center, and so on.

Plate 4.5: Vertical cracks developed at the end face of the specimen.

### 4.4.2 Shear performance of DHSBs triplet specimen.

**Vertical load vs. displacement curves**

Shear performance of the DHSBs masonry walls were determined by triplet shear test set-up modified to establish shear strength of the interlocking features of the DHSBs masonry. Six masonry specimens were built for each DHSBs type for the triplet tests. The vertical load versus vertical displacement curves for the triplet tests on T-DHSBSs and R-DHSBs masonry wall are shown in Figure 4.20 to Figure 4.27. Figure 4.20 and Figure 4.24 provides a summary of the combined results for T-DHSB and R-DHSB respectively. The average ultimate loads for specimens tested with a pre-compression of 0.2 MPa was 24.8 kN in T-DHSB specimen, and 6.47 kN in R-DHSBs specimen. For a pre-compression of 0.6 MPa, the T-DHSBs specimen had an ultimate load of 27.4 kN and R-DHSB specimen was 7.90kN. For a pre-compression of 1.0 MPa, the ultimate load of 30.1kN and 9.25 kN were obtained for T-DHSBs and R-DHSBs specimen respectively. It was observed that at higher horizontal pre-compression higher shear resistances was produced. T-DHSBs specimen produced higher shear load compared to R-DHSBs specimen. This is attributed to the design of the interlocking blocks which provided the higher resistance. In the manual design and fabrication of the molds for R-DHSBs, it was difficult to produce interlocking grooves that were broader in thickness and at the same time develop easy to use manual mold.

For T-DHSBs, only the interlocks in the direction of the applied vertical load provided the shear resistance.

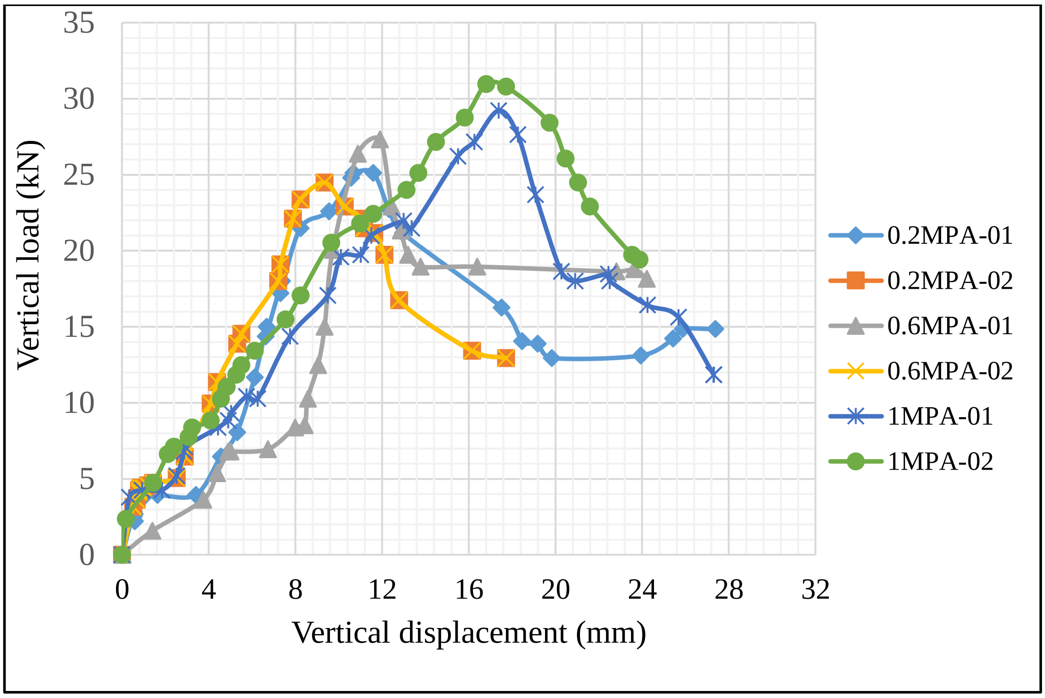



Figure 4.20: Combined vertical load vs displacement curve for T-DHSBs specimen

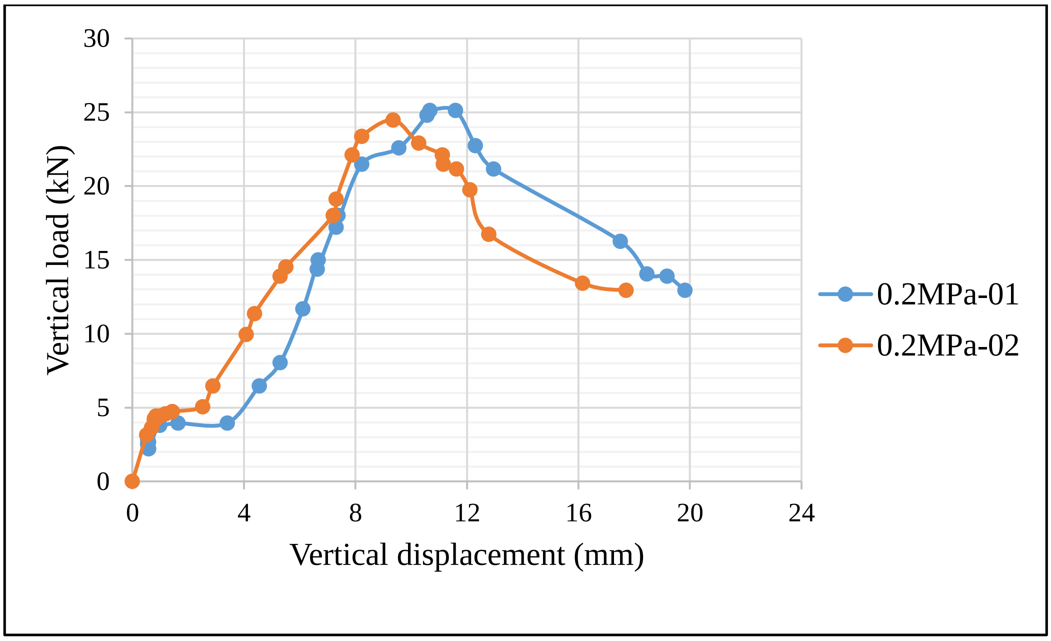



Figure 4.21: Vertical load-displacement curve for T- DHSBs-0.2MPa horizontal stress

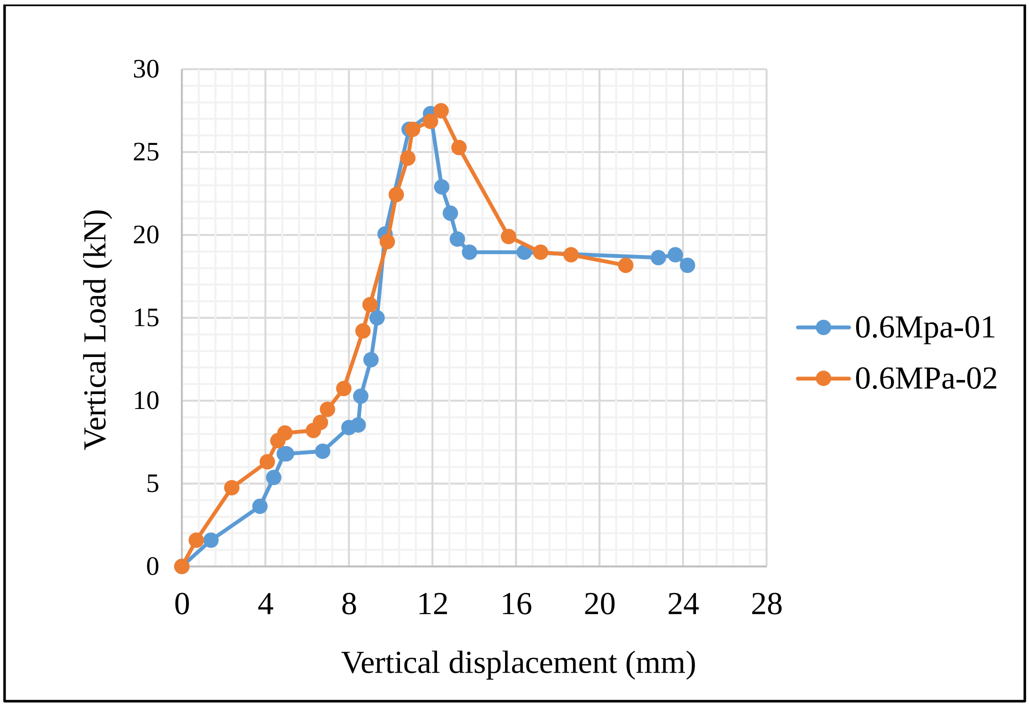



Figure 4.22: Vertical load- displacement curve for T-DHSBs -0.6MPa horizontal stress

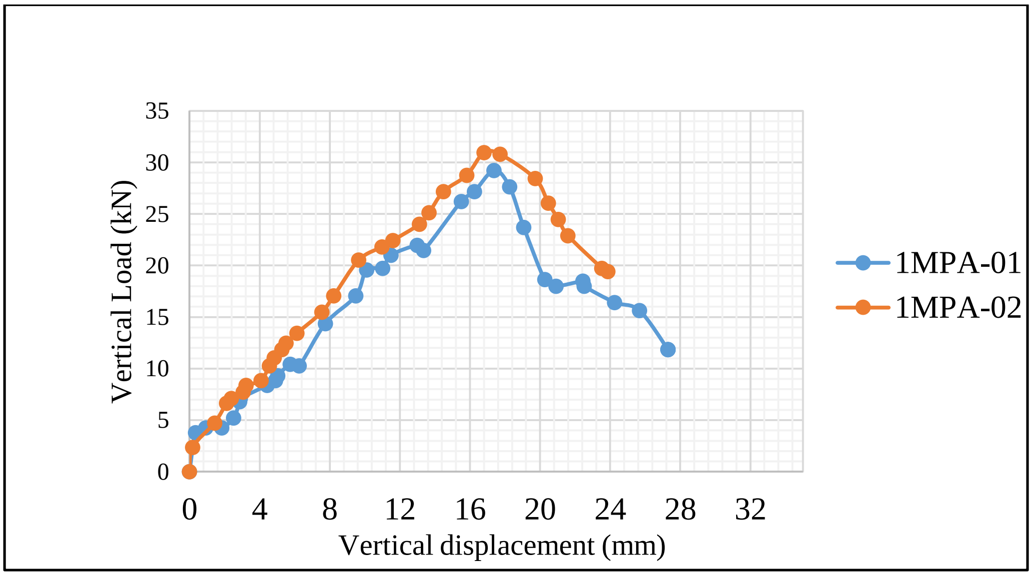



Figure 4.23: Vertical load- displacement curve for T-DHSBs 1MPa horizontal stress.

