STRUCTURAL RESPONSE OF INTERLOCKING STABILIZED LATERITE SOIL BLOCK PANELS FOR SINGLE STOREY HOUSING

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(Construction Engineering and Management)

JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

2019

Structural Response of Interlocking Stabilized Laterite Soil Block Panels for Single Storey Housing

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A thesis submitted in partial fulfilment for the degree of Doctor of Philosophy in Construction Engineering and Management in the Jomo Kenyatta University of Agriculture and Technology

2019

DECLARATION

This research study is my original work and has not been presented for academic research work in any other University.

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DEDICATION

With special thanks to my wife Nduya Christine and my parents Elizabeth Monah Sanewu and John Fundi Sanewu.

ACKNOWLEGMENT

I would like to express my sincere gratitude and deep appreciation to Prof. James Wambua Kaluli, Prof. Walter Oyawa Odhiambo and Prof. John Mungai Kinuthia for their kindness, valuable suggestions and helpful guidance. Prof. Wambua has mentored me patiently along the way and am grateful for that. Prof. Oyawa contributed greatly in structural analysis and in-depth guidance on the data collected. I am greatly thankful to Prof. Kinuthia for his continuous encouragement throughout the research period and valuable guidance in publishing the research findings.

The author wishes to thank the Department of Civil, Construction and Environmental Engineering of Jomo Kenyatta University of Agriculture and Technology for allowing me to use the Structures and Materials laboratory. Additional thanks are extended to lab technicians Mr. Karugu and Mr. Kimuli Obadia for their assistance in laboratory operations. I am thankful to God for giving me an opportunity and strength to contribute in adding value to the construction engineering sector.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABMT	Alternative Building Materials and Technology
ASTM	American Society for Testing and Materials
BS	British standard
C	Cement
CD	Cow dung
CSW1	Clay soil wall 1
CSW2	Clay soil wall 2
CSW3	Clay soil wall 3
FE	Finite element
GATE	Germany Appropriate Technology Exchange
HABRI	Housing and Building Research Institute
ISSB	Interlocking stabilized soil block
KS	Kenya standard
Ksh	Kenya shillings
L	Lime
LL	Liquid limit
LSW1	Laterite soil wall 1
LSW2	Laterite soil wall 2
LSW3	Laterite soil wall 3
LVDT	Linear variable displacement transducer
NBRRI	Nigerian Building and Road Research Institute
NTU	Non-technology users
PC	Pozzolanic cement
PI	Plasticity index
PL	Plastic limit
RHA	Rice husk ash
SPSS	Statistical package for the social sciences
TU	Technology users
UTM	Universal testing machine

LIST OF SYMBOLS

f_{cb}	Interlocking block compressive strength
f_{cw}	Wall characteristic compressive strength

ABSTRACT

The right to housing in Kenya has led to increasing demand for adequate and affordable housing units. The use of interlocking stabilised soil blocks (ISSB) is one of the technologies used to meet the shortage. The ISSB is a technology that encourages utilization of locally available building materials for walling structures. The performance of un-reinforced interlocking block masonry walls made using CINVA-Ram blocks subjected to static compression loads was investigated. Since masonry structures are mainly subjected to compressive stresses, the stress-strain relationship of ISSB masonry was used to model its behaviour and develop empirical formulae for predicting the compressive strength. Further, the social acceptability of ISSB technology in Kenyan construction industry was also determined through a survey design. In a laboratory study, Pozzolanic cement (PC), lime (L), rice husk ash (RHA) and cow dung (CD) were used to stabilize soil. Two types of soils: laterite soil with sandy clay loam texture (25% clay and 75% sand), and plasticity index (PI) of 12.09% and clay soil with 5.0 coefficient of uniformity were used. The stabilized blocks were used to make six types of walls of size 900 mm long x 1200 mm high. A finite element analysis adopting the Rankine failure criterion was performed using Abaqus software to simulate the deformability behaviour of the wall which was validated through experimental tests. The predictive empirical formulae for the compressive strength of the ISSB masonry was developed by performing statistical multiple regression analysis. The social acceptability of the ISSB technology was carried out through use of semi-structured interviews on two target groups: technology users and non-technology users. The collected data was analysed by use of thematic analysis. The experimental results indicated that block compressive strength, water absorption and durability (1-min abrasion test) were within the recommended levels at the optimum stabilizer percentages. It was found that lime stabilization causes a delayed gain of compressive strength in soils with higher clay content as compared to pozzolanic cement. However, for lime to perform better in clay soil stabilization it should be used together with pozzolanic cement. The wall failure modes were characterized by either diagonal cracking of individual blocks or spalling of block debris. The performance of interlocking block walls in load capacity can be divided into three parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure. Through finite element modelling, contribution of stress distribution to the wall mode of failure was depicted. In addition to the mechanical properties of masonry, the FE simulation results indicated that the deformability behaviour of ISSB masonry is influenced by the type of stabilizer used on the target material. This dictates the stress distribution and vertical displacement of the masonry. The interview results found that the technology is most useful in the construction of residential houses, perimeter fencing walls and partition walls. Perceived low performance and inadequate demonstration projects amongst non-users limited their willingness to use the ISSB technology. Desirable features of the ISSB technology include: aesthetic value, ease of construction and non-use of mortar. The study recommends a combined system of constructing columns and ISSB masonry. Furthermore, clear design standards containing workmanship and construction guidelines must be provided to members of the construction industry.

CHAPTER ONE
INTRODUCTION

1.1 Background

Housing is universally acknowledged as one of the basic needs of humans. Unfortunately, because of the large population of poor citizens, many Kenyans are unable to afford houses of their own. The ownership of houses has largely eluded them because of the high cost of building materials. The value of new private buildings has been reported to increase by 10.2 per cent from KSh 77.7 billion in 2016 to KSh 85.6 billion in 2017, mainly on account of a 9.7 per cent increase in the value of residential buildings (Kenya National Bureau of Statistics, 2018). According to Sessional Paper No.3 (2004) on National Housing Policy for Kenya, it is estimated that urban housing needs stand at 150,000 units per year. It is also estimated that a paltry 20,000 – 30,000 units are constructed within the same period, giving a shortfall of over 120,000 units per annum. This shortfall in housing has been met through proliferation of squatter and informal settlements and overcrowding (Economic and social rights centre, 2012).

Currently, built up areas are initiated in areas with varying environmental conditions either due to population segregation or the right to housing (United Nations Centre for Human Settlement, 2001). This has led to subjection of buildings to varying environmental conditions and high vertical loadings arising from the demand to construct storey structures. In order to meet the need for adequate housing of Kenya's population, sustainable investments and continued innovations have been made on appropriate technologies that lower the cost of construction and the cost to the environment. The Ministry of Housing and Urban Development, Kenya, established the Alternative Building Materials and Technology (ABMT) programme in 2006 to address high cost of building material by facilitating provision of affordable housing to low income earners. The ministry through collaboration with the Housing and Building Research Institute (HABRI) and other stakeholders led in dissemination of ABMT that culminated in partial revision of the Kenya Building Code (Syagga, 1993). This has encouraged selection of building materials and technologies that are both economically viable and sustainable. The Interlocking Stabilised Soil Block (ISSB) technology is one such technology that is gaining recognition. The provision of small-scale housing is therefore being achieved through use of this technology. The interlocking nature of the blocks allows dry stacked, mortar-less construction, which reduces the need for skilled labour and shortens construction time. Anand and Ramamurthy (2005) found that the use of interlocking blocks lowers the cost of walling construction by 80%. Compared with alternatives such as fired brick, stabilized soil block technology has been established to offer lower construction costs at comparable quality and is suitable for a wide range of environments (United Nations Human Settlements Programme, 2009).

The mechanical behaviour of interlocking block masonry is mainly influenced by the mechanical properties of the block, effect of height to width aspect ratio, and presence of an opening. The estimation of the influence of these parameters on the behaviour of interlocking block walls is complex since there is no joining media between the block units. Bishnu and Kimiro (2004) suggest that simulation modelling helps in understanding the influence of loading condition, material characteristics and construction practices on the behaviour of masonry walls. Lourenco, Rots and Blaauwendraad (1995) argue that brick masonry can be modelled numerically on two levels: micro-modelling and macro-modelling. On the micro level a detailed consideration of the bricks and mortar is described by the actual geometry and individual mechanical behaviour of the bricks, mortar and interface between the brick and mortar. On the macro level the units and joints are smeared out in a homogenous continuum. Since the construction using interlocking blocks does not involve usage of mortar joints, this study therefore adopted a numerical simulation approach in macro-modelling to determining the overall behaviour of the interlocking block wall.

1.2 Problem statement

The most important characteristic of interlocking block construction is its simplicity. Laying interlocking blocks on each other is a simple though adequate technique that has proved viable in several pilot projects as shown by UN-HABITAT (2009). The technology has however received scepticism in its adoption due to shortage of its performance information. The structural behaviour of mortar bonded masonry has been well documented in codes of design with little being known on the performance of interlocking soil blocks. The lack of structural performance information compounded with high cost of cement stabilization has resulted to slow adoption rate of the interlocking soil blocks in the construction industry. Besides cement other stabilizers which are abundantly available and cheap have not been considered in cost reduction and improvement of interlocking soil block qualities. Therefore, this study sought to determine failure mode of interlocking soil block masonry under vertical and horizontal loading with a consideration of different stabilizers in order to find their socio-economic viability.

1.3 Objectives

1.3.1. Main objective

The main objective of the study was to evaluate the structural performance of interlocking stabilized laterite soil block panels for single storey housing.

1.3.2. Specific objectives

The specific objectives of this study were;

i. To determine the behaviour of differently stabilized interlocking soil blocks when exposed to loading, abrasion and wet conditions.
ii. To determine the failure mode of interlocking block masonry wall units when subjected to in-plane and out-of-plane loading.
iii. To develop a numerical simulation model for predicting the structural failure of interlocking block walls.
iv. To establish the social acceptability of interlocking stabilized soil block technology.

1.4 Research questions

The study was guided by the following questions;

i. How do ISSB walls fail when subjected to loading?
ii. What is the behaviour of blocks stabilized with different stabilizer when exposed to loading and wet conditions?
iii. Can the structural failure of ISSB walls be empirically predicted?
iv. What are the features of ISSB technology that need improvement to encourage its adoption?

1.5 Justification

The interlocking stabilized soil block (ISSB) technology has proven to be one of the construction technological improvements that can help in provision of affordable housing to single storey dwellers. However, its structural response and socio-acceptability viability need to be evaluated. This will ultimately increase its adoption rate in the construction industry. The understanding of the failure of the walls when loaded aids in overcoming the possible points of failure during the design stage. This facilitates construction of walls with an adequate factor of safety. More so, the blocks are used in different areas in a constructed house. Their durability behaviour and performance under wet conditions therefore, ultimately influence the appropriate area of application. In order to better understand performance of a full-scale interlocking block wall, numerical model was developed. Finally, a social acceptability study was performed to determine the sustainability of the technology in a holistic approach once adopted by the community.

1.6 Scope and limitations

The study considered that ISSB are only applied in construction of walling elements. The foundation walling however, are constructed using natural bush stones. Two types of soils (laterite and clay soil) were used in the study. Currently there exists many forms of interlocking blocks depending on the intended use and the press machine used, however the research adopted the form produced by Makiga Engineering Limited (Figure 1.1), since they are mostly used in the East Africa region (Makiga Engineering Services, 2005). The Finite Element modelling was performed using Abaqus/CAE 6.14-1 version. The blocks were subjected to accelerated abrasion test in a belt sander to determine their abrasion test per unit time. The masonry walls were subjected to static axial and horizontal loading to simulate superstructure loading and lateral loading by wind respectively. In the execution of the research it was assumed that the quality of the individual interlocking blocks produced had uniform mechanical properties.

Figure 0.1: Wide format interlocking soil blocks

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

The first evidence of the production of bricks dates back to the days of the Babylonians being more than 5000 years ago. At first they were used in their unbaked form, simply left to dry in the sun and it was only in 2500 BC that they began to be baked (Baiden, Agyekum and Kuragu, 2014). The term “brick” encompasses a wide range of products obtained by mixing clay, preparing and moulding it, before slowly drying and finally firing in an oven. Conville and Lee (2005) found that as the temperature rises, mineralogical and textural changes occur resulting to hardening of the block due to metamorphic processes under high temperature. The production of fired blocks is labour intensive and the process of firing is usually carried out using firewood which leads to ecological destruction. In addition to the firing environmental problem, clay blocks can only be produced in locations where suitable clay soil deposits exist. This shortfall of fired bricks necessitated the development of alternative technologies that lead to production of unfired building blocks that have a low environmental footprint.

The construction industry has over the years experienced introduction of different earth construction techniques geared toward improving the quality of earth construction. Some of the predominant techniques include adobe block construction, cob construction, earth sheltering, wattle and daub and rammed earth. Adobe brick construction mainly involves manufacture of clay bricks by mixing the clay using feet and use wooden frame moulds to make bricks. However, one disadvantage of non-baked adobe bricks is its lack of stability leading to volume changes. Cob construction on the other hand does not involve use of blocks or bricks, instead a mix of clay, sand and straw is made then moulded and compressed into flowing forms to make walls and roofs. This technique requires plastering of the walls in order to extend the building life, hence making it more expensive (UN-HABITAT, 2009).

Due to rapid rate of urbanisation and increasing pressure on the limited resources, there is need to address the issues of adequate housing and sustainable interventions on built environment. This requires concentrated action by all stakeholders involved in the construction industry. Clients need to demand a more sustainable built environment, professionals have to adopt and promote sustainable construction practices through their work, the construction industry should commit to follow sustainable construction processes, and regulatory bodies need to encourage, enable and enforce sustainable construction. The interlocking stabilized soil block (ISSB) technology is an alternative that encourages sustainable construction through utilization of locally available resources.

2.2 Interlocking stabilized soil block technology

Soil has been used as a traditional construction material to build houses in Africa (Rute, Thomas, Aires and Luis, 2011). One of the most common earthen masonry techniques is the use of sun dried or kiln fired adobe bricks with mud mortar. Although this technique is inexpensive, the bricks vary largely in shape, strength and durability. This has led to the use of compressed earth blocks. These blocks are manufactured by compressing stabilized soil in a mould with a manual or hydraulic press, and subsequently cured. The Germany Appropriate Technology Exchange (GATE) (1994) found these blocks to have higher durability as well as uniform geometric shapes. Since earth is available in almost all parts of the world, these building blocks can be manufactured on the construction site. The fact that these blocks are not burned and that the transportation may be unnecessary makes them economical and sustainable construction material from an energy point of view. However, the usage of stabilized blocks still requires joining the units using either mud mortar or lime or cement-sand mortars. GATE (1994) alludes that where mud mortar has been used the durability of the wall is normally compromised while use of lime or cement-sand mortar has significantly increased the cost. In order to overcome these challenges, the technology of interlocking blocks was introduced in the construction industry.