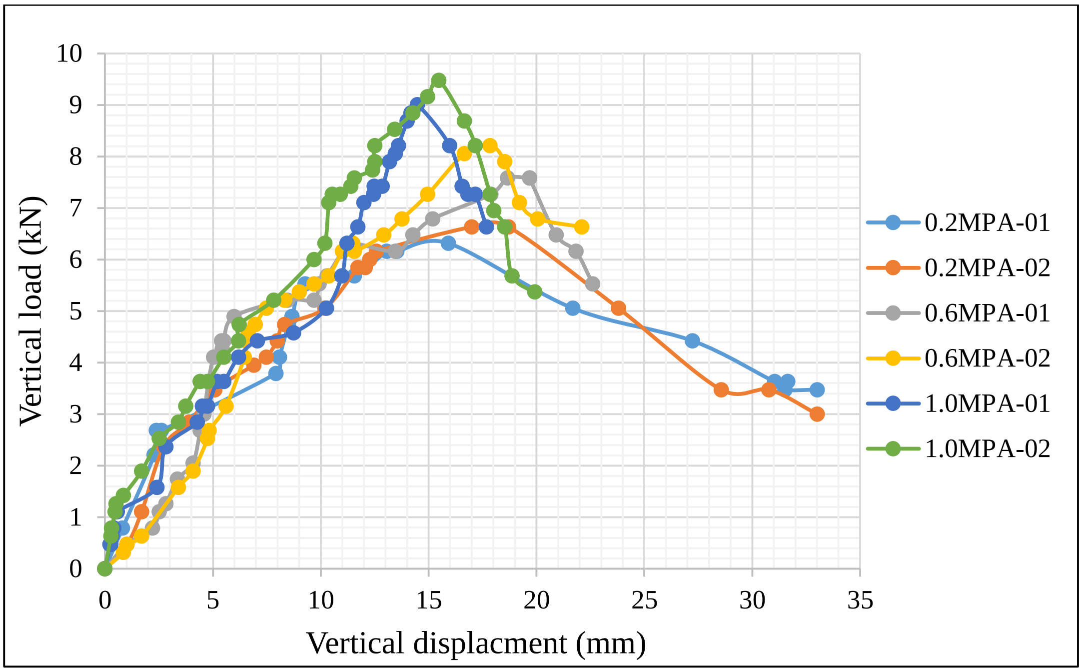



Figure 4.24: Combined vertical load- displacement curve for R-DHSBs specimen

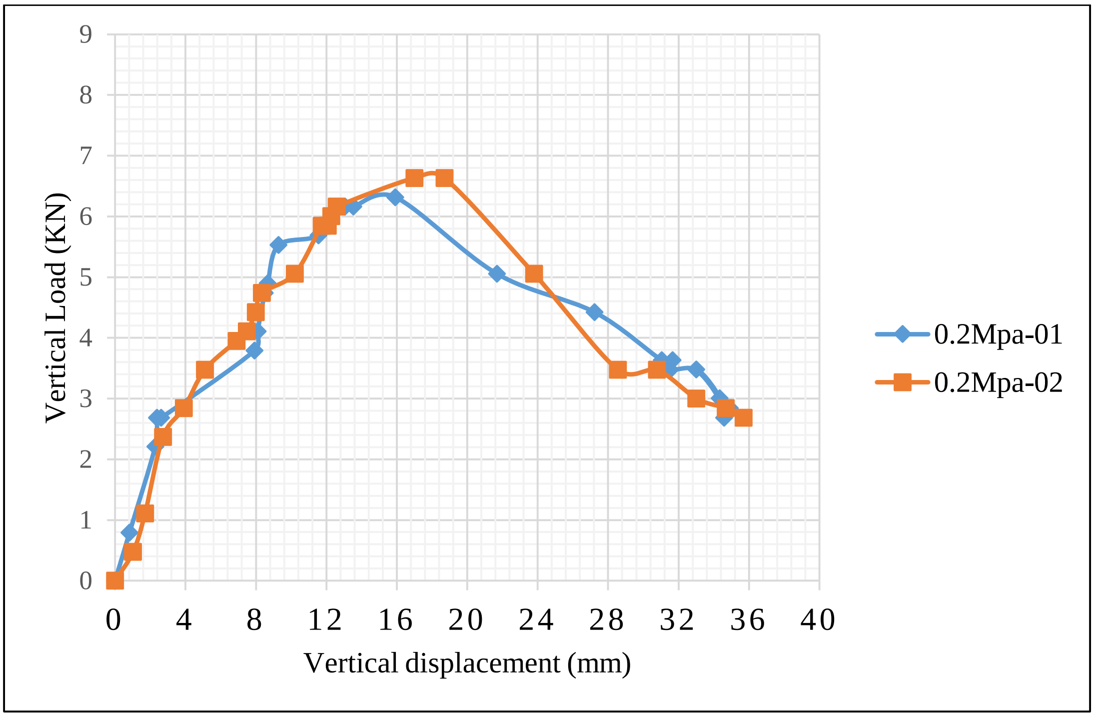



Figure 4.25: Vertical load- displacement curve for R- DHSBs-0.2MPa horizontal stress

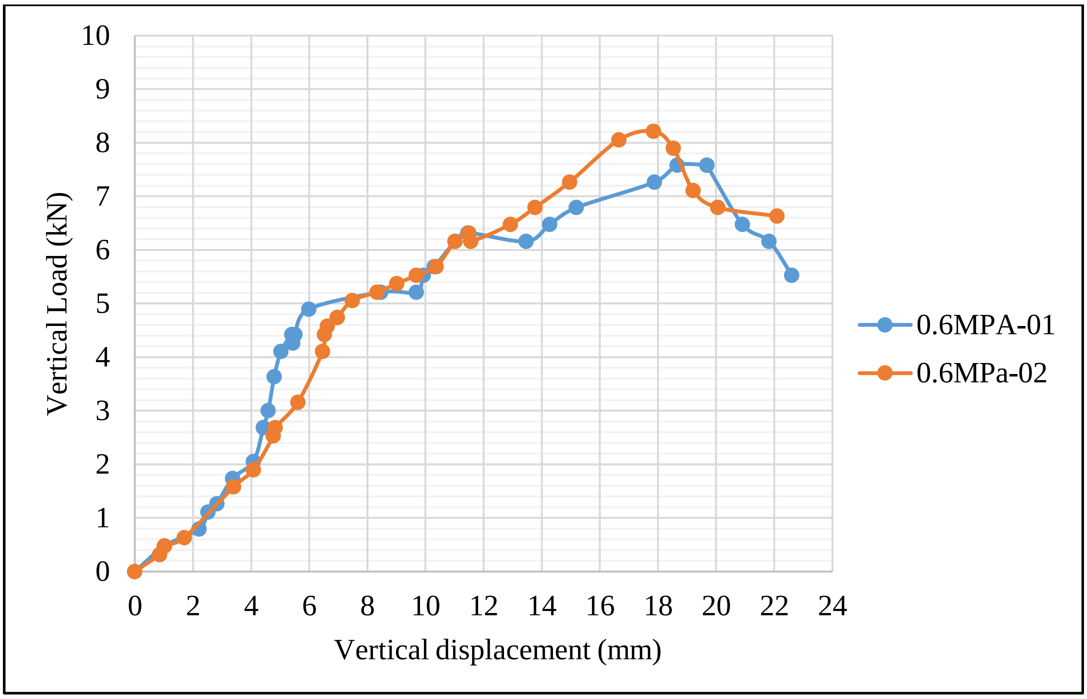



Figure 4.26: Vertical load- displacement curve for R-DHSBs 0.6 MPa horizontal stress

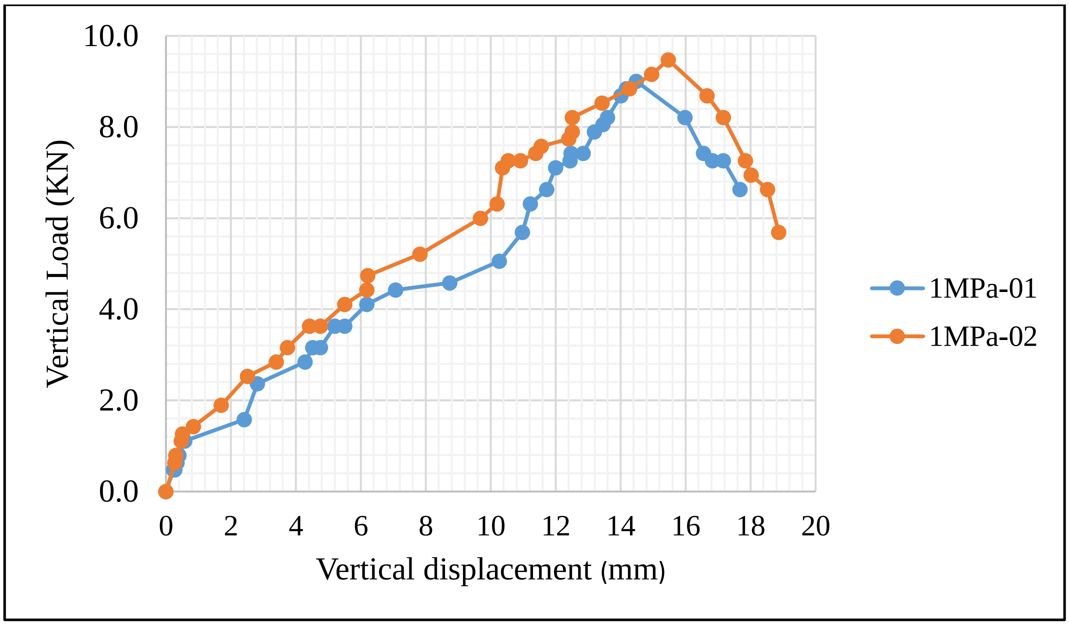



Figure 4.27: Vertical load- displacement curve for R-DHSBs-1 MPa horizontal stress

The curves in Figure 4.20 to Figure 4.27 shows the deformation characteristic of the interlocking grooves. Two different patterns for initial load displacement curve is observed. In the first pattern, slightly high displacement was observed at low applied vertical forces as illustrated for in Figure 4.22 for T-DHSBs and Figure 4.26 for R-

DHSBs. In the second pattern, minimal vertical displacement was observed at the initial stage. This is as illustrated for specimen 1MPa-01 and 1MPa-02 in Figure 4.23. This different patterns are due to the slight variability of the joint surface (up to 2mm) that allows slip of the triplet specimen at the initial stages. Generally, the vertical load increases gradually as displacement recorded by the LVDT increases. An increase in the load courses failure of the interlocking joints at ultimate shear load. Beyond this point the specimen are held together by the pre-compression stress and the bed joint friction force. The shear load drops significantly since the shear joints have failed. This trend was also reported by previous studies (Milosevic et al., 2012; Istegun & Celebi, 2017).

Figure 4.20 and Figure 4.24 show higher values of load were recorded at high pre-compression stress. High values of recompression stress hold the specimen tighter and hence friction provided by the two shearing joints requires more load to overcome.

**Mechanical shear parameters**

Mechanical shear parameters i.e. coefficient of friction (μ) cohesion ($C_O$) were determined by the coulomb criterion. Figure 4.28 shows the relation between the shear strength and normal stress for the T-DHSBs and R-DHSBs triplet specimen.

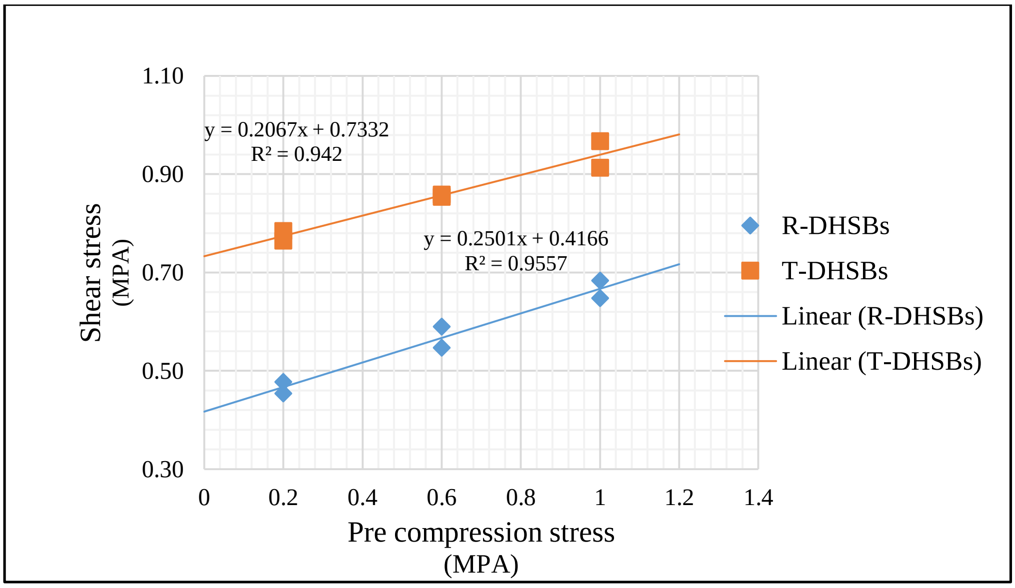
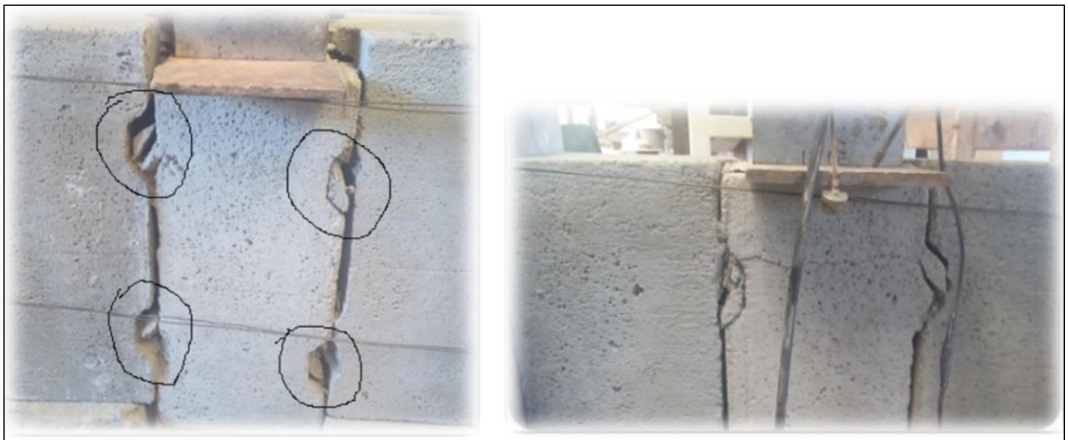



Figure 4.28: Relationship between shear strength and normal stress.