Stabilised interlocking blocks are produced using local suitable soil that is stabilized and pressed in a hydraulic press mould cured for 7 days before being used in wall construction (Bansal, 2011). The block sizes are modular and rectangular in shape. The amount of stabilization mainly depends on soil characteristics and the strength desired. Previous work by George (2014) on soil-cement block production found that the ideal soils must be sandy, containing predominantly non-expansive clay minerals (like kaolinite) and having sand content greater than 65% with a dry weight of 18 kN/m^3. On the other hand, it has been found that lime stabilization is suitable for soils with high clay content.

The interlocking blocks are manufactured with frogs (tongue and groove joints) that allows dry stack wall to be constructed through interlocking of the units resulting from keying action of the blocks. The interlocking mechanism enhances stability and horizontal and vertical alignment. The blocks may also be produced with ducts that can easily allow reinforcement of the walls and passage of service ducts within the walls. The interlocking blocks are suitable for low load bearing applications. Lawrence, Heath and Walker (2008) found that the blocks have environmental benefits like use of sustainable raw materials that present no biohazard as well as having reduced embodied energy and thermal mass. During wall construction the blocks are dry stacked, except for the first course above the damp proof course where plain mortar is applied. The walls may be left exposed, plastered/rendered or finished with other wall applications.

During the production of interlocking blocks, the method of installing plumbing and electrical conduits depend on whether they will run through, within or alongside the masonry wall. Their placement can contribute to the structural response of the wall due to loading. The service conduits that are parallel to the wall can reside either within the masonry block cores or in the cavities created after constructing. However, the use of hammers can cause cracking of adjacent blocks and lead to loss of vertical alignment of the walls. The alternate way of allowing accommodation of service conduits is that during construction process holes can be left in designated locations by cutting sections on the blocks before they are laid. This may, on the contrary interrupt the evenness of the interlocking block surface causing instability when laying. In addition, the precise location of the penetration may be altered after completion of construction. The alternative therefore is to allow ducts in the interlocking blocks when moulding them. Where this has been provided, it has enabled noise dampening during flushing operations of the plumbing appliances (Fletcher Concrete and Infrastructure Ltd, 2008). However, even with this development, there needs a well-designed coordination to ensure that the structural response of the wall to loading is not compromised. This will be required so that when the walls are subjected to loading when in service or when permanent ventilation are left during construction will not lead to collapse.

2.3 Soil classification for interlocking blocks

Soil is the basic material for moulding of the stabilized soil blocks. The type of stabilizer is normally selected based on the type of soil. The soil classification systems are based on properties such as grain size distribution and Atterberg limits.

2.3.1. Particle size distribution

Soil consists primarily of solid particles resulting from a variety of geological processes and is composed of a variety of minerals. Soil particles have been found by Rodrigo *et al* (2017) to range in size from less than a micron to several millimetres.

The texture of soil is usually expressed in terms of the percentages of sand, silt, and clay, with particles smaller than 2 mm in diameter being divided into three broad categories based on size. Particles of size 2 to 0.05 mm diameter are called sand; those of 0.05 to 0.002 mm diameter are silt and the less than 0.002 mm particles are clay (BS 1377-2, 1990). Kerry, Rawlins, Oliver and Lacinska (1994) explains that the standard analysis of particle size distribution involves the dispersion of mineral particles after destroying the organic matter.

Studies have shown that the type and percentage of clay minerals present in a soil dictates the selection of the stabilizing additive needed for interlocking stabilised blocks production. For the purpose of ISSB production, soils can be broadly classified as expansive (liquid limit between 20 – 35) and less expansive soils (between 50 – 70 liquid limit). The presence of clay expansive minerals in soils can cause excessive swelling when the soil comes in contact with water and also shrinkage when it undergoes drying.

2.3.2. Atterberg limits

The Atterberg limits are a basic measure of the critical water content of a fine-grained soil to determine its Liquid Limits (LL), Plastic Limit (PL) and Shrinkage Limit (SL). According to this soil classification system, Das (2002) argues that as water is added to a dry soil, the soil changes from solid to semi-solid to plastic to liquid. The moisture content in the soil at the threshold between semi-solid and plastic is called the plastic limit, while that between plastic and liquid is called the liquid limit. A large liquid limit indicates high compressibility and high shrink/swell soil tendencies. Subtracting the plastic limit from the liquid limit yields the plasticity index (Das, 2002). The Atterberg limits are not only used to identify the soil's classification, but also allows empirical correlation for other engineering properties.

The Casagrande plasticity chart has been used to determine the types of fines present in soil. The A-line on the plasticity chart separates the clays from the silts while the B-line on the liquid limit (LL = 50%) separates the high from the low compressible fine-grained soils (Ramirez, Gonzalez, Daniel and Santiago, 2015). Generally, a dense soil withstands greater applied loads (has greater bearing capacity) than a loose soil. From empirical tests, the BS 1377-4 (1990) records that well-drained, coarse grained soils generally can be compacted to a greater density than fine grained soils, because the smaller particles tend to fill the spaces between the larger ones. The soil characteristics therefore determine its suitability to be applied in ISSB production.

2.4 The occurrence and types of laterite soils

The chemical changes occurring in the primary minerals of rocks in tropical zones tend to produce end-products consisting of clay minerals predominantly represented by kaolinite. Raychaudhuri (1980) found that the chemical weathering of rocks in tropical zones is favoured by warm humid climates, presence of vegetation, and by gentle slopes. Thus, tropical and sub-tropical regions of low relief with abundant rainfall and high temperatures are the most susceptible to chemical alterations of soils (Morrin and Todor, 1980). Gidigasu (1976) argues that during the process of soil laterization, the drying alters the characteristics of the material remarkably. This causes the plasticity of the soil to decrease and its grain size to increase such that much of the clay-sized material agglomerates to the size of silt. This leads to formation of a red tropically weathered material referred as laterite soil (Gidigasu, 1976). Laterite has therefore been defined by Mahalinga-Iyer and Williams (1997) as a red tropical soil that is rich in iron oxide usually derived from rock weathering under strongly oxidising and leaching conditions. It forms in tropical and sub-tropical regions where the climate is humid and it is cable of hardening after a treatment of wetting and drying. The chemical properties of laterite soil are indicated in Table 2.1.

A study by Satyanarayana and Thomas (1961) found the main characteristic features of laterites to be their colour, consistency, structure, form and depth of the different horizons. According to them, they found honey-comb structures being confined to the surface of mature horizons, with the typical laterite quarried for building purposes having a vermicular or vesicular structure. Laterites are usually red-brown in colour with a moderately high specific gravity ranging 2.5 - 3.6, and usually contain secondary aluminium, quartz and kaolinite minerals (Raychaudhuri, 1980).

Table 0.1: Oxides composition of laterite soil

Oxides	Chemical composition (%)
Quartz (SiO_2)	25.46
Corundum (Al_2O_3)	31.10
Hematite (Fe_2O_3)	5.53
CO_2	7.91

(Source: *Latifi, Marto and Eisazadeh, 2013*)

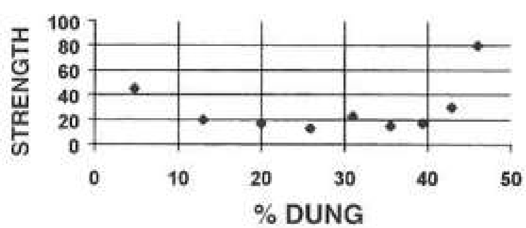
In Kenya, studies on soil types have shown that laterite soil occur in three types, namely Nitisols, Ferralsols and Acrisols (Muriithi, 1985). Nitisols are the most common especially in the tropical highlands and volcanic steep slopes like those of Mt. Kenya. They are more fertile than other laterite soils because of their higher nutrient content, texture and ability to hold water, due to insect activity in the top soil layers. Nitisols are about 30 per cent clay with low phosphorus levels and are dark red in colour. They support tropical rain forest and savannah growth and are resistant to erosion because of their good drainage and stable soil structure that encourages deep rooting (Dubois and Walsh, 1970). The acrisol laterite soil types are found in humid, tropical areas on undulating to hilly topography. This laterite soil type is very acidic and is characterized by extensive leaching, excess aluminium, and high erosion, yet it supports acid-tolerant plants and crops. Acrisol soils have a thin brown top layer and yellow subsurface layer. They are highly susceptible to erosion and surface crusting with weak structure, making them undesirable for planting crops other than pineapple, cashew or palm. In Kenya, they are mostly found around Thika area in Kiambu County. The ferralsols are found in flat or gently sloped temperate regions. This laterite soil type has a dark brown surface and grey to red-brown subsurface. They are good for agricultural uses because of their ability to absorb water with their texture.

2.5 The use of laterite soil for block making

Several researchers have reported that cement-stabilised laterite can be used in buildings and road construction (Folagbade, 1998; Agbede and Manasseh, 2008; Raheem, Osuolale, Onifade and Abubakar, 2010). The addition of small amounts of cement has been found to inhibit the weakening effect of water and increase strength. A previous study by the Nigerian Building and Road Research Institute (NBRRI) involved the production of laterite bricks that were used for the construction of a bungalow (Madedor, 1992). In that study, the NBRRI proposed the following minimum specifications as requirements for laterite bricks: a bulk density of 181 N/m^3, a water absorption of 12.5%, and a compressive strength of 1.65 N/mm^2 with a maximum cement content fixed at 5%.

2.6 Alternative material for soil stabilization

Soil stabilization process involves the addition of a stabilizing agent to the soil, intimate mixing with sufficient water to achieve the optimum moisture content, compacting the mixture and final curing to ensure that the strength potential is realized (Sherwood, 1993). The stabilizers in soil help to bond together soil particles resulting in a stronger product, increase in water proofing and reduction on the shrinkage and swelling properties of soil. Cow dung has been used traditionally as a construction material by low-income communities in many developing countries. It is used for two purposes: as a binder in moulding of soil blocks and in other instances as a render on walls and floor. A research by Mohammed (1999) found that adding cow dung to burnt clay bricks improved their plasticity, reduced green breakage and acted as internal fuel in firing the bricks thus reducing firing cracks. However, he noted that the higher the cow dung content in bricks the lower their strength and density and the higher the water absorption. Mohammed (1999) established an optimum mix proportion range of 5 – 10% of dry cow dung replacement in clay produced strength of $4.5N/m^2$ (Figure 2.1).



(Source: *Mohammed, 1999*)

Figure 0.1: Strength versus cow dung content

In their study of strength and durability properties of cow dung stabilized earth bricks, Peter and Manu (2013), stabilized earth having plastic limit of 24% and liquid limit of 35% using cow dung in the ranges of 0-30% (intervals of 5%). The researchers found that bricks with 20% of cow dung content had the highest dry compressive strength of 5.77 MPa.

On the other hand, Kwadwo and Evans (2015) mixed cow dung with laterite soil to improve the characteristics of earth blocks. The study involved mixing the soil with cow dung at ratios of 5, 10, 15 and 20% by volume. The soil was also separately added with a mixture of cow dung (3, 8, 13 and 18%) and 2% cement. The blocks were tested for compressive strength and permeability. The results showed that on adding 15% cow dung, maximum stress of 0.53 N/mm^2 was achieved while 2% cement with 8% cow dung produced strength of 0.95 N/mm^2. The blocks with 2% cement and 3% cow dung had the lowest permeability of 5.5% after 24-hour submersion in water.

Several researchers (TENSAR, 1998; Amu, Bamisaye and Komolafe, 2011; Harrier, Berger and Bonelli, 2012) have found lime to be effective in stabilizing plastic clayey soils with plasticity indices (PIs) ranging from 10 to greater than 50 by causing long term strength gain. Lime is not a cementitious material and therefore it cannot form a rigid skeleton with the soil. However, Chukwudi and Lateef (2014) reported that a reaction of pozzolanic type can take place between lime and certain clay minerals in the presence of water forming an insoluble gel similar to that formed during Portland cement hydration. The reaction however is slow. Lime causes a cation exchange which reduces the expansibility of the clay lattice thereby lowering its liquid limit and plasticity. The best soils for lime stabilization have therefore been found by Houben and Guillaud (2003) to be those with significant amount of clay minerals.

Attempts to independently utilize lime in making stabilized earth blocks has been carried out by several researchers (Guettala, Houari, Mezghiche and Chebili, 2002; Raheem, Osuolale, Onifade and Abubakar, 2010; Miqueleiz *et al*, 2012). A study by Raheem, Osuolale, Onifade and Abubakar (2010) found that the average 28-day dry compressive strength for lime stabilized laterite soil blocks was 0.92 N/mm^2, 1.25 N/mm^2, 1.15 N/mm^2, 1.06 N/mm^2 and 0.94 N/mm^2 at 5, 10, 15, 20 and 25% replacement, respectively. Raheem, Osuolale, Onifade and Abubakar (2010) reported a maximum amount of lime stabilizer content of 10% to achieve the highest dry compressive strength. From their study, it was clear that after an optimum value of lime content, any further increase in lime was not beneficial in strength gain of the block.

A study on the effects of hydrated lime on the physical and engineering properties of clay soil was conducted by Muhmed and Wanatowski (2013). The study tested the effect of hydrated lime on the Atterberg limits, compaction and unconfined compression strength of the soil. The researchers found that on adding 5% of lime it increased the plastic and liquid limit by 23.6% and 20.6% respectively and plasticity index reduced by 3%. In addition, the maximum dry density reduced by 4 N/m^3 with 5% lime addition.

Rice husk ash (RHA) is obtained from burning of rice husk. The husk is a by-product of the rice milling industry. Johari, Said, Jaya, Bakar and Ahmad (2011) concluded that RHA burnt in a controlled manner with high temperature has high percentage of silica (SiO_2). Haji, Adnan and Chew (1992) used RHA on a Malaysian soil with cement and lime as stabilizing agents. The results showed that based on strength development, lime is a more effective stabilizing agent. In their study, they concluded that RHA can only be used as a partial replacement for more expansive soils because it has inadequate cementations properties. RHA has therefore been used to improve the engineering properties of soil for sub-grade purposes. A study on the effect of RHA on structural properties of fired clay bricks by Perera, Madhushanka and Subashi (2015) established an optimum percentage of 4% of RHA. The fired clay bricks achieved a strength of 3.55 N/mm^2.

The chemistry of RHA and cement involves the chemical reactions of the amorphous silica in the ash with lime to form calcium silicate hydrates. While silicon burnt in the presence of oxygen gives the required silica (Equation 2.1 and 2.2).

$$Si + O_2 = SiO_2 \qquad 2.1$$

$$C_3S(cement) + H_2O = CSH + Ca(OH)_2 \qquad 2.2$$

The highly reactive silica reacts with Calcium Hydroxide released during the hydration of cement, resulting in the formation of Calcium Silicate Hydrate (Equation 2.3), which is responsible for strength development (Ravande, Bhikshma and Jeevana, 2011).

$$SiO_2 + Ca(OH)_2 = CSH + SiO_2 \qquad 2.3$$

Cement has also been adopted in the production of stabilized earth blocks. Cement reacts with water in soil mixture to form an insoluble cementation colloidal gel. The gel sets and hardens forming a continuous matrix of great strength which surrounds the particles of the soil and binds them together. The presence of high clay portion in soil-cement mixture however, has been found by Bhattacharja and Bhatty (2003) to be a disadvantage in strength gain since they tend to form a continuous matrix through the soil causing swelling and shrinkage. The best soils for cement stabilization have therefore been suggested by Chukwudi and Lateef (2014) to be those which have only small clay content and consist mostly of sand and gravel particles.

A research by Aguwa (2010) established a minimum cement content in laterite soil stabilization by comparing the compressive strengths of laterite-cement blocks to that of sandcrete. In his study, he replaced cement content in the ratios of 0-18% by weight at increment intervals of 2%. Adequate compressive strength of 2.5 N/mm^2 was achieved on day 28 for cement-laterite blocks stabilized with 5% cement content. However, at the same cement content, the sandcrete blocks had lower strength of 0.9 N/mm^2. The researcher concluded that it was more economical building with laterite material than sandcrete in terms of cement content required to achieve suitable strengths.

A study by Auroville Earth Institute found out that the optimum percentage of cement stabilization for sandy soils is in the range of 3 to 5% by weight. A research conducted by Otoko and Pedro (2014) sought to find the effect of cement and waste rubber fibre on the properties of laterite soil blocks. The tests conducted included California Bearing Ratio and unconfined compression tests. The laterite soil was stabilized with 5, 10 and 15% shredded rubber and cement at 2 and 4% content. The unconfined compression strength increased from 231 to 327 kPa from day 7 to 14 on stabilizing the soil using 4% cement and 5% rubber content. In the study, the optimum un-soaked California Bearing Ratio of laterite soil on day 14 (21.05%) was achieved on stabilizing the soil with 4% cement and 5% shredded rubber.

The reviewed work indicates that there have been attempts to stabilize soil by use of cow dung, lime, RHA and cement either individually or in combination. The summary of the reviewed work is presented in Table 2.2.

Table 0.2: Reviewed work on stabilization of soil using cow dung, lime, RHA and cement

Stabilizer	Researcher	Research interest	Optimum stabilizer replacement (% by weight)	Research finding
Cow dung	Mohammed (1999)	Effect of dried cow dung on the plasticity, strength and water absorption on burnt bricks	5-10%	Compressive strength of $45kg/m^2$ with an increase of water absorption
	Peter and Manu (2013)	Effect of cow dung on abrasive resistance and dry compressive strength	20%	Compressive strength of 5.77MPa
	Kwadwo and Evans (2015)	Improving permeability and strength characteristics of earth blocks	15%cow dung 2%cement 8%dung	$0.53\ N/mm^2$ $0.95N/mm^2$
Lime	Raheem *et al* (2010)	Comparative study on the effect of lime and cement on durability and compressive strength of soil	10%	$1.25\ N/mm^2$ dry compressive strength
	Muhmed and Wanatowski (2013)	Effect of hydrated lime on Atterberg limits, strength and compaction strength	5%	Increased PL and LL and reduced PI
RHA	Haji *et al* (1992)	Effect of RHA on Atterberg limits	7.5%	Decrease of LL on increase of RHA
	Perera *et al* (2015)	Effects of RHA on properties of fired clay bricks	4%	$3.55N/mm^2$ compressive strength
Cement	Aguwa (2010)	To establish minimum cement content in laterite soil for cheaper building material	5%	Compressive strength of $2.5N/mm^2$
	Otoko and Pedro (2014)	Effect of cement and waste rubber fibre of on properties of laterite soil blocks	4% cement and 5% rubber fibre	Unconfined compression strength increased from 231-327 kPa

2.7 Performance of interlocking stabilized soil block masonry walls

Masonry construction may be achieved either by using block units which are joined together using mortar or interlocking blocks that are dry stacked. Interlocking block load bearing walls are normally made by laying block units next to each other leaving no gaps.

Mortar layers are eliminated and instead the block units are interconnected through interlocking system of the blocks. The blocks are made plumb by help of a wooden or rubber hammer to knock them gently into place. When laying the first course, care must be taken that the blocks are perfectly horizontal and in a straight line, or at right angles at corners. The walls are finished at top below the roof with a ring beam. It has been shown by Portioli, Cascini, Landolfo and Foraboschi, (2012) that failure of interlocking blocks may involve separation, sliding and crushing of the block interfaces. Therefore, the performance of interlocking soil block walls is mainly influenced by the strength and deformation characteristics of the blocks.

Safiee (2011) in his study on structural behaviour of interlocking mortar-less Putra block wall system found that the failure of the wall was dominated by opening of dry joints, cracking and flexure deflection. It has also been noted by Uzoegbo, Senthivel and Ngowi (2007) that the performance of walls made of interlocking blocks is mainly influenced by the strength and deformation characteristics of the individual blocks. Sanewu, Kaluli, Maritim and Kabubo (2014) established that clay soil stabilized with 2% municipal solid waste ash led to failure of interlocking wall by diagonal cracking and bulging of wall sides. The structural behaviour problem of interlocking masonry system has been advanced to be due to lack of filler material at the block-to-block interface. Besides the problem of gradual closure of air space under load, the progressive development of strength carrying capacity as contributed by different stabilizers need to be examined.

Failure in masonry under axial compression has been associated with vertical splitting due to horizontal tension in the blocks (David, 1972). In conventional mortar bond masonry, both brick and mortar will be free to expand laterally. Mortar has been found to be less rigid compared to blocks which cause the mortar joint to tend to spread outward laterally when the load is applied. However, the strong bond between mortar and block prevent the spreading to happen. Subsequently, David (1972) argues that the mortar is put into a state of biaxial compression and the block into a combined bilateral tension and vertical compression. This being so, failure in the masonry occurs when the tensile stress in the block reaches its ultimate strength. In the absence of mortar, the blocks will be subjected to pure biaxial compression leading to failure by cracking, shear or crushing.

2.8 Durability of interlocking stabilized soil blocks

Obonyo, Exelbirt and Baskaran (2010) suggests that poor durability performance and associated short service life of earth-based construction materials reduces their sustainability. Besides assessment of how long an earth wall stands without falling, the integrity of how well the original texture of exposed surface lasts without deterioration is imperative. Durability tests have been developed (ASTM D559-03 (1989) wire brush test and Bulletin 5 spray test) to evaluate either minimum amount of stabilizer required or characterizing problems attributed to wind-driven rain erosion.

Surface erosion has been identified by Arooz and Halwatura (2018) as a major problem for ISSB. When rain drops fall on soil blocks, they tend to remove the loose particles. The state of erosivity of raindrops therefore depend on the state of bonding of the block surface and the characteristics of the rain. Houben and Guillaud (2003) have proposed several surface monitoring methods which include drip test, water spray test, brushing test, abrasion test and wet-and-dry cycling test. Where surfaces are left unprotected from effects of rain, humidity and high temperature, premature defects in the form of surface roughening, pitting, cracking and erosion have been found to occur. The weathering and durability performance should be satisfactory for general construction. Guettala, Houari, Mezghiche and Chebili (2002) found that the weight loss limit of 10% is applicable to regions with an annual rainfall less than 500 mm.

Clay blocks being porous in nature, can absorb water as it runs down after the wall has deflected rain water. Possible leak paths in the interlocking block wall surface are the block or the block/block interface. Since the interlocking blocks are not joined with mortar, the interior surface may experience wetting conditions due to capillary conduction proceeding from both vertical and horizontal pathways through the wall. Vertical water penetration occurs when water enters as ground water at the base of a structure, while penetration of driving rain into wall surface results in horizontal passage of water. The water that enters the masonry walls may lead to efflorescence, damage to interior wall finishes, floor coverings and building contents. In order to evaluate the leaks, it is required to evaluate the absorptivity of ISSB masonry units.

2.9 Structural performance modelling of masonry walls

Accurate modelling of masonry requires a comprehensive experimental description of the material and consideration of its variability in the properties due to its high reliance on workmanship. Given these facts, Zahra and Dhanasekar (2016) proposed that analytical and numerical models can be adopted in predicting the behaviour of masonry. Analytical analysis of the behaviour of masonry predicts the failure criteria by use of material constitutive laws. These leads to development of empirical relations. The numerical models employ finite element in simulating the behaviour of real materials under loading conditions.

2.9.1 Compressive strength empirical model for interlocking stabilised block masonry

The strength of masonry is based on its compressive load carrying capacity, with the properties of the assemblage therefore, mainly influenced by the blocks stress-strain characteristics. Empirical formulae for mortar bonded masonry have been developed to enable prediction of its compressive stress-strain behaviour (Magenes and Menon, 2009). Under static loading conditions, empirical formulae can be used to predict masonry compressive strength, though unsatisfactorily. As suggested by Tassios (2010), Equations 2.4(a) and (b) can be used to estimate the compressive strength of a well-built mortar bonded brick masonry.

$$f_{wc} = [f_{mc} + 0.4(f_{bc} - f_{mc})].\left(1 - 0.8\sqrt[3]{\propto}\right), f_{bc} > f_{mc} \qquad 2.4a$$

$$f_{wc} = f_{bc}.\left(1 - 0.8\sqrt[3]{\propto}\right), f_{bc} < f_{mc} \qquad 2.4b$$

Where

f_{bc} – masonry compressive strength

f_{bc}, f_{mc} – compressive strengths of blocks and mortars

$\propto$ - the ratio between average (horizontal) joint thickness and average block height

Equations 2.4(a) and (b), however, do not consider any existing interlocking nature of blocks or consider the type and amount of soil stabilizer used, thus limiting its application in ISSB masonry. In this case therefore, the empirical equation need to be modified to include the accurate conditions of interlocking stabilised block masonry.

According to BS 5628:1 (2002), Equation 2.5 has been adopted in evaluating the compressive strength of mortar-bonded masonry wall in terms of the compressive strength of the individual block and the designation of the mortar layer

$$f_k = \frac{f_m}{A} * \frac{\varphi_u \varphi_m}{1.2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.5$$

Where

f_k – masonry characteristic compressive strength

f_m – mean of the maximum load carried by two test panels

A – cross-sectional area of each panel

φ_m– reduction factor for strength of mortar

φ_u – unit reduction factor for sample structural material (not exceeding 1)

It is noted that Equations 2.4 and 2.5 considers the thickness and properties of the mortar that has been used to bond the blocks. These material properties are however not considered in the ISSB technology. Furthermore, they do not explicitly address interlocking masonry wall. This may suggest that using the conventional masonry code (BS 5628:1-2002) to calculate the characteristic compressive strength of interlocking stabilized masonry wall is inaccurate. Therefore Equations 2.4 and 2.5 can only be used to determine the compressive strength of mortar bonded masonry. For ISSB masonry, there is need to develop mathematical equations that accurately depicts its performance by considering its assemblage unit properties.

Due to the structural difference of ISSB masonry from mortar bonded masonry, Uzoegbo and Ngowi (2003) proposed Equation 2.6 for the determination of the average compressive strength of dry-stacked wall panel as a function of the masonry unit cube strength

$$f_{panel} = \phi_m 0.15 f_{cu} + 1 \qquad 2.6$$

Where,

f_{panel} – compressive strength of dry-stacked panel

$\phi_m = 0.9$ – safety factor for material used

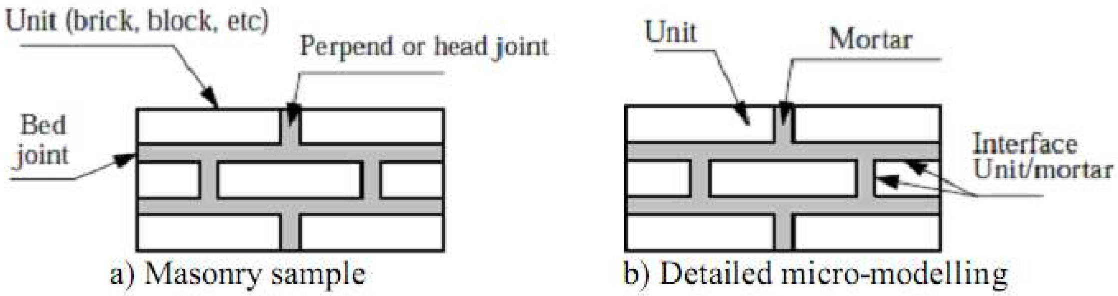
f_{cu} – masonry unit cube strength.

Uzoegbo and Ngowi (2003) in developing Equation 2.6, considered pozzolanic cement as the only stabilizing agent for interlocking soil blocks. Besides pozzolanic cement it has been established in this research that a blend of lime and rice husk ash with pozzolanic cement results to improved properties of interlocking blocks. It is from this back drop that empirical formulae considering alternative stabilizers have been developed.

2.9.2 Finite element modelling of interlocking stabilised soil block masonry

The application of finite element (FE) modelling in the analysis of masonry structures has received a growing attention from researchers over the years. A large number of computer and numerical models have been formulated to solve large scale masonry problems (Magenes and Menon, 2009). As suggested by Lourenco, Rots and Blaauwendraad (1995), use of numerical tools and modelling can predict the behaviour of a structure from linear stage, through cracking and degradation until complete loss of strength. The finite element modelling gives the opportunity to study the wall specimens more thoroughly because of the large amount of results that can be analysed. However, validation through experimental tests are still needed to verify that the FE analyses correspond to the actual behaviour.

Therefore, in Finite Element (FE) modelling, there are two main approaches used to describe the structural response of masonry to loading: macro-modelling and micro-modelling (Milani, Lourenco and Tralli, 2006). According to Lourenco *et al* (1995), a detailed micro-model approach is normally adopted in representing masonry as a composite material consisting of block units and mortar joint. In the micro-modelling approach, the constituent units (mortar and blocks) are arranged in an average interface and lumped as discontinuous line interface elements (Lotfi and Shing, 1994). Thus, masonry is considered as a set of blocks bonded by potential slip lines at the joints (Figure 2.2). However, a disadvantage to this approach is that it requires separate modelling of block units and mortar, thereby limiting its applicability to small panels. Micro-modelling studies have therefore been found necessary to give a better understanding of the local behaviour of masonry structures.