The shear stress varies proportionally to the pre compression normal stress. Coefficient of friction, μ, was established from the slope of the correlation, whereas the extrapolated intercept was the cohesion ($C_O$). The cohesion (Co) represents the initial shear stress when the normal stress is zero. This values are 0.73 and 0.42 for T-DHSB and R-DHSBs respectively. Lin (2015) reported a value of zero for mortar less joint, such a results were possible due to insignificant roughness at the interface. The protrusion on the interface in this study provide significant shear stress at zero pre compression stress since the specimens were well confined and restricted from horizontal movement. The linear regression reveals friction coefficient value equal to 0.21 and 0.25 for T-DHSBs and R-DHSBs specimens respectively. This values characterizes the contact shear surface. There is no code provision available for the shear parameters of mortar less system. For different mortared hollow masonry block, the value of friction coefficient highly varies from 0.21 to 1 (Alwathaf et al., 2005). The characteristic values for cohesion and coefficient of friction can be estimated as (about) 80% of the experimental values (BS EN, 2002). In this study, the characteristic values for cohesion are 0.58 MPa and 0.34 MPa, and coefficient of friction are 0.17 and 0.2 for T-DHSBs and R-DHSBs respectively.

**Failure mode under shear**

For all the specimen, when ultimate shear load was reached, the interlocking keys failed along the shearing plane after a shear slip of about 15mm. Minimal failure of the blocks ware observed for dry stack hollow block specimen R-DHSBs. For T-DHSBs, depending on the interlocking specimen, minimal micro cracks would propagate from the recession part of the interlocking joints (see Plate 4.6 B). Plate 4.6A shows the failed interlocking joints for T-DHSBs and Plate 4.7 shows the shear slip of DHSBs after failure of the interlocking keys.



A B

Plate 4.6: Failure mode for T-DHSBs specimen

Plate 4.7: Failure mode for R-DHSBs specimen

## 4.5 Summary

This study has focused on the performance of sandcrete blocks produced using nonconventional materials mainly; Sugarcane Bagasse Ash (SBA) and optimal amount of lateritic and marine sand .The research was conducted in various stages with one stage leading to another. Firstly, the engineering properties of sandcrete blocks produced with blended lateritic and marine sand were established by laboratory experiments. From the tests it was established that 30% by weight of marine sand would combined with 70% clean lateritic sand to produce sandcrete blocks having the highest and acceptable compressive strength. This ratio was adopted in production of the nonconventional hollow sandcrete blocks containing optimal amount of Sugarcane

Bagasse Ash (SBA). The suitability of these blocks were established experimentally by conducting compressive strength, density, water absorption and abrasion test. Up to 15% replacement of cement with SBA met the minimum compressive strength recommended in standards. The results for water absorption, density and durability of the blocks were also within the acceptable limits. An optimal mixture for production of non-conventional sandcrete block was thus established as 15% SBA replacement of cement by weight in a 30:70 marine: lateritic sand matrix.

The optimal mixture obtained in the previous stage was used in the production of the T-DHSBs and R-DHSBs .These blocks where produced by manually fabricated mold. The general dimensions for load bearing blocks (450 × 225 × 225 mm) was maintained. The two DHSBs had different interlocking features. The performance of the two blocks type were established in view of determining their suitability as load bearing sandcrete blocks. The compressive strength, water absorption, density and durability of the DHSBs units were checked against the standard specification of load bearing sandcrete blocks. This research revealed that both T-DHSBs and R-DHSBs can be used as load bearing sandcrete block. The 28 compressive strength of T-DHSBs and R-DHSBs compressive strength were found to be 3.58 Mpa and 4.04 Mpa respectively. This values were above the minimum recommended values proposed in BS 6073-1 (2008) and NIS 87 (2000). Further, the blocks met the recommended standards with regard to the recommended density (1500 kg/m$^3$) and water absorption (12%). The low values of obtained in the abrasion test ascertained the suitability of the mix to produce durable dry stacked hollow sandcrete blocks (DHSBs).

This study concluded by investigation on the structural performance and failure mode of the masonry panels made from the two types of DHSBs. Each DHSBs masonry panels were evaluated by testing wall models under axial compression. Triplet tests were also conducted to simulate the shear characteristic of the interlocking surfaces. Load-deflection curves were drawn to simulate the deformation characteristic of the wall under axial compression load. Both the wall specimens followed a similar failure trend. The failure of the wall models were gradual and several micro and macro cracks formed before ultimate failure. At ultimate failure, the load dropped with cracking and spalling of the sandcrete block. A similar load –displacement curve was also observed by Ahmed et al. (2011). The first crack load was reported at 166 kN and 316kN for T-DHSBs and of R-DHSBs wall respectively. The ultimate failure occurs when the load reaches at 245.8 KN for T-DHSBs and 332.5 kN for R-DHSBs wall models. The compressive strength for T-DHSBs and of R-DHSBs wall models were established to be 1.28 N/mm$^2$ and 1.41 N/mm$^2$ respectively. However, with no laboratory testing method or standard values of characteristic compressive strength for dry stacked masonry this results were compared with previous researched Pave and Uzoegbo (2007) for dry stacked masonry walls.

The general failure mode of the DHSBs walls model under compression stress was by formation of tensile cracks parallel to the axis of loading at approximately center of the block units. T- DHSBs wall models experienced additional shear cracks propagating from the interlocking joints of the blocks. At ultimate load, R-DHSBs wall models exhibited spalling of the sandcrete majorly at the mid-course layers.

Shear performance of the DHSBs masonry was determined by triplet shear test set-up. The ultimate load of T-DHSBs wall model were 24.8, 27.4 and 30.1Mpa and that of R-DHSBs wall model were 6.47, 7.90 and 9.25Mpa for pre-compression stresses of 0.2, 0.6 and 1.0 Mpa respectively.

Using the Mohr coulomb criteria the mechanical shear parameters were established. The cohesion $\tau_0$ which represents the initial shear stress when the normal stress is zero was 0.73 and 0.42 for T-DHSBs and R-DHSBs respectively whereas friction coefficient value were 0.21 and 0.25 for T-DHSBs and R-DHSBs specimens respectively.

In this research dry stacked sandcrete block made from the predetermined optimal mix produced load bearing blocks that are as good as the conventional sandcrete blocks. The fact that the DHSBs is produced from alternative materials other than the conventional river sand means that the burden of river sand extraction and pollution coursed by cement production is minimized. This study thus provides data to encourage its use.

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

This chapter focusses on the conclusions and the recommendation of the research thesis. For each specific objectives, the conclusions emerging from the research work is succinctly summarized. Recommendations and areas that need further research is highlighted.

## 5.2 Conclusions

### 5.2.1 Performance of sandcrete blocks containing non-conventional materials

i. The highest 28 days strength that meets the strength requirement recommended by NIS 87 (2000) of sandcrete blocks is achieved when 30% of marine sand is blended with 70% of clean lateritic sand. This 28 day strength was 5.33 $N/mm^2$.

ii. Up to 15% SBA replacement of cement levels satisfies the strength requirement of 3.45 $N/mm^2$ recommended standards for load bearing walls provided in NIS 87 (2000).

iii. Water absorption for all SBA % content does not exceed the maximum allowed water absorption of 12% as specified by BS 5628-1 (2005).

iv. The loss of weight due to abrasion for 28 days sandcrete blocks increases as the percentage of the percentage of SBA is increased with a high value of 0.066% recorded at 25% SBA replacement. The low values obtained in this study ascertained the suitability of the mix to produce a more durable sandcrete block.

v. The optimal mixture required in the manufacture of non-conventional hollow sandcrete blocks is 15% SBA replacement of cement by weight in a 30:70 marine: Lateritic sand matrix i.e the optimum Cement/SBA: Marine/lateritic sand: water ratio was 1(0.85/0.15):2(0.30/0.70):0.5. This mix produces load bearing sandcrete blocks having a compressive strength of 4.47 $kN/m^2$ with a water absorption and abrasion values of 6.52% and 0.036% respectively.

### 5.2.2 Performance of dry stack hollow sandcrete blocks made from optimal mix

i. The average 28 day compressive strength for T-DHSBs and R-DHSBs are 3.58 $N/mm^2$ and 4.04 $N/mm^2$ respectively. It can be concluded that the strength of sandcrete block is dependent on the shape of the blocks. Particularly, the volume of cavity have an impact on the performance of the dry stacked hollow sandcrete blocks.
ii. The water absorption of block T-DHSBs and R-DHSBs are 8.98 and 9.39 % respectively. These values do not exceed the maximum allowed water absorption of 12% as specified by BS 5628-1, (2005). The water absorption of the blocks made from the same mix is dependent on the volume. DHSBs having higher volume will have higher water absorption values.
iii. The materials abraded away from the surface of the two blocks were 0.056% and 0.051% for T-DHSBs and R-DHSBs respectively. The minimal percentage is an indication that the blocks are durable under abrasion force.
iv. The optimal mixture of SBA and blended lateritic and marine sand produces dry stacked hollow sandrete blocks that meets the strength and durability requirements for hollow sandcrete block.

### 5.2.3 Structural behavior and failure mode of wall models made from dry stack hollow sandcrete blocks

i. The compressive strength for T-DHSBs and R-DHSBs wall models are 1.28 $N/mm^2$ and 1.41 $N/mm^2$. This values reveals a similar trend to the results obtained in a previous research on dry stacked masonry (Pave & Uzoegbo, 2007).
ii. The general failure mode of the DHSBs walls model under compression load was by formation of tensile cracks running parallel to the axis of loading. Uneven distribution of bed stress due to variability in interlocking surface caused T-DHSBs wall models to experience additional shear crack which propagated from the interlocking joints. DHSBs wall model made from R-DHSBs block units exhibited spalling of the face shell majorly at the mid-course layers.
iii. The ultimate shear load of T-DHSBs wall model and R-DHSBs models were 24.8, 27.4 and 30.1 kN and 6.47, 7.90 and 9.25 kN for pre-compression stresses of 0.2,

0.6 and 1.0 Mpa respectively. Thus, the shear resistance increased with the increase of pre-compression load.

iv. The cohesion $\tau_0$ is 0.73 and 0.42 for T-DHSBs and R-DHSBs respectively whereas friction coefficient value were 0.21 and 0.25 for T-DHSBs and R- DHSBs specimens respectively. The mechanical parameters indicate that T-DHSBs blocks have higher shear characteristics than those of R-DHSBs.

v. The shear failure mode of T-DHSBs and R-DHSBs shear models failed along the shearing plane after a shear travel of about 15mm at ultimate shear load.