(Source: Lourenco *et al*, 1995)
Figure 0.2: Micro-modelling strategy for masonry

The alternative macro-modelling approach does not make any distinction between masonry units and joints assuming formulation of a fictitious continuous material (Lourenco and Rots, 1997). The masonry is considered as a homogeneous, anisotropic continuum with equivalent mechanical properties. Anthonine (1992) further, suggests that a complete macro-model must be able to reproduce an orthotropic material with different inelastic behaviour for each material axis. The macro-modelling has been found advantageous since it permits large finite elements for simulation of the masonry which reduces the number of unknowns in the system and shortens the analysis time (Baloevic, Radnic, Matesan, Nikola and Banovic, 2016). Interlocking block masonry utilize nearly zero-thickness interface at the joints enabling the materials to be of one form. In this study therefore, the macro-model approach has been adopted to model the structural performance of the ISSB masonry.

2.10 Yield criterion of masonry blocks

It has been found by Blackard, Kim, Citto, William and Metupalayan (2007) that mortar-bonded masonry sustains damage in form of cracks in early stage of loading as the mortar breaks at a low level of load compared to brick units. When the masonry is subjected to compression, the bond between the mortar and the units induces a stress state in which the units experience biaxial tension-compression while sandwiched mortar layers undergo triaxial compression as studied by Anthonine (1992). Langenbach (1992) concluded that unlike in reinforced concrete where cracks can signify vulnerability to collapse, the onset of cracking along the mortar joints in masonry is an indication of inelastic response rather than failure.

The strength of an earth material means its ability to resist deformation and fracture by virtue of its properties of cohesion and internal friction. The material properties that enable it to remain in equilibrium when forces are acting to break it has been established by Langenbach (1992) to be its shear strength and tensile strength. According to Horri and Nasser (1986), inelastic deformation in brittle materials may lead to the following failure modes depending on the magnitude of confining pressure: (1) axial splitting of the sample by microscopic cracks extending in the direction of axial compression, in the absence of any lateral confining pressure; (2) faulting, when axial compression is accompanied by moderate confining pressure; and (3) ductile flow in the presence of a suitably large confining pressure. When unconfined masonry is subjected to compression loading, it may fail under the first two modes when stress exceeds the yield point of the material.

In ductile materials, yielding occurs as a result of shear stress phenomenon which is due to sliding of atoms (movement of dislocations). Thus, the stress or energy required for yielding is much less than that required for separating the atomic planes. Hence in a ductile material the maximum shear stress causes yielding of the material. In pure tension or compression, the maximum shear stresses have been found by Silva (2006) to occur on 45-degrees planes. Therefore, based on the material constitutive laws, the theories of predicting failure for ductile materials are maximum shear stress theory and maximum distortion energy theory. The maximum shear stress theory postulates that failure will occur if the magnitude of the maximum shear stress in the part of the material exceeds the shear strength of the material determined from uniaxial testing (Silva, 2006).

In brittle materials, the failure or rapture also occurs due to separation of atomic planes. However, the high-energy values of stress required is provided locally by stress concentration caused by small pre-existing cracks in the material. Therefore, the applied stress is amplified by enormous amount due to the presence of cracks and it is sufficient to separate the atoms. When this process becomes unstable, the material separates over a large area causing brittle failure of the material. Therefore, the material failure theory best suited in predicting the failure of brittle materials has been found by Silva (2006) to be the maximum principal stress theory.

Interlocking blocks manufactured from soil can be categorised as brittle materials. The blocks fail by fracture due to development of certain displacement discontinuity surfaces within the solid. Therefore, in determination of their multi-axial states of stress under loading the maximum principal stress theory (Rankine) is adopted. According to the Rankine theory, a brittle material ruptures when the maximum principal stress in the specimen exceeds the yield stress of the material.

2.11 Social acceptability of interlocking stabilized soil block technology

There is growing concern about the potentially negative consequences of housing development. This has been caused by extraction of raw materials from finite sources which are highly depleted. The processing of construction materials utilizes high energy with high emission of greenhouse gases. Moreover, waste disposal from housing development leaves a big carbon footprint to environment. This therefore calls for selection of building materials that are both economically viable and sustainable. In this sense sustainability means more than just development activities that are environmentally sensitive, to imply that the development would lead to improvements that will persist and spread beyond the project boundary and time span and not create dependency.

The choice of building materials is determined by circumstances such as the availability of raw materials, the culture of making building materials, the construction methods, the economic power of developers and the willingness of entrepreneurs to use the material. To meet the need for adequate housing in Kenya's population, Oyawa (2009) proposes that sustainable investments and continued innovations have to be made on technologies that not only lower the cost of construction but also to the environment.

2.12 Summary of literature review and research gap

Technological development on stabilization of soil for construction has led to low cost building material as compared to burnt bricks. Interlocking stabilized soil blocks have been found adequate in constructing buildings. The interlocking mechanism enables them to be stacked without use of cement mortar further reducing the cost of construction. Despite its benefits, the ISSB technology has not been widely utilized in the construction industry. Among the challenges to its applicability is the partial information on its performance under built up conditions.

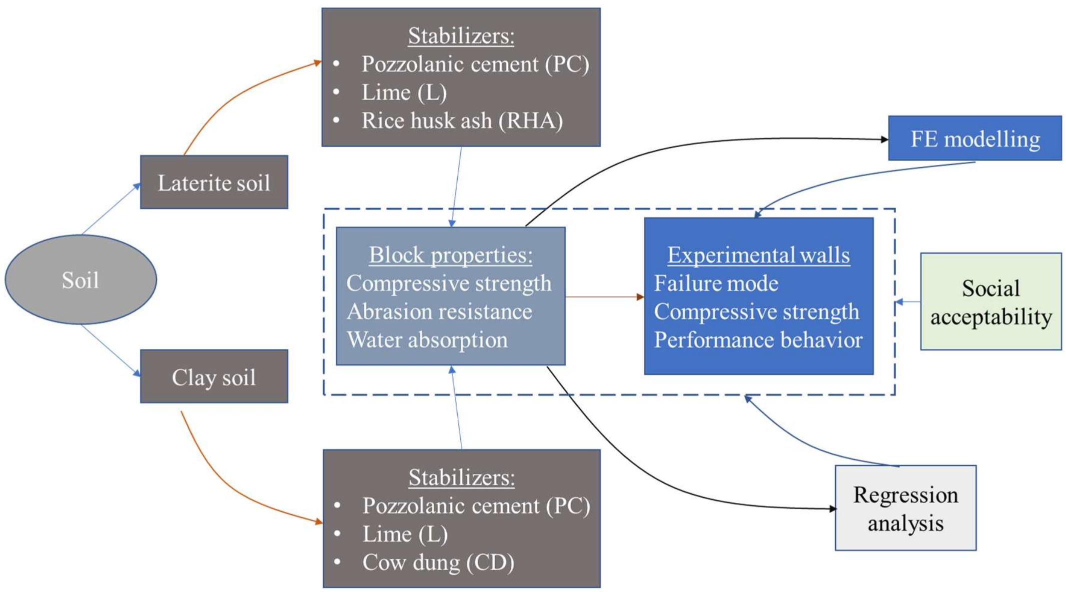
The kind of stabilizer utilized has been based on the type of soil with cement mostly been used to stabilize granular soils while lime clayey soils. Research indicate that cement causes increase in strength and lime inhibits ingress of water into the soil matrix. Lime helps to reduce expansion of clay lattice by lowering its liquid limit and plasticity index. Surface erosion has been identified as major problem of ISSB. Therefore, their durability performance should be satisfactory for general construction. However, little has been done to study the complementary advantages of blended stabilizers and simulation of wall behaviour once constructed.

The reviewed literature indicate that performance of walls made of interlocking soil blocks is mainly influenced by strength and deformation characteristics of the individual blocks. Attempts have been to study its behaviour under in-plane loading only without considering the out-of-plane loading. In order to estimate the compressive strength of masonry walls, empirical formulae have been suggested in masonry codes of design. Unfortunately, the formulae consider mortar bonded bricks and they do not explicitly address interlocking block walls.

Finite element modelling gives the opportunity to study the wall specimens and evaluate the contribution of individual parameters on the performance of the walls. Based on the literature findings this approach has not been fully considered in providing a detailed understanding of the performance of ISSB wall technology. Therefore, numerical modelling with use of material constitutive laws for stress distribution would be useful in design of ISSB walls.

This study sought to determine the failure mode of interlocking soil blocks walls subjected to combined vertical (in-plane) and horizonal (out-of-plane) loading. This represents the typical case of loading on built structures. Since durability of soil blocks affects their performance, the study examines the behaviour of the ISSB when exposed to loading, abrasion and wet conditions. This will enable to specify the appropriate areas where the technology can be utilized in order to achieve its full benefit. Finite element modelling is also carried out to aid in understanding the performance behaviour of the wall and through multiple regression analysis, empirical formulae are proposed to predict the compressive strength of the walls. The study also established the social acceptability of this technology in Kenya's construction industry. A clarification of the attractive attributes and on-site performance of this technology will aid in facilitating its acceptability.

2.13. Conceptual framework



CHAPTER THREE
MATERIALS AND METHODS

3.1 Materials

Laterite and clay soil samples used for this study were collected from Kigwi and Juja sites in Kiambu county which lies within the geographical coordinates of 1.1748°S, 36.8034°E. The soil was obtained at a depth of 1m below the earth surface in order to avoid the inclusion of organic materials. To limit the size of gravel and remove other large particles, the soil was passed through a sieve with 6 mm openings. Particle size distribution analysis was performed for the two soil samples. The soil samples (three kilograms per sample) were dried at 105±5°C and allowed to stand in a kiln overnight as described in BS 1377:2 (1990). This helped to destroy any organic matter present in the soil and drive out any moisture present enabling the soil to attain its dry mass. The samples were then cooled at room temperature before sieving.

Cow dung was collected from Jomo Kenyatta University of Agriculture and Technology cow sheds since it was near the laboratory site. The dung was collected either when it had just been dropped from the animals or one which was not older than 5 days. The cow dung was mainly collected in the morning hours before the cows were let out for grazing. The fresh cow dung collected was wrapped in plastic bags to ensure that the moisture content was maintained.

Rice husk ash (RHA) was sourced from un-controlled burning source at Mwea rice irrigation scheme, Kenya. The rice husk ash was sieved through 150 µm sieve before using as a stabilizer.

Portland pozzolanic cement 32.5N sourced from a hardware in Kiambu County and commercial hydrated lime, Rhino lime, produced by Athi River Mining Company were used to stabilize the soil. The chemical composition of the hydrated lime (Table 3.1) was obtained from the mining company.

3.2 Characterization of the soil

The transition behaviour from solid to liquid state of the soils was determined by evaluating their liquid-limits, plastic limits, linear shrinkage and plasticity index. The indices that allowed classification of the soils were determined following BS 1377:2

(1990) provisions. The liquid limit of the soil was determined using the cone penetrometer method while the plastic and shrinkage limits were determined by the standard procedure provided in BS 1377:2 (1990).

Table 0.1: Chemical analysis of Rhino Lime

Compounds	Rhino Lime
Available lime as calcium hydroxide ($Ca(OH)_2$)	94%
Available lime as calcium oxide (CaO)	72%
Al_2O_3	0.12%
Fe_2O_3	0.09%
SiO_2	0.10%
MgO	0.90%

(Sourc*e: Athi River Mining Company)*

3.3 Preparation of stabilized soil and moulding of interlocking blocks

The soil was sieved through a 10 mm sieve for use in block making while disposing what was retained on the sieve. The respective quantities of laterite soil, clay soil, pozzolanic cement, lime, RHA and cow dung were proportioned and batched by weight at determined ratios of their dry weight. The percentage replacement ratios on the soil using the different stabilizers are shown in Table 3.2.

The proportioned dry mix was spread in a mixing trough and water was sprinkled to obtain soil paste. To test whether the water added to the mix had achieved the right consistency, the soil paste was pressed in the hand and dropped on a hard surface. When the soil lump broke into four to six pieces, it was assumed to have achieved the required optimum moisture content. The soil mixture was then manually mixed by turning from one side to the other for five times to achieve proper mixed soil paste.

The interlocking blocks were moulded using the CINVA-Ram press machine, producing units having dimensions 220 mm (length) x 220 mm (width) x 120 mm (height). The soil paste was manually pressed to become solid and rigid with an interlocking shape. The freshly moulded blocks were extruded from the press machine and placed under a shade for curing. The blocks stabilized with cow dung were cured by covering them with plastic sheets. The blocks properties were then tested after curing for 7, 14 and 28 days.

Table 0.2: Mix ratio replacement of stabilizers in the soils

Soil type	Stabilizer	Replacement %				Code
		Cement	Lime	Cow dung	RHA	
Laterite	Cement	4.8	0	0	0	4.8%C
		5	0	0	0	5%C
		5.2	0	0	0	5.2%C
		6	0	0	0	6%C
Laterite	Cement + Lime	6	5	0	0	6%C 5%L
		6	4	0	0	6%C 4%L
		6	3	0	0	6%C 3%L
		6	2	0	0	6%C 2%L
		6	1	0	0	6%C 1%L
Laterite	Cement + RHA	6	0	0	4	6%C 4%RHA
		6	0	0	3	6%C 3%RHA
		6	0	0	2	6%C 2%RHA
		6	0	0	1	6%C 1%RHA
		0	0	0	5	5%RHA
Clay soil	Cement	5	0	0		5%C
	Lime	0	5	0		5%L
	Cement + Lime	5	1	0		5%C 1%L
		5	2	0		5%C 2%L
		5	3	0		5%C 3%L
		5	4	0		5%C 4%L
Clay soil	Cow dung	0	0	20		20%CD
		0	0	15		15%CD
		0	0	10		10%CD
		0	0	5		5%CD

3.4 Compressive strength test of the blocks

A random sample of three blocks was used to determine the dry compressive strength in accordance to BS EN 772-1 (2003). The blocks were weighed and dimensions measured. The blocks were then wiped out of any debris and placed between the platens in the universal testing machine (UTM) such that the centre of the block coincided with the loading axle of the machine. A linear displacement transducer was attached at the base plate of the UTM and connected to a data logger to record the compressive displacement (Figure 3.1). The blocks were loaded manually until failure occurred and the failure mode was observed. The compressive strength of each block was obtained from its failure load and averaged bed face area.

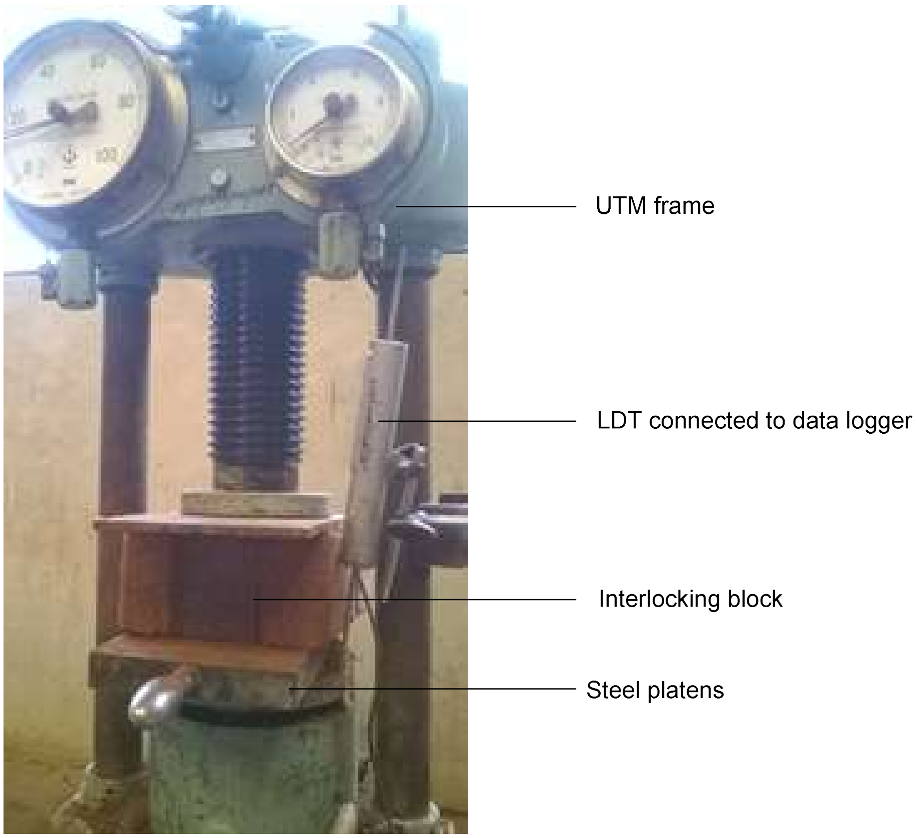


Figure 0.1: Loading arrangement for compression testing of blocks

3.5 Durability of the stabilized interlocking blocks

The durability and physical characteristics of the blocks were determined by abrasion test and water absorption respectively. The water uptake ability of the blocks was determined in accordance to KS 02-1070 (1993). Initially the blocks were cured for 28 days and water uptake was tested on submerged blocks allowed to stand for 24 hours.

The abrasion test was carried out by use of a horizontal belt sander model HYS-900 having a frequency of 60 rpm. The sander utilised a sand paper belt type GXK50-P60 with a width of 180 mm. The blocks were subjected against the belt for a duration of one minute before determining their final weight.

3.6 Testing of interlocking masonry wall subjected to in-plane and out-of-plane loading

Six types of wall panels (two specimens of each), Laterite soil wall 1 (LSW1), Laterite soil wall 2 (LWS2), Laterite soil wall 3 (LWS3), Clay soil wall 4 (CSW4), Clay soil wall 5 (CSW5) and Clay soil wall 6 (CSW6) of size 900 mm (length) x 1200 mm (height) were prepared in accordance to BS 1052-1 (1999). The length to thickness (l/t) and the height to thickness (h/t) ratios were 5.45 and 4.09 respectively for all wall panels. The blocks were stacked utilising the interlocking system provided by the blocks. The walls were constructed on a concrete floor forming a pinned connection at the base. A grooved steel plate was placed at the top course of the wall to cover the projection and uniformly distribute the load. Testing of the walls was done following the set up shown in Figure 3.2. The compressive strength was tested perpendicular to the bed joints without the effects of eccentricity. Vertical load displacement was determined at mid length while lateral displacement was determined at three points equally spaced at 325 mm (Figure 3.2) using linear variable displacement transducers (LVDT). Strain gauges were positioned at the bed and head joints to measure the strains induced at these weak points. The cracking pattern was studied by pictures recorded during the loading procedure.

The testing procedure was divided into two phases; first the vertical load was applied up to about 75% of the ultimate load before the horizontal load was introduced. These loads were applied simultaneously until failure. The choice of the testing procedure was based on previous studies due to lack of specific norms. The stress-strain curves of the wall panels were obtained by plotting the strength values up to the failure point of the wall. The compressive strength of the wall panel was calculated by considering a net contact area of 45% of the gross area as recommended by BS 5628:1 (2002). The Young's modulus of the wall was determined from the initial linear part of the stress-strain plot.

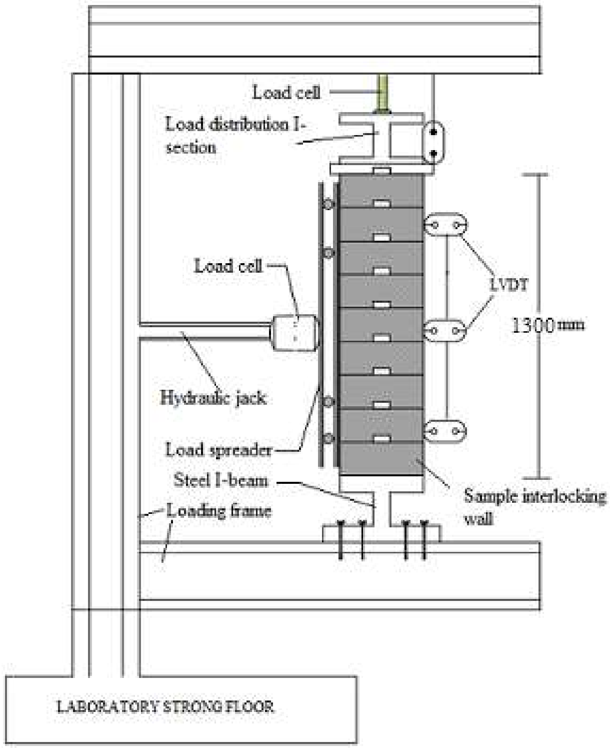


Figure 0.2: Experimental test set up for masonry wall testing

3.7 Regression analysis of compressive strength of masonry wall

Regression analysis was carried out using Statistical Package for the Social Sciences (SPSS) version 20. Multiple regression gave the opportunity to establish interdependence of variables. In this case the independent variables included block compressive strength, type of stabilizer and stabilizer content while the dependent variable was the wall compressive strength. The analysis considered a relationship between the compressive strength of the wall to that of the individual blocks as contributed by the type and amount of stabilizer content. The results obtained for 28-day compressive strength of individual blocks were used to derive a prediction relation between the blocks properties and the strength of the wall panels.

3.8 Finite element modelling of interlocking soil block masonry wall

A numerical simulation of the structural response of the wall to compressive and horizontal loading was performed using Abaqus CAE 6.14-1 version. The wall components were discretized using a three-dimensional deformable solid of 8-nodded element (C3D8R) as a homogeneous continuum without intermediate layers. A standard

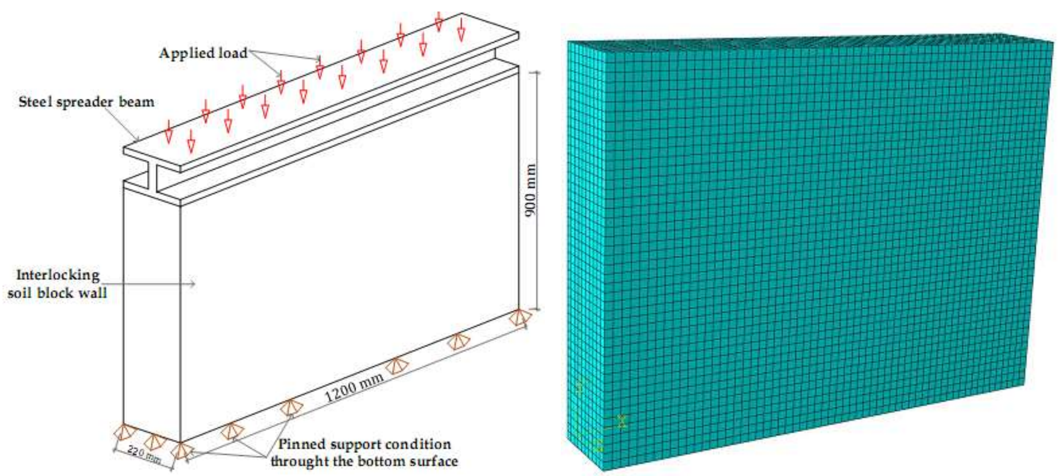
8-node plane hexahedral element with reduced integration was chosen based on the macro-model approach. The geometry of the assembled parts was defined by creating independent instances for analysis. For this purpose, linear static analysis procedure was used. A second-order element consisting of a global seed size of 20 was considered. The mesh size was selected based on the model size limits of the Abaqus Standard/Explicit product. The wall models were 1200 mm long and 900 mm high. The model assumed no imperfections at the point of loading.

The combination of mortar and stone in conventional masonry results to a material with anisotropic characteristics in elastic-plastic condition. However, the consideration of interlocking soil block as a homogenous one material eliminating the block-to-mortar interaction makes its deformation unvarying under loaded state. Tarque, Spacone, Blondet and Varum (2012) further argue that adobe masonry behaves well under compression but can only resist low tensile stresses with quite brittle post-peak tensile behaviour. They noted that since adobe bricks and the mortar are composed of mud, both can be assumed as a homogeneous material. This study utilised dry stacked interlocking soil blocks without mortar. Therefore, the ISSB walls were modelled using elastic-plastic constitutive material model, implementable in the Abaqus program. Consequently, the model was based on anisotropic plasticity theory using the standard Rankine yield surface with assorted plastic flow since the masonry was considered brittle. The basic properties for ISSB masonry (compressive strength, modulus of elasticity, density and Poisson's ratio) defined in the FE model were in line with the results of laboratory tests (Table 3.3). The density of interlocking blocks was measured gravimetrically, while the Poisson ratio (υ=0.35) was deduced from recorded values of axial and transversal strains. The blocks Young's modulus was derived from the stress-strain curves of the 28-day compression experimental test. The value was set to be approximately equal to the slope of the stress-strain curve. Figures 3.3 (a) and (b) show the model wall set up and the generated mesh of the modelled wall.

The steel I-sections acting as the load spreader beam was modelled as a linear elastic material with its mechanical properties being obtained from documented literature as: density (ρ) 785 N/m^3, Poisson ratio (υ) 0.30, and Young's modulus (E) 205 GPa. Since the walls were constructed on a concrete floor, the bottom course of the wall was considered simply supported along the entire surface. The bottom course was therefore modelled with pinned boundary condition constraining the three structural degrees of freedom at the connection (Figure 3.3a). The maximum compressive strength sustained by the experimental walls was assigned to the upper steel plate as uniformly distributed load.

Table 0.3: Interlocking soil block properties

Wall type	Block density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Max. wall compressive strength (MPa)
LSW1	1878.33	3850.27	0.35	0.90
LSW2	1981.32	4795.77	0.35	1.08
LSW3	1900.40	4476.67	0.35	1.14
CSW4	583.48	1716.03	0.35	0.37
CSW5	1947.23	1520.88	0.35	0.51
CSW6	1543.89	1380.38	0.35	0.31
Steel I-beam	7850	205000	0.3	-



(a) Model wall set up (b) Generated mesh on modelled wall

Figure 0.3: Schematic of the modelled wall

3.9 Social acceptability of interlocking soil block technology

To assess the social acceptability of ISSB technology in Kenya, a survey design was adopted in order to have an in-depth discussion and capture the respondent's reflection, knowledge and experience with the ISSB technology. To attain this objective, the research adopted a qualitative research strategy. The qualitative strategy facilitated cross verification and extension of quantitative data collected through laboratory experiments.

3.9.1. Sampling techniques

Onwuebuzie and Collins (2007) suggested that in qualitative research the sample size should not be too small as to make it difficult to achieve data saturation, while at the same time should not be so large that it is difficult to undertake deep case-oriented analysis. The study therefore targeted 32 respondents. Sixteen technology users (identified as TU1 to TU16) were purposively selected from the recorded users of ISSB technology in Kenya by the Ministry of transport, infrastructure, housing and urban development (2018). The selection criteria considered location (whether rural or urban) and availability of conventional wall materials. Sixteen non-technology users (NTU1 to NTU16) were sampled using the snowballing technique (Bryman, 2012) considering the referrals from the technology users and their proximity to the constructed wall structures. Since the purpose of the study was to extend the laboratory findings, the number of interviewees was majorly guided by the point of data collection when no new or relevant information emerged from the interviewees (saturation point).

3.9.2. Data collection procedure and analysis

The study involved use of semi-structured interviews with the respondents. The study was undertaken in Nairobi, Mombasa, Kiambu and Taita-Taveta counties. Two groups of respondents were considered: (1) Technology users (TU); and (2) Non-technology users (NTU). Technology users are those who have carried out construction using the ISSB technology while the Non-technology users have seen it being used on different projects but have had no opportunity to use it. The two target groups enabled a comparative approach in the study. Semi-structured interviews were preferred since they provided flexibility to modify the questions to the two target groups while still covering the same areas of data collection. The interview schedules included a set of open-ended questions to define the areas to be explored. All interviews were face-to-face with participants. Before the interview, the respondents were informed about the study details and assured of their anonymity. The participant’s consent to participate in the study was sought using a consent form (Appendix D). The interviews were audio-recorded and field notes made in order to re-transcribe the oral interviews. On overage, an interview session took 30 minutes to 45 minutes per respondent. The collected data was analysed by use of thematic analysis.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1. Material properties of laterite and clay soils

4.1.1. Particle size distribution of laterite and clay soils

The cumulative percentages of masses passing the sieves were plotted against the particle size ranges on a logarithmic scale (Figure 4.1). The laterite soil consisted of 25% fine gravel and 75% sand. The clay soil had a coefficient of uniformity of 5.0 and a coefficient of curvature of 12. The clay soil was well graded. The laterite soil, classified according to the unified soil classification system as having a texture of sandy loam. The comparison of the particle size distribution of the soils (Figure 4.1) indicated that the laterite soil has coarse-grained sand particles while the clay soil has proportions of silt particles.