## 5.3 Recommendations

### 5.3.1 Recommendations

i. When clean lateritic sand is blended with marine sand, a higher compressive strength than that produced by river sand is achieved. Therefore, in order to enable a higher volume of cement to be replaced by an agro waste pozzolanic material such as SBA, without compromising on the recommended strength of sandcrete blocks, a coarser sand such as lateritic sand should be blended with a finer sand such as marine sand so as to improve their compressive strength.

ii. Owing to its better shear strength (30.1 kN) properties and less volume of materials used in its production than R-DHSBs (9.25 kN), the study recommends T-DHSBs in preference to R-DHSBs for use as an alternative to the existing load bearing hollow sandcrete blocks.

iii. Odeyemi et al. (2015) revealed that the 28 day compressive strength of manually produced and machine compacted blocks were 2.89 $N/m^2$ and 3.03 $N/mm^2$ respectively. In this research, a manual machine was used and the strength of T-DHSBs and R-DHSBs were 3.58 $N/mm^2$ and 4.04 $N/mm^2$ respectively. This study thus recommends for the use of a machine in production of dry stack hollow sandcrete blocks since to enhance its compressive strength.

### 5.3.2 Areas for further studies

i. Research has shown that the compressive strength of sandcrete blocks improves when it is machine produced as opposed to manual production. This research thus recommends for further studies on the structural performance of machine produced

T-DHSBs and R-DHSBs and the results compared with manually produced blocks obtained in this study.

ii. It has been revealed that the compressive strength of mortared walls are higher than the dry stack wall models. Thus, further research needs to be carried out to investigate the methods that can be used to improve the axial compressive strength of dry stacked walling system. Methods to be used in construction, and methods used to reduce the variability in the interlocking blocks are some of the factors that need to be investigated.

iii. The unavailability of worldwide accepted standards for methods and standards for determination of characteristic strength of different types of stacked masonry walls, demands that an extensive research should be carried out in this area.

iv. Research has revealed that the higher content of sodium chloride in marine sand affect durability properties. This research proposes for evaluation of the effect of chlorides and sulfates ions on the durability of DHSBs.

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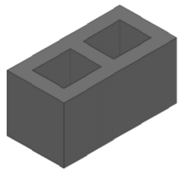
# APPENDICES

## Appendix: A Materials and equipment used

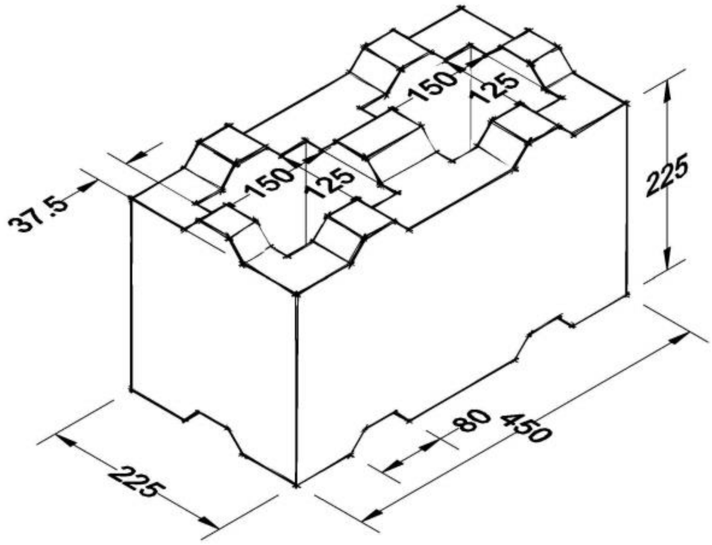
A1: Sugarcane bagasse ash A2: Clean lateritic sand

A3: Marine sand. A4: Compression machine A5: Block making mold

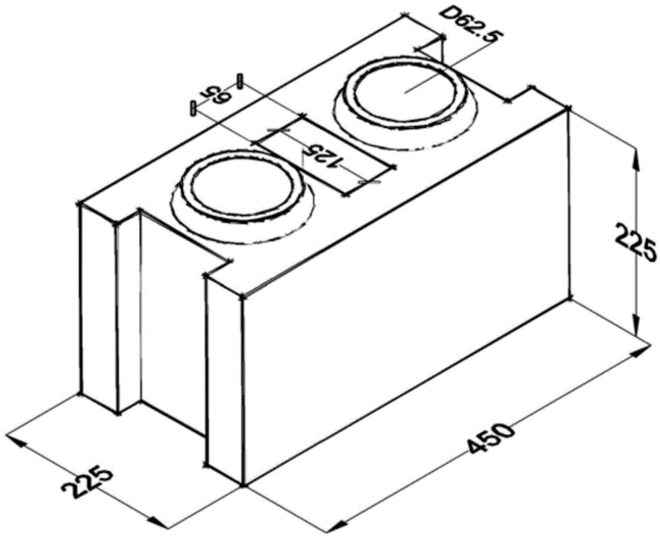
## Appendix: B Mix design for sandcrete block

| **MIX DESIGN FOR SANDCRETE** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Type** | **HOLLOW SANDCRETE BLOCK** | | | | | | |
| **Dimensions** | Length (m) | | 0.45 | |  | | |
| | Width (m) | | 0.225 | | | | |
| | Height (m) | | 0.225 | | | | |
| | Web thickness (m) | | 0.05 | | | | |
| | Net volume $m^3$ | | 0.01434375 | | | | |
| **Materials** | Type of Cement: | | OPC 42.5N | | | | |
| | Type of aggregate: | | Fine aggregate <4.75 | | | | |
| | Cement: Aggregate ratio | | 1:6 | | | | |
| | Water cement ratio | | 0.4,0.5,0.6 | | | | |
| | | | | | | | |
| **% Total sand** | 100 | **SBA** | **Lateritic sand** | **Marine sand** | **W/C Ratio** | | |
| | **Cement** | | | | | | |
| **% of materials** | 100 | 0 | 100 | 0 | **Trail 1** | **Trail 2** | **Trail 3** |
| | 1 | | 5.23 | | | | |
| **Mix ratio by mass** | **1** | **0** | **5.23** | **0** | **0.4** | **0.5** | **0.6** |
| | | | | | | | |
| **Bulk densities** | 1398 | 555 | 1662 | 1746 | 1000 | 1000 | 1000 |
| **Total ratio** | | | | | 6.63 | 6.73 | 6.83 |
| **Expected density** | | | | | 1582.24 | 1573.59 | 1565.19 |
| | | | | | | | |
| | | **Cement** | **SBA** | **lateritic sand** | **marine sand** | **water** | **Density** |
| **Mix proportion at SSD** | Trial mix 1 | 238.65 | 0.00 | 1248.13 | 0.00 | 95.46 | 1582.24 |
| | Trial mix 2 | 233.82 | 0.00 | 1222.86 | 0.00 | 116.91 | 1573.59 |
| | Trial mix 3 | 229.16 | 0.00 | 1198.53 | 0.00 | 137.50 | 1565.19 |
| **Absorption%** | | | | 5.30 | 13.80 | | |
| **Moisture content %** | | | | 2.30 | 3.20 | | |
| **% Adjustments** | | | | 0.03 | 0.11 | | |
| **Adjustments ($Kg/m^3$)** | Trial mix 1 | 0.00 | 0.00 | 36.35 | 0.00 | 36.35 | |
| | Trial mix 2 | 0.00 | 0.00 | 35.62 | 0.00 | 35.62 | |
| | Trial mix 3 | 0.00 | 0.00 | 34.91 | 0.00 | 34.91 | |
| | | | | | | | |
| **Mix proportion ($Kg/m^3$)** | Trial mix 1 | 238.65 | 0.00 | 1211.78 | 0.00 | 131.81 | 1582.24 |
| | Trial mix 2 | 233.82 | 0.00 | 1187.25 | 0.00 | 152.53 | 1573.59 |
| | Trial mix 3 | 229.16 | 0.00 | 1163.62 | 0.00 | 172.41 | 1565.19 |

## Appendix: C Blocks geometry




**C1:** T-DHSB




**C2:** R-DHSB

**Appendix: D Photographs of sandcrete blocks**


**D1**: Sandcrete blocks containing 20:80 Lateritic sand: Marine sand blend.

**D2:** Sandcrete blocks containing Lateritic sand: Marine sand blend stacked for curing

**D3**: Sandcrete blocks containing SBA at varying content.

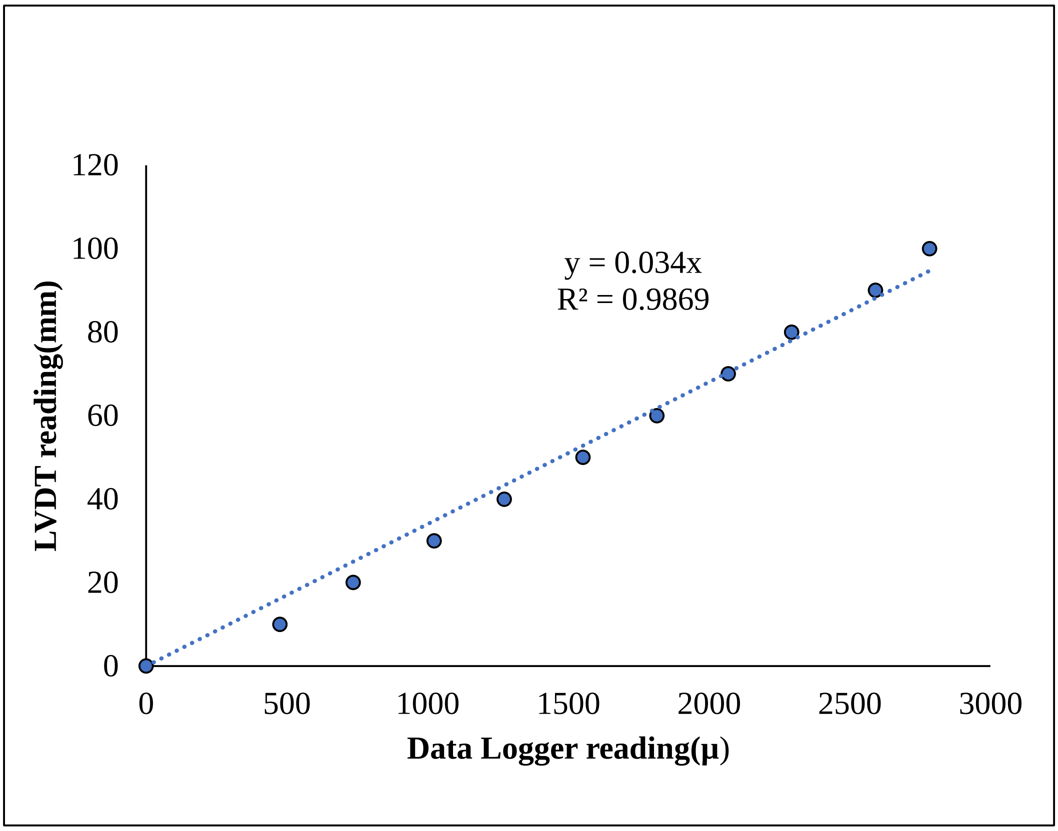
**D4**: Sandcrete blocks immediately after casting

**D5:** Dry stack hollow sandcrete blocks

**D6**: Dry stack hollow sandcrete blocks on curing bay.

**Appendix: E Calibration of the LVDT**

| **LVDT (mm)** | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **μ** | 0 | 476 | 736 | 1023 | 1272 | 1552 | 1815 | 2068 | 2293 | 2592 | 2784 |