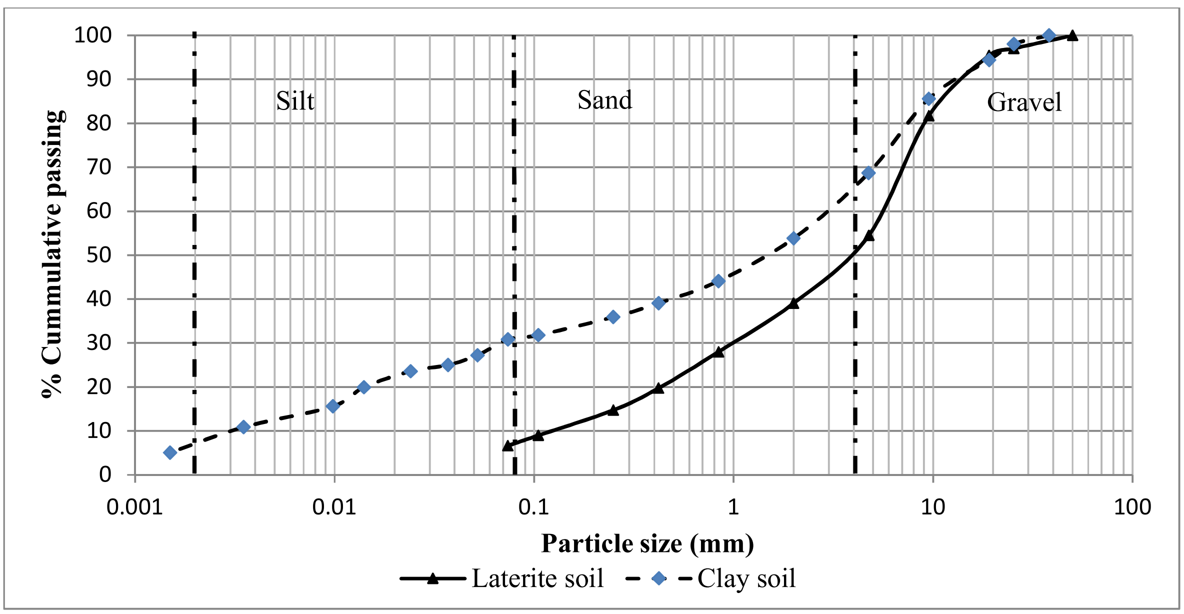


Figure 0.1: Comparison of particle size distribution of laterite and clay soil

4.1.2. Atterberg limits

The laterite soil plasticity index (12.09%) lies in the range (5 – 15%) proposed by Walker (1995) for soils which can be effectively stabilized using cement (Table 4.1). The plasticity index versus liquid limit comparison in a Casagrande Plasticity index chart indicates that laterite soil is inorganic with a low compressibility while clay soil is dense and has medium compressibility. This shows that clay soil can withstand greater applied load than laterite soil in its un-stabilized state.

Table 0.1: Atterberg limit properties for un-stabilized and stabilized laterite and clay soil

Specimen	Type of test Liquid limit (LL) (%)	Plastic limit (PL) (%)	Plasticity index (PI) (%)	Linear shrinkage (LS) (%)
Laterite soil	29	16.91	12.09	7.47
Laterite soil + 6%C	39.1	31.3	7.8	5.5
Laterite soil + 6%C+1%L	38.4	27.13	11.27	5.97
Laterite soil + 6%C+2%L	36.4	non-plastic	-	4.4
Laterite soil + 6%C+3%L	37.2	non-plastic	-	5.79
Laterite soil + 6%C+4%L	38.1	non-plastic	-	4.9
Clay soil	44.5	25.21	19.29	12.53
Clay soil + 6%C1%L	39.5	30.64	8.86	7.59
Clay soil + 6%C2%L	50	non-plastic	-	6.73
Clay soil + 6%C3%L	53.5	non-plastic	-	7.93
Clay soil + 6%C4%L	52.75	non-plastic	-	7.36
Clay soil + 6%C5%L	50.6	non-plastic	-	5.22

Clay soil has a higher liquid limit than laterite soil (34.8% higher), indicating high clay content thereby easily converted into liquid state than laterite soil. The coarse-grained laterite soil therefore has good drainage characteristics than clay soil which will require considerable treatment before being used in a moist location.

The addition of lime to cement stabilized laterite soil resulted in a modification in the Atterberg limits of the soil. At 6% cement and 0% lime stabilization, there was an increase in liquid limit of the stabilized laterite soil, followed by a decrease in liquid limit on further addition of lime. The liquid limit reduced to 36.4% for 2% lime addition, which then increased to 38.1% for 4% lime addition. According to Sivapullaiah and Jha (2014), a reduction in liquid limit on addition of lime to fly ash stabilized soil occurs due to replacement of sodium ions with calcium ions, reduction in diffused double layer, and increase in electrolyte concentration of pore fluid. The findings of this study were consistent with their observation indicting a similar effect of lime on cement stabilized soil. The results show that the addition of lime beyond 2% to 6% cement stabilized clay soil increased the liquid limit and made the soil non-plastic.

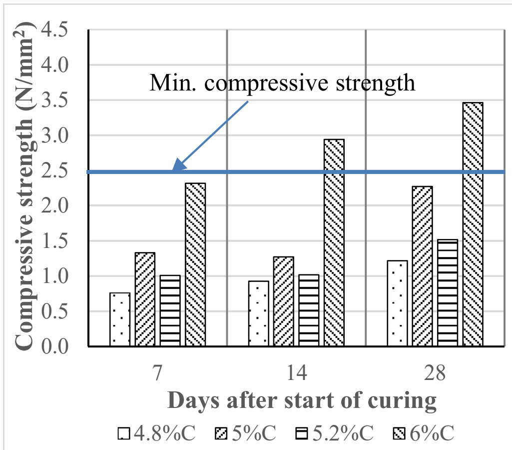
4.2. Behaviour of stabilized interlocking soil blocks when subjected to loading, abrasion and wet conditions

4.2.1. Compressive strength of interlocking stabilized laterite soil blocks

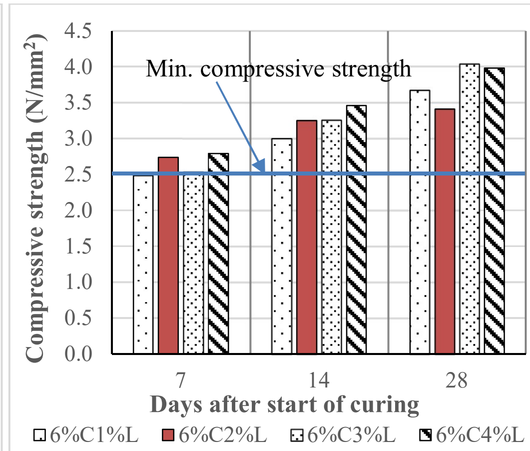
The stabilization of laterite soil with pozzolanic cement at percentage ratios of 4.8, 5, 5.2 and 6%, indicated a gain in compressive strength cumulatively with days (Figure 4.2a). However, this phenomenon was highest achieved with 6% cement replacement (compressive strength 3.46 N/mm^2 on 28-day). It was observed that blocks stabilised with 6% cement were 67.24% stronger than those stabilized with 4.8% cement on day 7 of curing (Figure 4.2). The 28-day compressive strength of 6%C blocks was higher than the minimum set value of 2.5 N/mm^2 according to KS 02-1070 (1993). Generally, the blocks compressive strength increased with pozzolanic cement dosage. Bhattacharja and Bhatty (2003) established that with the presence of Portland cement in soil, calcium ions are easily provided that aid in improving the soil engineering properties. Therefore, the increase in compressive strength with pozzolanic cement dosage can be explained by the fact that the higher cement content greatly enhanced the hydration process due to high amounts of calcium ions introduced.

The correlation coefficients obtained for percentage of pozzolanic cement stabilization and gain of compressive strength of the blocks were 0.940, 0.952 and 0.891 on 7, 14 and 28-day, respectively. A fairly strong positive correlation coefficient was established on 7 and 14 days which decreased with progression of days. This indicates that pozzolanic cements' contribution to block compressive strength is higher on early days of curing and reduces with progression of days. These results agreed to the findings of Paige (2008).

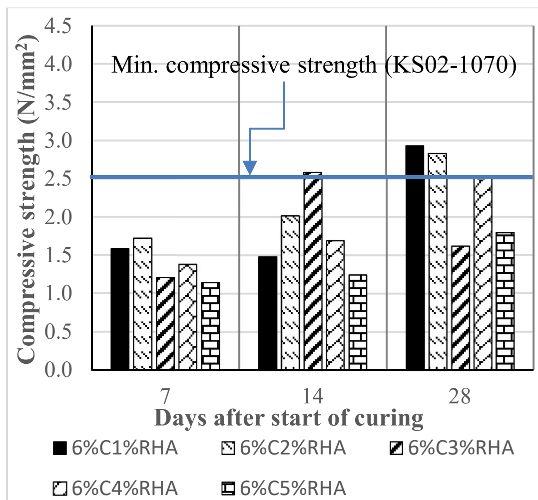
A highest 28-day compressive strength of 4.03 N/mm^2 was reached on adding 3% of hydrated lime in presence of 6% pozzolanic cement. The addition of 3% lime caused a 42.43% increase on 28-day compressive strength as compared to a 32.95% increase in



(a) Laterite soil + cement



(b) Laterite soil + cement + lime



(c) Laterite soil + cement + RHA

Figure 0.2: Laterite soil stabilized block compressive strength

absence of lime. For blocks produced with lime quantities lower than 3% they had relatively low compressive strength. It is reported by Bell (1996) that when lime is added to clay soil it is first absorbed by the clay mineral until lime affinity for the soil is achieved. He argued that this amount of lime is between 1% and 3% by weight of the soil. Therefore, lower dosages of lime may not be sufficient to increase the pH of the soil matrix to release silica and make it available for producing cementitious gel needed to stabilise the soil. This could probably be the reason for marginally lower compressive strength of blocks stabilizer with 1% and 2% lime blended with 6% cement (Figure 4.2b).

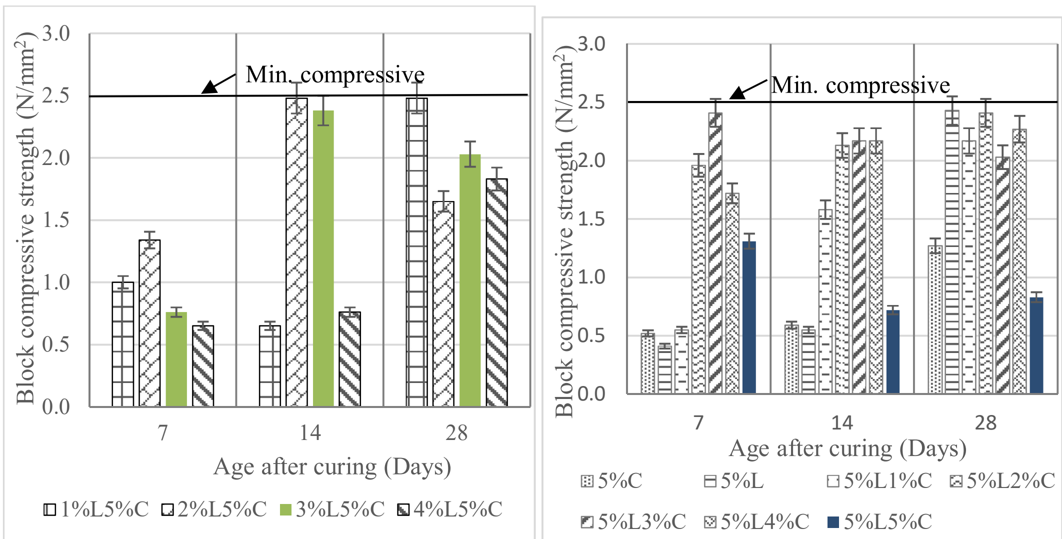
Figure 4.2(c) shows that the addition of 1% RHA to a given 6% of cement, led to the highest 28-day compressive strength (2.93 N/mm^2). It was also observed that there is decrease in compressive strength with increase in RHA. However, in comparison to the effect of adding 1% lime to 6% cement, the lime-cement blocks had a 28-day compressive strength 20.16% higher than adding 1% RHA. It can be inferred from the results that lime-cement-laterite soil mixture leads to blocks of higher compressive strength as compared to cement-RHA-laterite soil. The reason can be attributed to the insufficient availability of free lime for pozzolanic reaction in the cement-RHA-laterite mixture. Also, the presence of excess RHA cannot be easily mobilized for pozzolanic reaction which consequently occupies space within the soil thus reducing the strength. This was consistent with the findings of Jha and Kulbir (2006).

4.2.2. Compressive strength of stabilized clay soil blocks

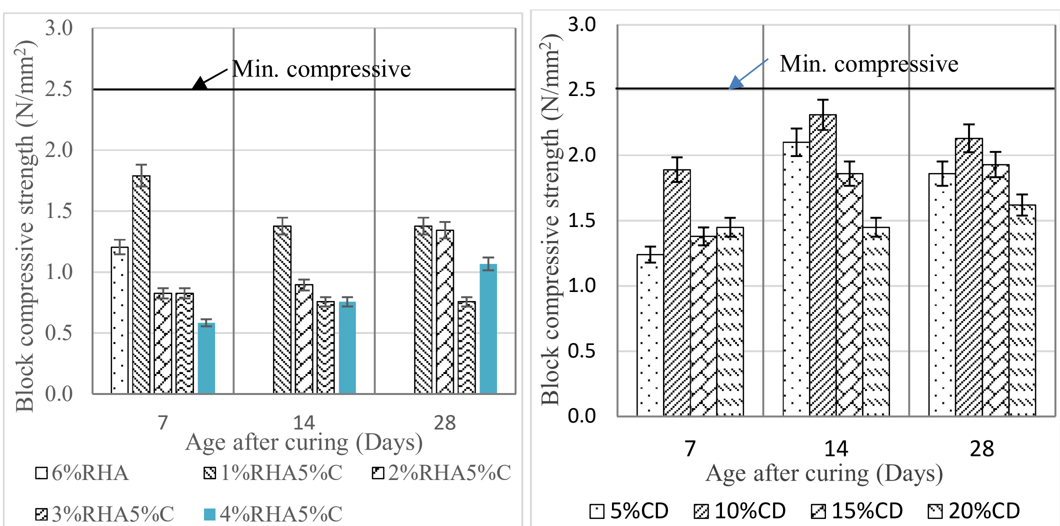
The dry compressive strength of clay soil blocks was also tested on considering varying stabilization dosages of lime at a constant dosage of cement (5%) and vice versa respectively. It was observed that clay soil blocks stabilized with 5%L1%C were still very wet on 7-day of curing. However, on increasing the cement content the blocks were found much drier on the 7th day. It was also observed that blocks with lower percentage of pozzolanic cement had less than 50% drying cracks developed on the surface as compared to those with higher cement content. On average stabilized clay soil blocks with 5% lime had higher gain in compressive strength over the period of curing. This observation was consistent with findings of Muhmed and Wanatowski (2013) who in their investigation found that stabilizing active clay soils with lime reduced their plasticity index and increased the liquid limit and plastic limit.

On 7-day of curing, clay soil blocks stabilized with a constant amount of 5% lime and cement added incrementally had higher compressive strength as compared to those which had lime added incrementally (Figure 4.3(a) and (b)). The results indicate that there is a steady increase of compressive strength on adding cement up to a defined point followed by decrease of strength on addition of cement beyond the optimum level.

Clay soil blocks stabilized with 5%L had a higher increase in compressive strength (77.34%) as compared to 5%C stabilized clay soil blocks (53.54%) from 14 to 28-day of curing. The highest 28-day dry compressive strength (2.48 N/mm^2) was achieved on stabilizing clay soil with 1%L5%C (Figure 4.3(a)).



(a) Clay soil + cement + varying lime (b) Clay soil + varying cement + lime



(c) Clay soil + cement + RHA (d) Clay soil + Cow dung

Figure 0.3: Clay soil stabilized block compressive strength

It is clear from these results that lime stabilization causes a delayed gain of strength in soils having higher clay content as compared to pozzolanic cement. This phenomenon can be attributed to pozzolanic cement hydration which produces a cementing colloidal gel that binds the clay, silt and sand particles causing them to set and harden over a short time (Bhattacharja and Bhatty, 2003). This process initiates a pozzolanic reaction between calcium oxide (CaO) liberated during the hydration of cement and the clay. However due to high amounts of clay particles present in clay soil, they tend to form a continuous matrix through the soil causing swelling and shrinkage. It is worth noting therefore, higher pozzolanic cement content does not necessarily make blocks with higher clay particles to have higher compressive strengths on early curing days.

The addition of lime aids the pozzolanic reaction which was initiated by addition of cement. Lime is not a cementitious material but it has an additional effect in soil known as cation exchange (the exchange of the metallic ions on the surface of clay particles which control the water absorption). This has effect in reducing the expansibility of the soil caused by the cement and makes it suitable for compaction thereby aiding in gain of compressive strength. The pozzolanic reaction is slow, that's why the gain of compressive strength of blocks was more evident from 14 to 28-day as opposed to that achieved 7-day of curing.

The relationship of RHA quantity with compressive strength indicated a varied discernible trend. On 7-day of curing, blocks with lower percentage of RHA sustained higher compressive strength which decreased with curing time (Figure 4.3c). Comparably, RHA stabilization of clay soil resulted to low 28-day compressive strength compared to lime stabilization. Thus, replacement of lime with RHA in clay soil only resulted to soil modification rather than stabilization since the compressive strengths are very low as recommended by KS 02-1070 (1993).

The 28-day compressive strength of 10%CD blocks expressed the highest strength (2.13 N/mm^2), though it was lower than recommended value of 2.5 N/mm^2 (Figure 4.3d). The blocks exhibited increase in strength from 7 to 14-day, which later slowed down beyond 14-day. The compression deflection for clay soil blocks stabilized with cow dung increased with higher levels of cow dung content. There was a 22.5% increase of compression deflection on increasing the cow dung percentage from 5 to 20%. In compression strength testing, the blocks behaved like a sponge and they took a longer time to fail. This could be attributed to the physico-mechanical properties of the cow dung which makes the soil to have voids leading to high accommodation of compression deflection. It was further observed that the cow dung stabilized blocks which were cured by plastic sheeting developed efflorescence. The degree of efflorescence increased with increase in cow dung content in the blocks. As the cow dung stabilized blocks dried, they attracted termites that bore holes on the surfaces.

4.2.3. Interlocking block failure mechanism

The failure pattern for laterite soil blocks stabilized with cement and lime failed in shear that resulted to spalling of materials (Table 4.2). The blocks suffered considerable inelastic deformations but sustained their ability to withstand compressive loading.

Table 0.2: Failure patterns of interlocking stabilized blocks

Block sample	Observed mode of failure	Failure pattern
Laterite soil stabilized with cement and lime		Conical failure pattern
Laterite soil stabilized with cement only		Pyramidal pattern of failure
Clay soil stabilized with lime and cement		Split failure
Clay soil stabilized with cow dung		Compressional crushing of the material without spalling

The mode of failure for cow dung stabilized clay soil blocks was characterized by gradual formation of a mixture of vertical and diagonal cracks as described in ASTM C1314-03b (2012). The cow dung stabilized blocks behaved plastically during failure with compression being the dominant failure mode. This particular behaviour could be attributed to addition of fibrous materials in the soil paste. This can be further justified by the observation that on completion of compression test, the block material had not fully disintegrated. This failure criteria made the blocks to have a higher compression strain as compared to those stabilized with cement and lime.

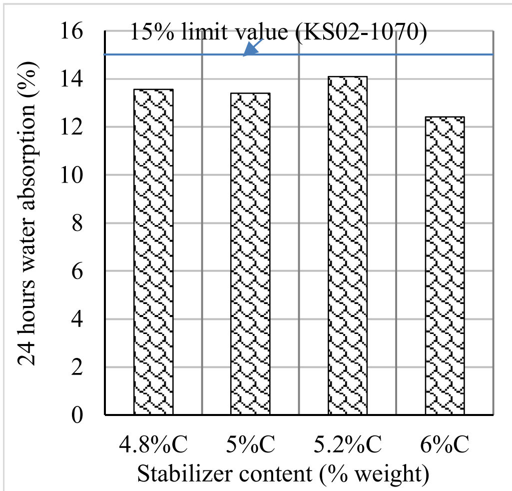
4.2.4. Water absorption by interlocking laterite blocks

Generally, the total water absorption by laterite soil blocks indicated that increase of pozzolanic cement dosage led to reduction of water absorption, though minimally (Figure 4.4a). Increasing pozzolanic cement content from 4.8 to 6% in laterite soil resulted in 8.48% reduction in water absorption by the blocks (Figure 4.4a). These results were expected because cement binds the laterite particles together thereby reducing the size of the pores through which water could flow into the blocks.

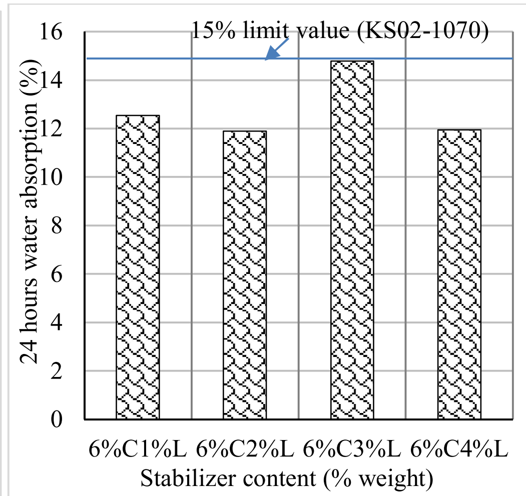
The increase in hydrated lime in presence of 6% cement led to decrease in water absorption (Figure 4.4b). It has been found by Manasseh and Joseph (2015) that when hydrated lime is used in soil modification, the calcium ions from the hydrated lime migrate to the surface of the clay particles and displace water and other ions. This has an effect of drying the soil through flocculation of the particles. The results show that adding 2% of lime to laterite soil stabilized with 6% cement resulted to 4.1% reduction of water absorption (Figure 4.4b).

Contrary to water reduction in pozzolanic cement stabilization alone, there was an increase from 8.61 to 11.60% in water absorption on increasing RHA from 1 to 3% (Figure 4.4c). This phenomenon was found by Haji, Adnan and Chew (1992) to be contributed by the weakening of the interparticle bonding that could have formed by the soil particles.

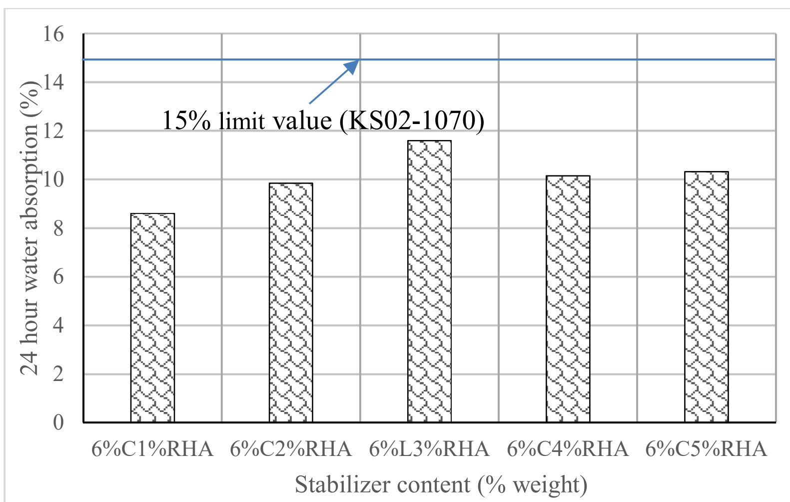
The results evidenced that blocks incorporating RHA have less absorptive capacity as compared to those with lime of the same content in presence of 6% cement. Therefore, replacing hydrated lime with RHA lowers the water absorption of laterite soil blocks. As noted by Walker and Pavia (2010), hydrated lime combines with water more than RHA due to its fine particle size. They argued that the higher affinity of lime is due to its higher surface area and lower superficial tension forces. This agrees well with this research since blocks stabilized with lime had higher absorption than those of RHA (Figure 4.4b). However, the maximum water absorption of 15% recommended by KS 02-1070 (1993) was satisfied by the laterite soil stabilized blocks.



(a) Laterite soil + cement



(b) Laterite soil + cement + lime



(c) Laterite soil + cement + RHA

Figure 0.4: Water absorption by stabilized laterite soil blocks

4.2.5. Water absorption by interlocking clay soil blocks

The water absorption by clay soil blocks increased with cow dung content but reduced on stabilizing with pozzolanic cement and hydrated lime (Figure 4.5). The high absorptivity by cow dung stabilized blocks could be contributed by voids introduced by fibrous nature of cow dung. Fibres increase water absorption as the absorbent nature of fibres creates pathways through soil blocks, thereby allowing more water absorption. A similar observation was made by Kwadwo and Evans (2015) in their investigation on the improvement of earth blocks for low income communities in Ghana. The high permeability makes cow dung stabilized blocks vulnerable to repeated swelling and shrinkage. This is likely to lead to high rate of deterioration of blocks having higher percentages of cow dung content.

A decrease in water absorption by clay blocks was experienced with increase in lime content (Figure 4.5). Addition of 3% lime to clay soil at specified 5% cement reduced the water absorption by the blocks to a lowest value of 12.06%. However, there was an increase beyond 3% lime dosage level. The decrease has been explained by Musa (2008) to be as a result of formulation of cementitious compounds by calcium from lime which fills the soil voids thereby obstructing the flow of water. These findings were also consistent with the findings of Guettala, Houari, Mezghiche and Chebili (2002) who found that increase in lime content from 5 to 12% decreased the water absorption capacity of clay blocks. This therefore indicates that for lime to perform better in clay soil stabilization it should be used together with other stabilizers.

There was no measurement obtained in most of clay blocks stabilized with RHA since they fully disintegrated in water. It was observed that water absorption increased with the percentage of RHA. This may be due to the high porosity introduced in the clay blocks by the soft nature of RHA.

The results indicated that water absorption in clay soil blocks decrease with increased percentages of cement and lime, but it increases with increasing content of cow dung. RHA stabilized soil blocks disintegrate easily in water.

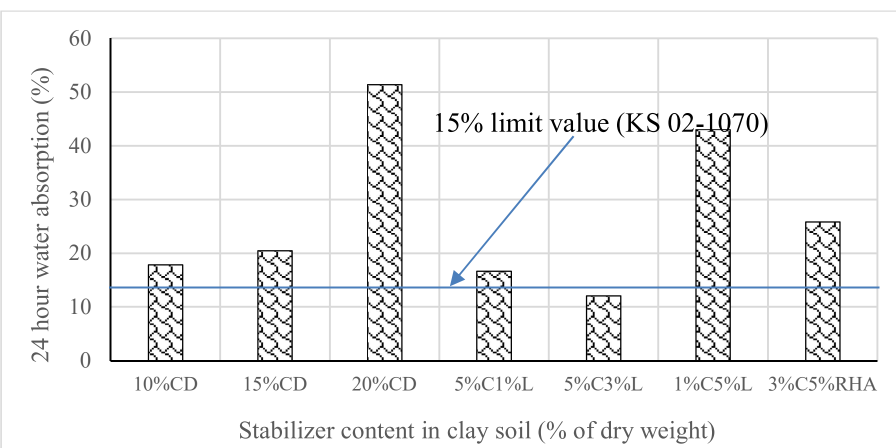


Figure 0.5: Water absorption by stabilized clay soil blocks

The laterite stabilized blocks did not experience deterioration on soaking them in water for 24 hours. Notwithstanding, the clay soil interlocking blocks severely deteriorated in

Table 0.3: Physical properties of 24 hours soaked interlocking blocks

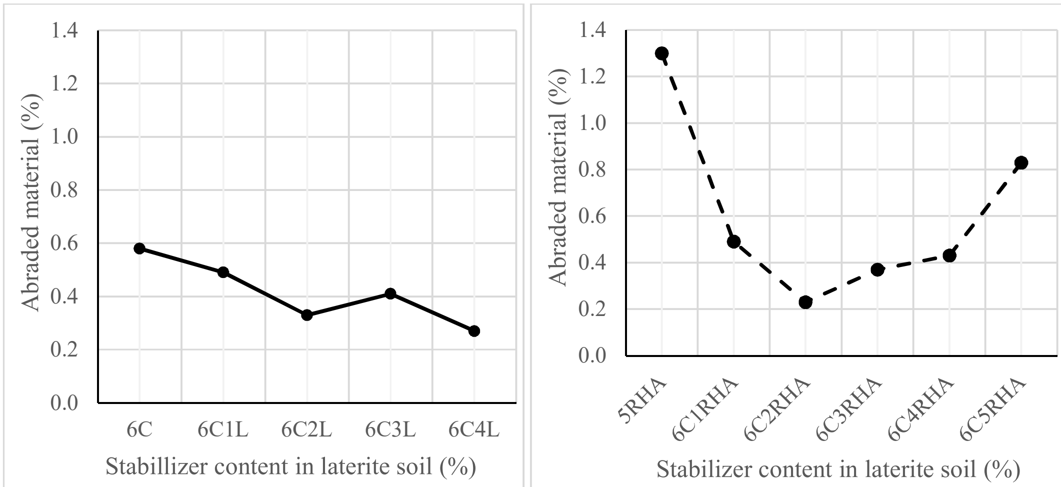
Stabilization mode	**Block apperance**	**Remark**
5.2%C laterite		The blocks maintained their structural integrity
5%C laterite		No disintegration of the blocks
4.8%C laterite		No disintegration of the blocks
5%C clay soil		An irregular shaped block was achieved with pieces spalled off
3%L5%C clay soil		Blocks had cracked severally but could be lifted out of water
4%L5%C clay soil		Block cracked with coners erroded
20%CD clay soil		Blocks bulged but they could be lifted out of water and the coners were not broken
10%CD clay soil		The blocks disintegrated into pieces
1%C5%L clay soil		Blocks disintegrated in water and were disfigured
2%C5%L clay soil		Blocks completely disfigured and disintegrated in water and could not be lifted

water (Table 4.3). It was observed that the 3%L5%C clay soil blocks had cracks on the surfaces but were intact compared to other clay soil blocks stabilized with cement and lime. The blocks with high lime quantity were very severely deteriorated as compared to those which had high quantity of cement. Blocks stabilized with cow dung had mild deterioration with dominant mode of failure being pitting. This phenomenon could be attributed to the fact that cow dung possesses fibrous materials that makes the blocks to be bound together and avoid spalling of materials.