**Appendix: F Result for sandcrete blocks containing marine and lateritic sand blends**

**Table F1: Density**

| | | 7 DAYS | | | 14 DAYS | | | 28 DAYS | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Marine Sand % | Sample No | Weight (Kg) | Bulk density (Kg/m$^3$) | Average (Kg/m$^3$) | Weight Kg | Bulk Density (Kg/m$^3$) | Average (Kg/m$^3$) | Weight (Kg) | Bulk Density (Kg/m$^3$) | Average (Kg/m$^3$) |
| 0 | 1 | 28.50 | 1986.93 | 1986.93 | 28.50 | 1986.93 | 1989.25 | 28.40 | 1979.96 | 1970.66 |
| | 2 | 28.50 | 1986.93 | | 28.50 | 1986.93 | | 28.30 | 1972.98 | |
| | 3 | 28.50 | 1986.93 | | 28.60 | 1993.90 | | 28.10 | 1959.04 | |
| 10 | 1 | 28.50 | 1986.93 | 1986.93 | 28.50 | 1986.93 | 1986.93 | 28.00 | 1952.07 | 1961.37 |
| | 2 | 28.30 | 1972.98 | | 28.50 | 1986.93 | | 28.20 | 1966.01 | |
| | 3 | 28.70 | 2000.87 | | 28.50 | 1986.93 | | 28.20 | 1966.01 | |
| 20 | 1 | 28.30 | 1972.98 | 1977.63 | 28.10 | 1959.04 | 1959.04 | 28.40 | 1979.96 | 1956.72 |
| | 2 | 28.50 | 1986.93 | | 28.80 | 2007.84 | | 27.80 | 1938.13 | |
| | 3 | 28.30 | 1972.98 | | 27.40 | 1910.24 | | 28.00 | 1952.07 | |
| 30 | 1 | 28.30 | 1972.98 | 1959.04 | 28.10 | 1959.04 | 1956.72 | 27.70 | 1931.15 | 1954.39 |
| | 2 | 28.00 | 1952.07 | | 28.00 | 1952.07 | | 28.20 | 1966.01 | |
| | 3 | 28.00 | 1952.07 | | 28.10 | 1959.04 | | 28.20 | 1966.01 | |
| 40 | 1 | 28.10 | 1959.04 | 1956.72 | 28.30 | 1972.98 | 1949.75 | 27.60 | 1924.18 | 1935.80 |
| | 2 | 28.00 | 1952.07 | | 27.80 | 1938.13 | | 28.00 | 1952.07 | |
| | 3 | 28.10 | 1959.04 | | 27.80 | 1938.13 | | 27.70 | 1931.15 | |
| 50 | 1 | 27.50 | 1917.21 | 1924.18 | 27.40 | 1910.24 | 1903.27 | 27.60 | 1924.18 | 1896.30 |
| | 2 | 27.80 | 1938.13 | | 27.40 | 1910.24 | | 27.00 | 1882.35 | |
| | 3 | 27.50 | 1917.21 | | 27.10 | 1889.32 | | 27.00 | 1882.35 | |
| 60 | 1 | 27.40 | 1910.24 | 1910.24 | 27.30 | 1903.27 | 1907.92 | 26.30 | 1833.55 | 1828.90 |
| | 2 | 27.40 | 1910.24 | | 27.30 | 1903.27 | | 26.30 | 1833.55 | |
| | 3 | 27.40 | 1910.24 | | 27.50 | 1917.21 | | 26.10 | 1819.61 | |
| 80 | 1 | 27.10 | 1889.32 | 1887.00 | 26.50 | 1847.49 | 1847.49 | 26.10 | 1819.61 | 1812.64 |
| | 2 | 26.70 | 1861.44 | | 26.50 | 1847.49 | | 25.80 | 1798.69 | |
| | 3 | 27.40 | 1910.24 | | 26.50 | 1847.49 | | 26.10 | 1819.61 | |
| 100 | 1 | 26.50 | 1847.49 | 1835.88 | 25.50 | 1777.78 | 1780.10 | 24.80 | 1728.98 | 1749.89 |
| | 2 | 26.50 | 1847.49 | | 25.50 | 1777.78 | | 24.80 | 1728.98 | |
| | 3 | 26.00 | 1812.64 | | 25.60 | 1784.75 | | 25.70 | 1791.72 | |
| 100% River Sand | 1 | 28.10 | 1959.04 | 1961.37 | 28.00 | 1952.07 | 1954.39 | 28.00 | 1952.07 | 1952.07 |
| | 2 | 28.20 | 1966.01 | | 28.00 | 1952.07 | | 27.90 | 1945.10 | |
| | 3 | 28.1 | 1959.04 | | 28.10 | 1959.04 | | 28.10 | 1959.04 | |

## Table F2: Compressive strength

| Batch | | Compressive strength in N/mm$^2$ | | |
|---|---|---|---|---|
| Marine sand % | **Lateritic sand %** | **7 Days** | **14 Days** | **28 Days** |
| 0 | 100 | 3.92 | 4.08 | 4.47 |
| 10 | 90 | 4.60 | 4.71 | 5.10 |
| 20 | 80 | 4.68 | 4.94 | 5.25 |
| 30 | 70 | 4.78 | 5.07 | 5.33 |
| 40 | 60 | 3.84 | 4.78 | 5.20 |
| 50 | 50 | 3.50 | 4.26 | 4.63 |
| 60 | 40 | 3.24 | 4.24 | 4.58 |
| 80 | 20 | 2.54 | 3.50 | 3.88 |
| 100 | 0 | 1.96 | 2.67 | 3.76 |
| 100% River sand | | 4.08 | 4.24 | 4.67 |

## Appendix: G Results on sandcrete blocks made by SBA cement blends

**Table G1:** Density of sandcrete blocks made by SBA cement blends

| | | 7 days | | | 14 days | | | 28 days | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SBA %** | **Batch No** | **Weight Kg** | **Density Kg/m$^3$** | **Average Kg/m$^3$** | **Weight Kg** | **Density Kg/m$^3$** | **Average Kg/m$^3$** | **Weight Kg** | **Density Kg/m$^3$** | **Average Kg/m$^3$** |
| 0 | 1 | 28.30 | 1972.98 | | 28.10 | 1959.04 | | 27.70 | 1931.15 | |
| | 2 | 28.00 | 1952.07 | 1959.04 | 28.00 | 1952.07 | 1959.04 | 28.20 | 1966.01 | 1954.39 |
| | 3 | 28.00 | 1952.07 | | 28.10 | 1959.04 | | 28.20 | 1966.01 | |
| 5 | 1 | 27.90 | 1945.10 | | 27.30 | 1903.27 | | 27.10 | 1889.32 | |
| | 2 | 27.60 | 1924.18 | 1935.80 | 27.60 | 1924.18 | 1914.89 | 27.40 | 1910.24 | 1903.27 |
| | 3 | 27.80 | 1938.13 | | 27.50 | 1917.21 | | 27.40 | 1910.24 | |
| 10 | 1 | 27.70 | 1931.15 | | 27.10 | 1889.32 | | 27.00 | 1882.35 | |
| | 2 | 27.40 | 1910.24 | 1919.54 | 27.50 | 1917.21 | 1900.94 | 27.40 | 1910.24 | 1891.65 |
| | 3 | 27.50 | 1917.21 | | 27.20 | 1896.30 | | 27.00 | 1882.35 | |
| 15 | 1 | 27.00 | 1882.35 | | 27.00 | 1882.35 | | 27.20 | 1896.30 | |
| | 2 | 27.50 | 1917.21 | 1893.97 | 27.00 | 1882.35 | 1887.00 | 26.80 | 1868.41 | 1882.35 |
| | 3 | 27.00 | 1882.35 | | 27.20 | 1896.30 | | 27.00 | 1882.35 | |
| 20 | 1 | 26.10 | 1819.61 | | 26.30 | 1833.55 | | 26.00 | 1812.64 | |
| | 2 | 26.30 | 1833.55 | 1826.58 | 26.20 | 1826.58 | 1824.26 | 26.10 | 1819.61 | 1814.96 |
| | 3 | 26.20 | 1826.58 | | 26.00 | 1812.64 | | 26.00 | 1812.64 | |
| 25 | 1 | 25.80 | 1798.69 | | 25.80 | 1798.69 | | 25.80 | 1798.69 | |
| | 2 | 26.20 | 1826.58 | 1814.96 | 26.20 | 1826.58 | 1812.64 | 25.60 | 1784.75 | 1798.69 |
| | 3 | 26.10 | 1819.61 | | 26.00 | 1812.64 | | 26.00 | 1812.64 | |

**Table G2:** Water absorption

| SBA % | S.N | Weight of oven dried block (Kg) | Weight of soaked block (Kg) | Weight of water absorbed (kg) | Water Absorption (%) | Average water absorption (%) |
|---|---|---|---|---|---|---|
| 0 | 1 | 27.80 | 29.20 | 1.40 | 5.04 | 5.01 |
| | 2 | 28.00 | 29.40 | 1.40 | 5.00 | |
| | 3 | 28.00 | 29.40 | 1.40 | 5.00 | |
| 5 | 1 | 27.90 | 29.40 | 1.50 | 5.38 | 5.39 |
| | 2 | 27.80 | 29.10 | 1.30 | 4.68 | |
| | 3 | 27.80 | 29.50 | 1.70 | 6.12 | |
| 10 | 1 | 27.70 | 29.40 | 1.70 | 6.14 | 6.02 |
| | 2 | 27.70 | 29.20 | 1.50 | 5.42 | |
| | 3 | 27.70 | 29.50 | 1.80 | 6.50 | |
| 15 | 1 | 27.60 | 29.40 | 1.80 | 6.52 | 6.52 |
| | 2 | 27.70 | 29.50 | 1.80 | 6.50 | |
| | 3 | 27.50 | 29.30 | 1.80 | 6.55 | |
| 20 | 1 | 26.30 | 28.00 | 1.70 | 6.46 | 7.01 |
| | 2 | 26.10 | 28.00 | 1.90 | 7.28 | |
| | 3 | 26.10 | 28.00 | 1.90 | 7.28 | |
| 25 | 1 | 25.70 | 27.60 | 1.90 | 7.39 | 7.23 |
| | 2 | 25.70 | 27.50 | 1.80 | 7.00 | |
| | 3 | 26.00 | 27.90 | 1.90 | 7.31 | |

## Appendix: H Results on dry stack hollow sandcrete blocks.

**Table H1**: Dry density of T-DHSBs and R-DHSBs.

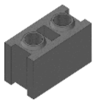
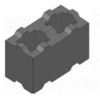
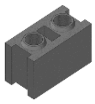
| | | 7 days | | | 14 days | | | 28 days | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Block type** | **Batch No** | **Weight Kg** | **Density $Kg/m^3$** | **Average $Kg/m^3$** | **Weight Kg** | **Density $Kg/m^3$** | **Average $Kg/m^3$** | **Weight Kg** | **Density $Kg/m^3$** | **Average $Kg/m^3$** |
| T-DHSB  | 1 | 23.80 | 1659.26 | 1659.26 | 23.80 | 1659.26 | 1656.94 | 23.80 | 1659.26 | 1654.61 |
| | 2 | 23.80 | 1659.26 | | 23.70 | 1652.29 | | 23.70 | 1652.29 | |
| | 3 | 23.80 | 1659.26 | | 23.80 | 1659.26 | | 23.70 | 1652.29 | |
| R-DHSB  | 1 | 29.60 | 1668.15 | 1671.90 | 29.50 | 1662.51 | 1666.27 | 29.50 | 1662.51 | 1662.51 |
| | 2 | 29.70 | 1673.78 | | 29.60 | 1668.15 | | 29.50 | 1662.51 | |
| | 3 | 29.70 | 1673.78 | | 29.60 | 1668.15 | | 29.50 | 1662.51 | |

**Table H2:** Compressive strength of the DHSBs and R-DHSBs.

| | | 7 days | | | 14 days | | | 28 days | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Block type** | | **Load** | **Strength** | **Average** | **Load** | **Strength** | **Average** | **Load** | **Strength** | **Average** |
| | **No** | **kN** | **$N/mm^2$** | **$N/mm^2$** | **kN** | **$N/mm^2$** | **$N/mm^2$** | **kN** | **$N/mm^2$** | **$N/mm^2$** |
| T-DHSB  | 1 | 140 | 2.20 | 2.17 | 180 | 2.82 | 2.82 | 230 | 3.61 | 3.58 |
| | 2 | 140 | 2.20 | | 180 | 2.82 | | 230 | 3.61 | |
| | 3 | 135 | 2.12 | | 180 | 2.82 | | 225 | 3.53 | |
| R-DHSB  | 1 | 180 | 2.28 | 2.24 | 230 | 2.92 | 2.92 | 315 | 3.99 | 4.04 |
| | 2 | 180 | 2.28 | | 230 | 2.92 | | 320 | 4.06 | |
| | 3 | 170 | 2.16 | | 230 | 2.92 | | 320 | 4.06 | |

## Appendix: I Axial compression test results for T-DHSBs

| TEST NO | VERT. LVDT 1 ( µ) | LOAD CELL ( µ) | SG1 ( µ) | SG2 ( µ) | SG3 ( µ) | SG4 ( µ) | HOR. LVDT 2 ( µ) |
|---|---|---|---|---|---|---|---|
| 70 | 0 | 0 | -3 | -1 | 1 | 0 | 1 |
| 74 | -96 | -50 | 0 | -50 | -7 | -17 | -17 |
| 75 | -137 | -88 | -32 | -9 | -22 | -36 | 31 |
| 76 | -151 | -98 | -57 | -12 | -30 | -45 | 63 |
| 77 | -169 | -97 | -57 | -10 | -27 | -42 | 57 |
| 79 | -221 | -115 | -58 | -11 | -33 | -53 | 59 |
| 80 | -246 | -122 | -58 | -11 | -34 | -55 | 92 |
| 81 | -262 | -125 | -58 | -10 | -35 | -56 | 65 |
| 82 | -262 | -138 | -59 | -12 | -37 | -60 | 66 |
| 83 | -307 | -153 | -62 | -15 | -41 | -67 | 74 |
| 84 | -333 | -165 | -70 | -19 | -43 | -72 | 81 |
| 85 | -341 | -181 | -73 | -21 | -48 | -80 | 90 |
| 86 | -358 | -199 | -76 | -24 | -54 | -89 | 103 |
| 87 | -359 | -208 | -79 | -26 | -57 | -94 | 115 |
| 89 | -395 | -255 | -90 | -40 | -69 | -114 | 139 |
| 90 | -405 | -277 | -96 | -49 | -75 | -120 | 162 |
| 91 | -423 | -300 | -102 | -61 | -85 | -125 | 179 |
| 92 | -439 | -333 | -108 | -72 | -98 | -150 | 204 |
| 93 | -460 | -365 | -113 | -85 | -111 | -151 | 130 |
| 94 | -466 | -373 | -114 | -90 | -113 | -151 | 144 |
| 95 | -477 | -402 | -119 | -100 | -118 | -157 | 162 |
| 96 | -488 | -445 | -129 | -120 | -130 | -172 | 160 |
| 97 | -506 | -482 | -139 | -141 | -141 | -181 | 179 |
| 98 | -511 | -498 | -147 | -169 | -148 | -190 | 189 |
| 100 | -546 | -530 | -199 | -414 | -180 | -236 | 102 |
| 102 | -562 | -524 | -221 | -498 | -352 | -288 | 84 |
| 108 | -620 | -739 | -302 | -702 | -752 | -412 | 40 |
| 109 | -634 | -755 | -314 | -783 | -798 | -402 | 22 |
| 110 | -652 | -755 | -278 | -877 | -901 | -381 | 26 |
| 121 | -745 | -860 | -225 | -1755 | -1144 | -372 | 428 |
| 123 | -743 | -907 | -228 | -1777 | -1152 | -380 | 429 |
| 124 | -751 | -975 | -231 | -1818 | -1169 | -396 | 402 |
| 125 | -764 | -1012 | -230 | -1851 | -1187 | -406 | 420 |
| 126 | -780 | -1048 | -230 | -1803 | -1037 | -341 | 468 |
| 127 | -796 | -1055 | -224 | -1792 | -861 | -274 | 513 |
| 128 | -798 | -936 | -230 | -1829 | -758 | -257 | 506 |
| 129 | -797 | -928 | -230 | -1827 | -755 | -256 | 507 |
| 130 | -801 | -1002 | -234 | -1847 | -768 | -265 | 507 |
| 131 | -808 | -1051 | -237 | -1872 | -776 | -272 | 507 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 133 | -821 | -1116 | -252 | -1912 | -772 | -286 | 557 |
| 134 | -821 | -1112 | -253 | -1921 | -771 | -288 | 537 |
| 160 | -781 | -885 | -224 | -1935 | -718 | -259 | 567 |
| 161 | -781 | -883 | -225 | -1935 | -718 | -259 | 568 |
| 167 | -784 | -950 | -231 | -1950 | -728 | -267 | 568 |
| 171 | -871 | -1336 | -277 | -2142 | -450 | -337 | 613 |
| 172 | -871 | -1311 | -275 | -2153 | -396 | -338 | 623 |
| 173 | -875 | -1264 | -275 | -2183 | -301 | -343 | 605 |
| 175 | -902 | -1460 | -292 | -2213 | -189 | -378 | 563 |
| 176 | -919 | -1546 | -315 | -2216 | -233 | -233 | 176 |
| 177 | -932 | -1556 | -335 | -2248 | -256 | -412 | 591 |
| 181 | -975 | -1452 | -323 | -2371 | -422 | -376 | 686 |
| 182 | -980 | -1420 | -323 | -2461 | -428 | -366 | 677 |
| 186 | -979 | -1337 | -313 | -2534 | -427 | -349 | 690 |
| 187 | 987 | -1335 | -313 | -2534 | -425 | -349 | 690 |
| 188 | -978 | -1322 | -313 | -2536 | -424 | -347 | 692 |
| 192 | -978 | -1311 | -312 | -2537 | -423 | -345 | 693 |
| 193 | -978 | -1309 | -312 | -2537 | -423 | -345 | 693 |

## Appendix: J Axial compression test results for R-DHSBs

| TEST NO | VERT. LVDT 1 ( µ) | LOAD CELL ( µ) | SG1 ( µ) | SG2 ( µ) | SG3 ( µ) | SG4 ( µ) | HOR. LVDT 2 ( µ) |
|---|---|---|---|---|---|---|---|
| 22 | 0 | 0 | 1 | 1 | 0 | -5 | -1 |
| 23 | -16 | -18 | 1 | 0 | 0 | -8 | -2 |
| 24 | -30 | -35 | 1 | 1 | 0 | -10 | -3 |
| 25 | -37 | -42 | 1 | 1 | 0 | 12 | 1 |
| 26 | -47 | -52 | 0 | 1 | 0 | -14 | 10 |
| 28 | -70 | -71 | 0 | 0 | -2 | -16 | 39 |
| 30 | -92 | -80 | 0 | 0 | -3 | -18 | 60 |
| 31 | -111 | -84 | 1 | 0 | -4 | -19 | 79 |
| 32 | -130 | -86 | 0 | 0 | 3 | -20 | 91 |
| 34 | -146 | -94 | 1 | 1 | -6 | -21 | 106 |
| 35 | 0 | -100 | 0 | 0 | -6 | -21 | 113 |
| 37 | -187 | -114 | 0 | 1 | -8 | -23 | 125 |
| 38 | -202 | -123 | 0 | 1 | -8 | -24 | 128 |
| 41 | -224 | -136 | 0 | 1 | -9 | -24 | 130 |
| 42 | -233 | -157 | 0 | 0 | -10 | -27 | 131 |
| 44 | -260 | -178 | 0 | 1 | -11 | -28 | 130 |
| 47 | -271 | -208 | 1 | 1 | -13 | -30 | 90 |
| 49 | -280 | -217 | 0 | 1 | -14 | -30 | 96 |
| 53 | -293 | -242 | -1 | 1 | -18 | -31 | 94 |
| 56 | -311 | -280 | 0 | 0 | -21 | -33 | 88 |
| 57 | -313 | -280 | 0 | 0 | -20 | -34 | 58 |
| 65 | -305 | -267 | 1 | 1 | -21 | -28 | 58 |
| 66 | -305 | -267 | 1 | 1 | -20 | -28 | 58 |
| 67 | -305 | -267 | 0 | 2 | -20 | -28 | 58 |
| 68 | -319 | -302 | 1 | 1 | -24 | -30 | 58 |
| 69 | -350 | -359 | 0 | 2 | -31 | -33 | 57 |
| 70 | 369 | -414 | 0 | 1 | -36 | -36 | 52 |
| 71 | -382 | -450 | 1 | 0 | -42 | -39 | 51 |
| 77 | -420 | -526 | 1 | -2 | -61 | -43 | 61 |
| 78 | -422 | -548 | 2 | -1 | -65 | -45 | 60 |
| 79 | -428 | -573 | 2 | -2 | -67 | -45 | 59 |
| 84 | -456 | -655 | 3 | -4 | -93 | -160 | 28 |
| 87 | -456 | -640 | 3 | -3 | -91 | -157 | 28 |
| 91 | -484 | -774 | 4 | -7 | -131 | -160 | 22 |
| 92 | -501 | -826 | 5 | -10 | -147 | -164 | 21 |
| 94 | -547 | -977 | 8 | -50 | -313 | -195 | -22 |
| 98 | -521 | -892 | 5 | -80 | -289 | -185 | -36 |
| 99 | -515 | -886 | 5 | -90 | -284 | -185 | -44 |
| 100 | -532 | -928 | 5 | -96 | -295 | -188 | -51 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| `103 | -545 | -1034 | 4 | -166 | -357 | -203 | -83 |
| 104 | -544 | -1024 | 3 | -172 | -355 | -203 | -87 |
| 113 | -585 | -1164 | 30 | -259 | -423 | -215 | -118 |
| 125 | -617 | -1379 | 28 | -287 | -515 | -230 | -124 |
| 128 | -630 | -1404 | 25 | -299 | -573 | -240 | -130 |
| 131 | -625 | -1373 | 25 | -299 | -568 | -239 | -130 |
| 135 | -613 | -1320 | 25 | -296 | -557 | -237 | -130 |
| 137 | -641 | -1550 | 24 | -312 | -656 | -257 | -131 |
| 138 | -654 | -1620 | 24 | -321 | -701 | -260 | -136 |
| 141 | -654 | -1588 | 19 | -345 | -826 | -242 | -127 |
| 142 | -672 | -1660 | 20 | -351 | -851 | -244 | -130 |
| 143 | -680 | -1754 | 18 | -356 | -891 | -247 | -135 |
| 144 | -684 | -1803 | 17 | -357 | -926 | -248 | -142 |
| 146 | -726 | -1970 | -1 | -298 | -1139 | -235 | -156 |
| 148 | -768 | -2001 | -10 | -287 | -1392 | -231 | -164 |
| 149 | -771 | -1956 | -6 | -283 | -1437 | -228 | -157 |
| 150 | -790 | -2059 | -11 | -279 | -1517 | -218 | -165 |
| 151 | -803 | -2105 | -17 | -270 | -1567 | -211 | -186 |
| 153 | -785 | -1717 | -24 | -81 | -1412 | -235 | -178 |
| 154 | -687 | -1214 | -31 | -77 | -1347 | -229 | -1015 |

## Appendix: K Triplet test results for T-DHSBs

| T-DHSB wall 0.2 Mpa-01 | | | | | T-DHSB wall 0.2Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (µ)** | **Load cell (µ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (µ)** | **Load cell (µ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 129 | 0 | 0 | 0 | 0 | 11 | 0.0 | 0 | 0.0 | 0.00 |
| 130 | 16 | 18 | 0.5 | 2.84 | 12 | 15 | 10 | 0.5 | 1.58 |
| 131 | 17 | 17 | 0.6 | 2.68 | 13 | 20 | 15 | 0.7 | 2.37 |
| 133 | 16 | 16 | 0.5 | 2.53 | 15 | 23 | 26 | 0.8 | 4.11 |
| 135 | 17 | 14 | 0.6 | 2.21 | 16 | 23 | 27 | 0.8 | 4.26 |
| 136 | 17 | 14 | 0.6 | 2.21 | 17 | 25 | 28 | 0.9 | 4.42 |
| 137 | 28 | 25 | 1.0 | 3.95 | 18 | 29 | 28 | 1.0 | 4.42 |
| 138 | 29 | 24 | 1.0 | 3.79 | 19 | 35 | 29 | 1.2 | 4.58 |
| 139 | 48 | 25 | 1.6 | 3.95 | 20 | 42 | 30 | 1.4 | 4.74 |
| 140 | 100 | 25 | 3.4 | 3.95 | 22 | 74 | 32 | 2.5 | 5.05 |
| 141 | 134 | 41 | 4.6 | 6.48 | 24 | 85 | 41 | 2.9 | 6.48 |
| 142 | 156 | 51 | 5.3 | 8.05 | 26 | 120 | 63 | 4.1 | 9.95 |
| 145 | 180 | 74 | 6.1 | 11.69 | 27 | 129 | 72 | 4.4 | 11.37 |
| 146 | 196 | 95 | 6.7 | 15.00 | 30 | 156 | 88 | 5.3 | 13.90 |
| 147 | 195 | 91 | 6.6 | 14.37 | 32 | 162 | 92 | 5.5 | 14.53 |
| 148 | 217 | 114 | 7.4 | 18.01 | 33 | 195 | 114 | 7.2 | 18.01 |
| 149 | 215 | 109 | 7.3 | 17.22 | 34 | 215 | 121 | 7.3 | 19.11 |
| 151 | 242 | 136 | 8.2 | 21.48 | 35 | 232 | 140 | 7.9 | 22.11 |
| 155 | 281 | 143 | 9.6 | 22.59 | 38 | 242 | 148 | 8.2 | 23.38 |
| 157 | 311 | 157 | 10.6 | 24.80 | 40 | 275 | 155 | 9.4 | 24.48 |
| 158 | 314 | 159 | 10.7 | 25.11 | 41 | 302 | 145 | 10.3 | 22.90 |
| 162 | 341 | 159 | 11.6 | 25.11 | 42 | 327 | 140 | 11.1 | 22.11 |
| 163 | 362 | 144 | 12.3 | 22.74 | 43 | 328 | 136 | 11.2 | 21.48 |
| 167 | 381 | 134 | 13.0 | 21.16 | 44 | 342 | 134 | 11.6 | 21.16 |
| 169 | 515 | 103 | 17.5 | 16.27 | 45 | 356 | 125 | 12.1 | 19.74 |
| 170 | 543 | 89 | 18.5 | 14.06 | 51 | 376 | 106 | 12.8 | 16.74 |
| 171 | 564 | 88 | 19.2 | 13.90 | 52 | 475 | 85 | 16.2 | 13.42 |
| 172 | 583 | 82 | 19.8 | 12.95 | 56 | 521 | 82 | 17.7 | 12.95 |
| 174 | 704 | 83 | 23.9 | 13.11 | | | | | |
| 176 | 748 | 90 | 25.4 | 14.21 | | | | | |
| 177 | 761 | 94 | 25.9 | 14.85 | | | | | |
| 178 | 805 | 94 | 27.4 | 14.85 | | | | | |

| T-DHSB wall 0.6 Mpa-01 | | | | | T-DHSB wall 0.6Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (μ)** | **Load cell (μ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (μ)** | **Load cell (μ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 182 | 0 | 0 | 0.0 | 0.00 | 23 | 0 | 0 | 0.0 | 0.00 |
| 184 | 41 | 10 | 1.4 | 1.58 | 25 | 20 | 10 | 0.7 | 1.58 |
| 186 | 110 | 23 | 3.7 | 3.63 | 26 | 70 | 30 | 2.4 | 4.74 |
| 187 | 129 | 34 | 4.4 | 5.37 | 28 | 120 | 40 | 4.1 | 6.32 |
| 189 | 144 | 43 | 4.9 | 6.79 | 29 | 135 | 48 | 4.6 | 7.58 |
| 190 | 147 | 43 | 5.0 | 6.79 | 31 | 145 | 51 | 4.9 | 8.05 |
| 193 | 198 | 44 | 6.7 | 6.95 | 32 | 185 | 52 | 6.3 | 8.21 |
| 194 | 235 | 53 | 8.0 | 8.37 | 35 | 195 | 55 | 6.6 | 8.69 |
| 195 | 248 | 54 | 8.4 | 8.53 | 38 | 205 | 60 | 7.0 | 9.48 |
| 196 | 252 | 65 | 8.6 | 10.27 | 39 | 228 | 68 | 7.8 | 10.74 |
| 197 | 266 | 79 | 9.0 | 12.48 | 40 | 255 | 90 | 8.7 | 14.21 |
| 198 | 275 | 95 | 9.4 | 15.00 | 41 | 265 | 100 | 9.0 | 15.79 |
| 199 | 286 | 127 | 9.7 | 20.06 | 42 | 289 | 124 | 9.8 | 19.58 |
| 200 | 320 | 167 | 10.9 | 26.38 | 46 | 302 | 142 | 10.3 | 22.43 |
| 201 | 350 | 173 | 11.9 | 27.32 | 48 | 318 | 156 | 10.8 | 24.64 |
| 202 | 366 | 145 | 12.4 | 22.90 | 51 | 325 | 167 | 11.1 | 26.38 |
| 203 | 378 | 135 | 12.9 | 21.32 | 53 | 350 | 170 | 11.9 | 26.85 |
| 204 | 388 | 125 | 13.2 | 19.74 | 54 | 365 | 174 | 12.4 | 27.48 |
| 205 | 405 | 120 | 13.8 | 18.95 | 55 | 390 | 160 | 13.3 | 25.27 |
| 207 | 482 | 120 | 16.4 | 18.95 | 56 | 460 | 126 | 15.6 | 19.90 |
| 211 | 671 | 118 | 22.8 | 18.64 | 58 | 505 | 120 | 17.2 | 18.95 |
| 212 | 695 | 119 | 23.6 | 18.79 | 59 | 548 | 119 | 18.6 | 18.79 |
| 213 | 712 | 115 | 24.2 | 18.16 | 61 | 625 | 115 | 21.3 | 18.16 |
| 214 | 741 | 119 | 25.2 | 18.79 | 62 | 695 | 119 | 23.6 | 18.79 |
| 216 | 770 | 120 | 26.2 | 18.95 | 63 | 750 | 120 | 25.5 | 18.95 |
| 217 | 860 | 94 | 29.2 | 14.85 | 65 | 805 | 102 | 27.4 | 16.11 |
| 218 | 915 | 88 | 31.1 | 13.90 | 66 | 915 | 96 | 31.1 | 15.16 |
| 220 | 1031 | 89 | 35.1 | 14.06 | 69 | 970 | 82 | 33.0 | 12.95 |
| | | | | | 71 | 1015 | 80 | 34.5 | 12.64 |
| | | | | | 72 | 1090 | 80 | 37.6 | 12.63 |
| | | | | | 73 | 1150 | 80 | 39.1 | 12.64 |

| T-DHSB wall 1Mpa-01 | | | | | T-DHSB wall 1Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (µ)** | **Load cell (µ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (µ)** | **Load cell (µ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 59 | 0 | 0 | 0.0 | 0.00 | 41 | 0 | 0 | 0.0 | 0.00 |
| 69 | 10 | 24 | 0.3 | 3.79 | 42 | 5 | 15 | 0.2 | 2.37 |
| 70 | 27 | 27 | 0.9 | 4.26 | 56 | 42 | 30 | 1.4 | 4.74 |
| 71 | 54 | 27 | 1.8 | 4.26 | 57 | 62 | 42 | 2.1 | 6.63 |
| 72 | 74 | 33 | 2.5 | 5.21 | 59 | 70 | 45 | 2.4 | 7.11 |
| 73 | 84 | 43 | 2.9 | 6.79 | 61 | 90 | 49 | 3.1 | 7.74 |
| 74 | 85 | 45 | 2.9 | 7.11 | 63 | 95 | 53 | 3.2 | 8.37 |
| 77 | 130 | 53 | 4.4 | 8.37 | 64 | 120 | 56 | 4.1 | 8.84 |
| 78 | 144 | 56 | 4.9 | 8.84 | 65 | 134 | 65 | 4.6 | 10.27 |
| 79 | 148 | 59 | 5.0 | 9.32 | 67 | 142 | 70 | 4.8 | 11.06 |
| 80 | 169 | 66 | 5.7 | 10.42 | 68 | 155 | 75 | 5.3 | 11.85 |
| 81 | 184 | 65 | 6.3 | 10.27 | 69 | 162 | 79 | 5.5 | 12.48 |
| 85 | 228 | 91 | 7.8 | 14.37 | 72 | 180 | 85 | 6.1 | 13.42 |
| 87 | 279 | 108 | 9.5 | 17.06 | 74 | 222 | 98 | 7.5 | 15.48 |
| 88 | 297 | 124 | 10.1 | 19.58 | 75 | 242 | 108 | 8.2 | 17.06 |
| 89 | 324 | 125 | 11.0 | 19.74 | 76 | 284 | 130 | 9.7 | 20.53 |
| 90 | 338 | 133 | 11.5 | 21.01 | 77 | 323 | 138 | 11.0 | 21.80 |
| 92 | 382 | 139 | 13.0 | 21.95 | 79 | 341 | 142 | 11.6 | 22.43 |
| 93 | 393 | 136 | 13.4 | 21.48 | 80 | 386 | 152 | 13.1 | 24.01 |
| 94 | 456 | 166 | 15.5 | 26.22 | 81 | 402 | 159 | 13.7 | 25.11 |
| 95 | 478 | 172 | 16.3 | 27.17 | 82 | 426 | 172 | 14.5 | 27.17 |
| 101 | 511 | 185 | 17.4 | 29.22 | 83 | 465 | 182 | 15.8 | 28.75 |
| 102 | 537 | 175 | 18.3 | 27.64 | 84 | 494 | 196 | 16.8 | 30.96 |
| 104 | 561 | 150 | 19.1 | 23.69 | 85 | 521 | 195 | 17.7 | 30.80 |
| 106 | 596 | 118 | 20.3 | 18.64 | 86 | 580 | 180 | 19.7 | 28.43 |
| 107 | 615 | 114 | 20.9 | 18.01 | 87 | 602 | 165 | 20.5 | 26.06 |
| 109 | 660 | 117 | 22.4 | 18.48 | 88 | 619 | 155 | 21.0 | 24.48 |
| 111 | 662 | 114 | 22.5 | 18.01 | 105 | 635 | 145 | 21.6 | 22.90 |
| 112 | 713 | 104 | 24.2 | 16.43 | 106 | 692 | 125 | 23.5 | 19.74 |
| 114 | 755 | 99 | 25.7 | 15.64 | 109 | 702 | 123 | 23.9 | 19.43 |
| 117 | 803 | 75 | 27.3 | 11.85 | | | | | |
| 120 | 803 | 75 | 27.3 | 11.85 | | | | | |
| 121 | 803 | 75 | 27.3 | 11.85 | | | | | |

## Appendix: L Triplet test results for R- DHSBs

| R-DHSB wall 0.2 Mpa-01 | | | | | R-DHSB wall 0.2Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (µ)** | **Load cell (µ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (µ)** | **Load cell (µ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 0 | 0 | 0 | 0.0 | 0 | 45 | 0 | 0 | 0.0 | 0 |
| 89 | -24 | -5 | 0.8 | 0.79 | 46 | -30 | -3 | 1.0 | 0.47 |
| 93 | -67 | -14 | 2.3 | 2.21 | 48 | -50 | -7 | 1.7 | 1.11 |
| 94 | -70 | -17 | 2.4 | 2.68 | 50 | -80 | -15 | 2.7 | 2.37 |
| 95 | -77 | -17 | 2.6 | 2.68 | 51 | -115 | -18 | 3.9 | 2.84 |
| 110 | -233 | -24 | 7.9 | 3.79 | 52 | -150 | -22 | 5.1 | 3.47 |
| 111 | -238 | -26 | 8.1 | 4.11 | 53 | -203 | -25 | 6.9 | 3.95 |
| 113 | -250 | -30 | 8.5 | 4.74 | 54 | -220 | -26 | 7.5 | 4.11 |
| 114 | -255 | -31 | 8.7 | 4.90 | 55 | -235 | -28 | 8.0 | 4.42 |
| 115 | -273 | -35 | 9.3 | 5.53 | 56 | -245 | -30 | 8.3 | 4.74 |
| 118 | -340 | -36 | 11.6 | 5.69 | 57 | -300 | -32 | 10.2 | 5.05 |
| 122 | -384 | -39 | 13.1 | 6.16 | 58 | -345 | -37 | 11.7 | 5.84 |
| 123 | -398 | -39 | 13.5 | 6.16 | 59 | -355 | -37 | 12.1 | 5.84 |
| 124 | -468 | -40 | 15.9 | 6.32 | 60 | -361 | -38 | 12.3 | 6.00 |
| 125 | -638 | -32 | 21.7 | 5.05 | 61 | -370 | -39 | 12.6 | 6.16 |
| 127 | -801 | -28 | 27.2 | 4.42 | 62 | -500 | -42 | 17.0 | 6.63 |
| 131 | -913 | -23 | 31.0 | 3.63 | 63 | -550 | -42 | 18.7 | 6.63 |
| 134 | -931 | -23 | 31.7 | 3.63 | 64 | -700 | -32 | 23.8 | 5.05 |
| 135 | -927 | -22 | 31.5 | 3.47 | 65 | -840 | -22 | 28.6 | 3.47 |
| 137 | -971 | -22 | 33.0 | 3.47 | 66 | -905 | -22 | 30.8 | 3.47 |
| 139 | 1010 | -19 | 34.3 | 3.00 | 69 | -971 | -19 | 33.0 | 3.00 |
| 140 | -1017 | -17 | 34.6 | 2.68 | 70 | -1020 | -18 | 34.7 | 2.84 |
| 141 | -1027 | -18 | 34.9 | 2.84 | 71 | -1050 | -17 | 35.7 | 2.68 |
| 145 | -1143 | -22 | 38.9 | 3.47 | 72 | -1143 | -17 | 38.9 | 2.68 |
| 146 | -1171 | -21 | 39.8 | 3.32 | 73 | -1171 | -15 | 39.8 | 2.37 |
| 147 | -1201 | -22 | 40.8 | 3.47 | 75 | -1201 | -15 | 40.8 | 2.37 |
| | | | | | 78 | -1521 | -12 | 51.7 | 1.90 |

| R-DHSB wall 0.6 Mpa-01 | | | | | R-DHSB wall 0.6 Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (μ)** | **Load cell (μ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (μ)** | **Load cell (μ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 174 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 |
| 175 | -30 | -3 | 1.0 | 0.47 | 11 | -25 | -2 | 0.9 | 0.32 |
| 176 | -65 | -5 | 2.2 | 0.79 | 12 | -30 | -3 | 1.0 | 0.47 |
| 177 | -74 | -7 | 2.5 | 1.11 | 13 | -50 | -4 | 1.7 | 0.63 |
| 178 | -83 | -8 | 2.8 | 1.26 | 14 | -100 | -10 | 3.4 | 1.58 |
| 179 | -99 | -11 | 3.4 | 1.74 | 15 | -120 | -12 | 4.1 | 1.90 |
| 180 | -120 | -13 | 4.1 | 2.05 | 16 | -140 | -16 | 4.8 | 2.53 |
| 181 | -130 | -17 | 4.4 | 2.68 | 17 | -142 | -17 | 4.8 | 2.68 |
| 182 | -135 | -19 | 4.6 | 3.00 | 18 | -165 | -20 | 5.6 | 3.16 |
| 183 | -141 | -23 | 4.8 | 3.63 | 20 | -190 | -26 | 6.5 | 4.11 |
| 184 | -148 | -26 | 5.0 | 4.11 | 25 | -192 | -28 | 6.5 | 4.42 |
| 186 | -159 | -28 | 5.4 | 4.42 | 26 | -195 | -29 | 6.6 | 4.58 |
| 187 | -160 | -27 | 5.4 | 4.26 | 27 | -205 | -30 | 7.0 | 4.74 |
| 190 | -162 | -28 | 5.5 | 4.42 | 29 | -205 | -30 | 7.0 | 4.74 |
| 191 | -176 | -31 | 6.0 | 4.90 | 30 | -220 | -32 | 7.5 | 5.05 |
| 196 | -249 | -33 | 8.5 | 5.21 | 32 | -245 | -33 | 8.3 | 5.21 |
| 197 | -285 | -33 | 9.7 | 5.21 | 33 | -265 | -34 | 9.0 | 5.37 |
| 199 | -292 | -35 | 9.9 | 5.53 | 36 | -285 | -35 | 9.7 | 5.53 |
| 200 | -303 | -36 | 10.3 | 5.69 | 38 | -305 | -36 | 10.4 | 5.69 |
| 201 | -324 | -39 | 11.0 | 6.16 | 42 | -324 | -39 | 11.0 | 6.16 |
| 202 | -337 | -40 | 11.5 | 6.32 | 46 | -338 | -40 | 11.5 | 6.32 |
| 204 | -396 | -39 | 13.5 | 6.16 | 50 | -340 | -39 | 11.6 | 6.16 |
| 205 | -420 | -41 | 14.3 | 6.48 | 55 | -380 | -41 | 12.9 | 6.48 |
| 206 | -447 | -43 | 15.2 | 6.79 | 60 | -405 | -43 | 13.8 | 6.79 |
| 207 | -526 | -46 | 17.9 | 7.27 | 62 | -440 | -46 | 15.0 | 7.27 |
| 209 | -549 | -48 | 18.7 | 7.58 | 65 | -490 | -51 | 16.7 | 8.05 |
| 210 | -579 | -48 | 19.7 | 7.58 | 68 | -525 | -52 | 17.9 | 8.21 |
| 211 | -579 | -48 | 19.7 | 7.58 | 71 | -545 | -50 | 18.5 | 7.90 |
| 212 | -615 | -41 | 20.9 | 6.48 | 72 | -565 | -45 | 19.2 | 7.11 |
| 212 | -642 | -39 | 21.8 | 6.16 | 73 | -590 | -43 | 20.1 | 6.79 |
| 213 | -665 | -35 | 22.6 | 5.53 | 75 | -650 | -42 | 22.1 | 6.63 |
| 214 | -695 | -37 | 23.6 | 5.84 | | | | | |

| R-DHSB wall 1.0 Mpa-01 | | | | | R-DHSB wall 1.0 Mpa-02 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TEST NO** | **LVDT (μ)** | **Load cell (μ)** | **DISPL ACEMENT (mm)** | **FORCE (kN)** | **Test NO** | **LVDT (μ)** | **Load cell (μ)** | **DISP LACEMENT (mm)** | **FORCE (kN)** |
| 217 | 0 | 0 | 0.0 | 0.00 | 21 | 0 | 0 | 0.0 | 0.00 |
| 219 | -7 | -3 | 0.2 | 0.47 | 23 | -8 | -4 | 0.3 | 0.63 |
| 220 | -8 | -3 | 0.3 | 0.47 | 26 | -9 | -5 | 0.3 | 0.79 |
| 222 | -10 | -4 | 0.3 | 0.63 | 27 | -14 | -7 | 0.5 | 1.11 |
| 223 | -12 | -5 | 0.4 | 0.79 | 28 | -15 | -8 | 0.5 | 1.26 |
| 227 | -17 | -7 | 0.6 | 1.11 | 29 | -25 | -9 | 0.9 | 1.42 |
| 230 | -71 | -10 | 2.4 | 1.58 | 30 | -50 | -12 | 1.7 | 1.90 |
| 231 | -83 | -15 | 2.8 | 2.37 | 31 | -74 | -16 | 2.5 | 2.53 |
| 234 | -126 | -18 | 4.3 | 2.84 | 33 | -100 | -18 | 3.4 | 2.84 |
| 235 | -133 | -20 | 4.5 | 3.16 | 35 | -110 | -20 | 3.7 | 3.16 |
| 236 | -140 | -20 | 4.8 | 3.16 | 36 | -130 | -23 | 4.4 | 3.63 |
| 237 | -153 | -23 | 5.2 | 3.63 | 38 | -140 | -23 | 4.8 | 3.63 |
| 238 | -162 | -23 | 5.5 | 3.63 | 41 | -162 | -26 | 5.5 | 4.11 |
| 243 | -182 | -26 | 6.2 | 4.11 | 43 | -182 | -28 | 6.2 | 4.42 |
| 245 | -208 | -28 | 7.1 | 4.42 | 44 | -183 | -30 | 6.2 | 4.74 |
| 246 | -257 | -29 | 8.7 | 4.58 | 50 | -230 | -33 | 7.8 | 5.21 |
| 250 | -302 | -32 | 10.3 | 5.05 | 53 | -285 | -38 | 9.7 | 6.00 |
| 252 | -323 | -36 | 11.0 | 5.69 | 56 | -300 | -40 | 10.2 | 6.32 |
| 255 | -330 | -40 | 11.2 | 6.32 | 58 | -305 | -45 | 10.4 | 7.11 |
| 257 | -345 | -42 | 11.7 | 6.63 | 62 | -310 | -46 | 10.5 | 7.27 |
| 258 | -353 | -45 | 12.0 | 7.11 | 63 | -321 | -46 | 10.9 | 7.27 |
| 261 | -366 | -46 | 12.4 | 7.27 | 64 | -335 | -47 | 11.4 | 7.42 |
| 262 | -367 | -47 | 12.5 | 7.42 | 65 | -340 | -48 | 11.6 | 7.58 |
| 263 | -378 | -47 | 12.9 | 7.42 | 66 | -365 | -49 | 12.4 | 7.74 |
| 264 | -388 | -50 | 13.2 | 7.90 | 67 | -368 | -50 | 12.5 | 7.90 |
| 265 | -396 | -51 | 13.5 | 8.05 | 68 | -368 | -52 | 12.5 | 8.21 |
| 266 | -400 | -52 | 13.6 | 8.21 | 70 | -395 | -54 | 13.4 | 8.53 |
| 267 | -412 | -55 | 14.0 | 8.69 | 71 | -420 | -56 | 14.3 | 8.84 |
| 268 | -417 | -56 | 14.2 | 8.84 | 72 | -440 | -58 | 15.0 | 9.16 |
| 269 | -426 | -57 | 14.5 | 9.00 | 73 | -455 | -60 | 15.5 | 9.48 |
| 270 | -470 | -52 | 16.0 | 8.21 | 76 | -490 | -55 | 16.7 | 8.69 |
| 275 | -487 | -47 | 16.6 | 7.42 | 79 | -505 | -52 | 17.2 | 8.21 |
| 282 | -495 | -46 | 16.8 | 7.27 | 82 | -525 | -46 | 17.9 | 7.27 |
| 285 | -505 | -46 | 17.2 | 7.27 | 85 | -530 | -44 | 18.0 | 6.95 |
| | -520 | -42 | 17.7 | 6.63 | 90 | -545 | -42 | 18.5 | 6.63 |
| | | | | | 91 | -555 | -36 | 18.9 | 5.69 |
| | | | | | 92 | -586 | -34 | 19.9 | 5.37 |