4.2.6. Abrasion resistance of interlocking stabilized soil block surfaces

The total loss of mass due to abrasion at the laterite soil block surface decreased with increase in hydrated lime content (Figure 4.6a). The material erosion varied from 0.58 to 0.27% when hydrated lime content was varied from 0 to 4%. Thus, representing a 53.45% reduction of the abraded material. This demonstrated that abrasion resistance is enhanced with increase in hydrated lime content in laterite soil blocks.

The amount of abraded material decreased with increasing RHA content up to 2% and further addition of RHA caused an increase in the abraded material (Figure 4.6b). It has been reported by Pushpakumara and Subashi (2012) that presence of calcium ions from cement react with silica from RHA to aid in strength development. However, increasing the quantity of RHA decreases the strength due to lack of adequate calcium ions for the continuation of reaction. This explains the observed behaviour of Figure 4.6(b) where the blocks durability was reduced beyond the optimum quantity of 2%RHA. Comparatively, the durability of both hydrated lime and RHA stabilized laterite soil blocks is generally enhanced equally up to 2% replacement (Figure 4.6). However, beyond 2% stabilizer content, durability is better achieved with hydrated lime than RHA stabilization.

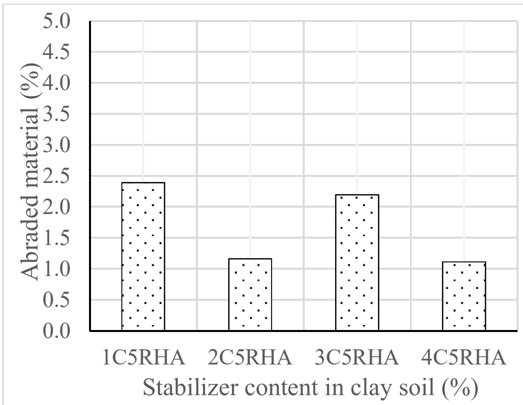


(a) Laterite soil with cement and lime (b) Laterite soil with cement and RHA

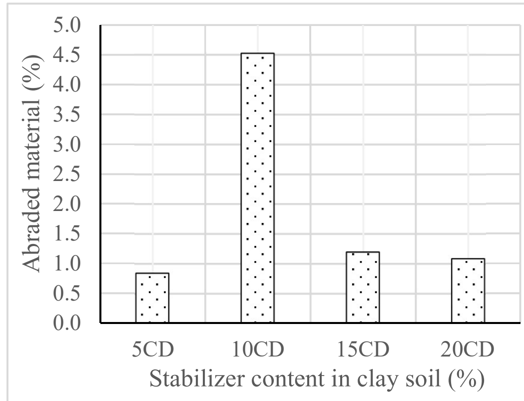
Figure 0.6: Abraded material in stabilized laterite soil blocks

The performance of clay blocks in abrasion was better on adding cow dung than hydrated lime and RHA in presence of cement (Figure 4.7). Cow dung has fibrous characteristic that may have imparted greater cohesion of clay particles. There was a 41.67% increment of abraded material on increasing cow dung from 5 to 15% (Figure 4.7b). The high concentration of fibres has been found by Ismail and Yaacob (2011) to cause them to bunch together and lose cohesion with the soil leading to breaking up of the soil matrix. This can cause weakening of the soil mixture thus increase in abraded material.

The results indicate that an increase of hydrated lime in clay soil having 5% cement results to a decrease in abraded material (Figure 4.7c). The reaction of cement and water liberates calcium hydroxide which reacts with clay to form pozzolanic binder. However, if the clay content is too high the free lime from cement hydration will not be sufficient to sustain the reaction. Therefore, the addition of hydrated lime aided the pozzolanic reaction in forming insoluble colloidal gels which led to increased resistance to abrasion. Generally, abrasion resistance of clay soil blocks is well achieved with addition of lime rather than RHA to cement.



(a) Clay soil with cement and RHA



(b) Clay soil with cow dung

(c) Clay soil with cement and lime

Figure 0.7: Behavior of abrasion resistance as a function of stabilizer content in clay soil blocks

4.3. Failure mode of interlocking block masonry wall units subjected to in-plane and out-of-plane loading

4.3.1. Structural performance of interlocking stabilized laterite soil block walls

Following the investigation of the physio-mechanical properties of individual interlocking blocks, the response of wall panels to loading was examined. The individual blocks that exhibited the highest compressive strength in each blend of the stabilizers were used in making the masonry walls. The properties of the blocks used in making the experimental walls are summarised in Table 4.4.

LSW1 developed cracks mainly on the blocks at an inclined angle and not on the joints (Figure 4.8a). The cracks were mainly a combination of cone and split mode of failure as described in ASTM C1314-03b (2012). No cracks appeared on the edges of the LSW1 panel. This flexural cracking could have been contributed by the unevenness of block bedding surfaces. The wall failed through crushing by opening up of fissures on individual blocks and finally propagation of cracks without opening up of joints. This could be attributed to the efficiency of the interlocking mechanism of the blocks. These results compare well with the finding of Uzoegbo, Senthivel and Ngowi (2007), who concluded that the general failure of interlocking masonry wall was similar to the yield pattern in loaded reinforced concrete slabs (Figure 4.8b) constrained at two edges.

Table 0.4: Summary of individual blocks used in wall making

Stabilizer percentage	Wall type	Soil type	28day Compressive strength (MPa)	24hour Water absorption (%)	Abrasion resistance (%)	Failure pattern
6%C	LSW1	Laterite	3.46	12.41	0.58	Pyramidal pattern
6%C3%L	LSW2	Laterite	4.03	14.78	0.41	Conical failure
6%C1%RHA	LSW3	Laterite	2.93	8.61	0.49	Conical failure
5%C1%L	CSW4	Clay	2.48	43.02	1.55	Splitting failure
1%C5%RHA	CSW5	Clay	1.38	-	2.39	Splitting failure
10%CD	CSW6	Clay	2.13	17.82	4.52	Compression cracking

The horizontal load led to spalling of the blocks due to gradual opening of the cracks that were created by vertical loading. As the horizontal load was applied, it made the wall plumb but eventually led to spalling of the blocks. The wall then experienced gradual sway with increasing horizontal load; the bottom part of the wall having a lesser vertical sway due to additional self-weight of the wall.

(a) Face cracks on LSW1 panel (b) Idealised yield line crack pattern

Figure 0.8: Failure mechanism of LSW1 panel

The failure of LSW2 was characterised by falling of block debris which spalled off due to the increase of horizontal loading. Cracks with wider widths mainly occurred at the middle height of the wall as compared to those at the top and bottom courses of the wall (Figure 4.9a). It was observed that increasing the lateral loading contributed to alignment of protruded blocks but ultimately pushed the wall out of vertical plane. At ultimate compressive load, blocks at the centre of LSW2 exhibited multiple cracks at their surface and vertical direction cracks were also observed at the sides of the wall (Figure 4.9b).

(a) Wall failure and crack pattern at face (b) Side cracks

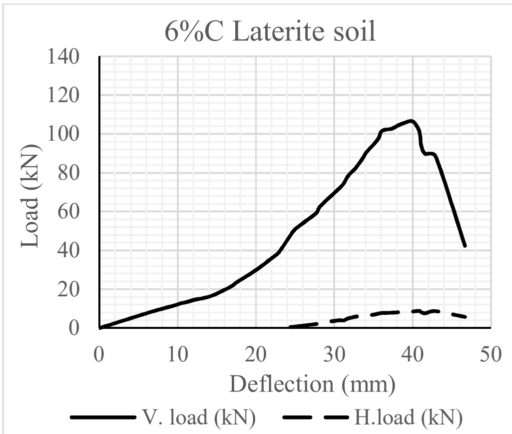
Figure 0.9: Failure mode and crack patterns for LSW2 panel

The mode of failure in LSW3 panel was by cracks that developed first mainly at the bottom layers (Figure 4.10). The cracks occurred through individual blocks just below the block header joint. There was gradual opening up of crack width with increase of vertical load but the wall did not experience spalling of materials. It was observed in all wall types, that the layer immediately below the spreader beam did not crack substantially to lead to collapse even when the other layers had failed. This phenomenon can be attributed to the deepening effect of the steel beam to the top layer in transferring the load to the entire wall.

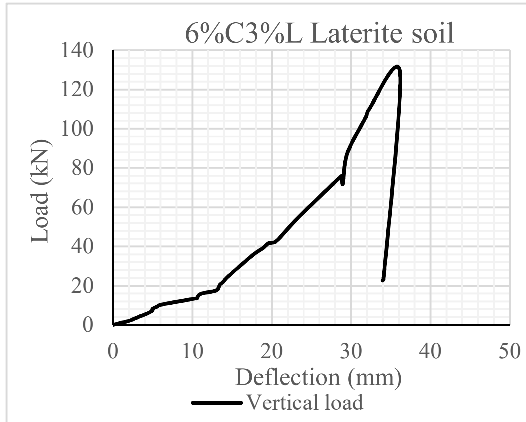
Figure 0.10: Crack propagation and wall failure mode for LSW3

The LSW1 ultimate compressive stress (0.90 N/mm^2) was 26.01% lower that of its individual interlocking blocks (3.46 N/mm^2). The correlation relation between the compressive strength of LSW1 and that of the interlocking block was found to be 0.649 indicating a positive linear relation. The reason for a lower compressive strength has been found to be contributed by the presence of a soft layer of mortar in the case of conventional masonry (Vermeltfoot, 2005). However, for interlocking masonry this can be caused by the blocks interface joints which leads to large displacements and structural instability.

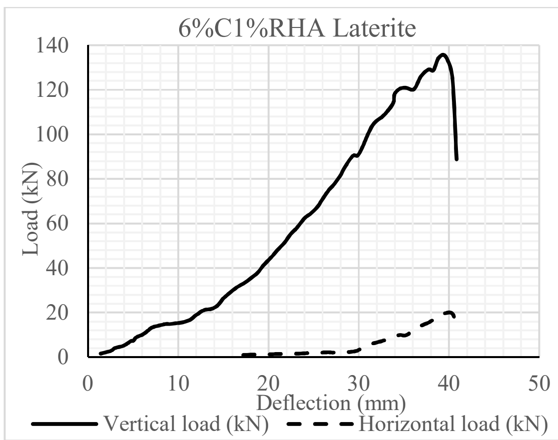
The first crack on LSW1 occurred at a vertical load value of 15.96 kN. This is depicted by flattening of the curve immediately after cracking which made the wall strength not to increase. As the vertical load increased, the wall bulged outwards as there was a considerable expansion of the block interface joints. The wall attained a maximum vertical load of 106.49 kN with a vertical deflection of 40 mm (Figure 4.11a). This first visual damages on LSW1 appeared at a strength that was 14.99% of the ultimate strength of the wall. The wall sustained a maximum horizontal load of 8.85 kN which was 8.31% of the ultimate compression load.



(a) LSW1 Panel



(b) LSW2 Panel



(c) LSW3 Panel

Figure 0.11: Load-deflection curve for laterite soil walls

The LSW2 sustained a maximum vertical load of 128.61 kN with a vertical load deflection of 36.16 mm (Figure 4.11b). The results indicated that the ultimate compressive strength of LSW2 wall was 26.8% lower than that of individual block. A regression analysis of the ultimate strengths of the wall and individual blocks indicated a positive correlation coefficient of 0.689. The addition of 3% lime to laterite soil caused 20% increment of strength capacity of the wall. This also led to a 9.6% reduction on the vertical load deflection at failure. These findings show that addition of lime to laterite soil makes the walls to have higher compressive strengths but they tend to be brittle.

A maximum vertical compression load of 135.09 kN with a vertical load deflection of 39.06 mm was achieved by LSW3 (Figure 4.11c). The presence of 1%RHA in laterite soil stabilized with 6% cement resulted in increase of ultimate compressive strength capacity of the wall from 106.49 to 135.09 kN. This also led to 2.35% reduction of vertical load deflection at failure. The LSW3 sustained a horizontal load of 19.75 kN. The addition of 1%RHA to laterite soil stabilized with 6% cement resulted to walls with compressive capacity 6.67% higher than adding 3% lime.

The performance of interlocking laterite soil blocks as presented in Figure 4.11(a), (b) and (c) can be divided into three parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure. In the first part, there was rapid increase in deflection as the load was applied. This may be attributed to the closing of the interlocking gaps between the blocks. After the closure of the gaps the deformation evened out with increase of vertical load. In part two, the walls experienced a rapid increase of load capacity. The sharp compression capacity increase occurred at a higher compressive load in LSW3 than in both LSW2 and LSW1. This increase on the second part of the curves was sustained until the ultimate load was achieved. The cause of the second increase of load capacity can therefore be associated to the unit blocks bearing the load as the gaps had closed up making the load to be transferred from one-unit block to the other. In the third part, there was a drop of the load curve as the walls had failed. This occurred after the ultimate load capacity of the walls was achieved.

4.3.2. Structural performance of interlocking stabilized clay soil block walls

The failure mode of CSW4 under loading (Fig. 4.12a) was characterised by gradual propagation of cracks in a diagonal direction on block faces. Splitting failure occurred on individual blocks as opposed to failure along the block interface. Therefore, the wall collapse mechanism was activated by some block local effect rather than a wall global failure condition. The wall failure mode was shown to be concentrated in the less restrained part of the wall (i.e. free edges and mid-height).

The CSW5 failed by spalling of blocks in form of smaller debris that easily disintegrated. The blocks lacked cohesiveness character and easily disintegrated when the load was increased. There was presence of shear cracks on blocks at the middle courses of the wall panel that widened and spread at a fast rate on the surface (Fig. 4.12b).

(a) CSW4 failure

(b) CSW5 failure

(c) CSW6 failure

Figure 0.12: Observed crack propagation and wall failure for clay soil block wall panels

The number of cracks formed in CSW6 were fewer with the width not opening appreciably to lead to failure of the wall by cracking (Figure 4.12c). This led to failure of CSW6 by compression crushing. Since the cracked length of the wall was relatively low, the cracked length contribution to failure of the wall was negligible. The limited formation of cracks in CSW6 can be associated with presence of fibres from cow dung which was used as a stabilizer. The CSW6 unit blocks bulged considerably with the wall attaining a vertical load deflection of 41.44 mm at the ultimate load. Such high deformation may be unsuitable for common structural applications and may probably result to failure of load bearing members and detachment of elements such as beams.

Therefore, there is need to check it against the recommended deflection limit in the application to flexural members.

The effect of stabilizer on load carrying capacity of clay soil block walls is shown in Figure 4.13. CSW4 attained a maximum compressive stress of 0.37 N/mm^2 as compared to 2.48 N/mm^2 attained by lime-cement blend individual blocks (being 80.08% higher). The load-deflection curve depicted a gradual increase in the load carrying capacity until the ultimate value (Figure 4.13a). The curve did not indicate clear point when the wall begins to yield depicting a brittle behaviour of the wall.

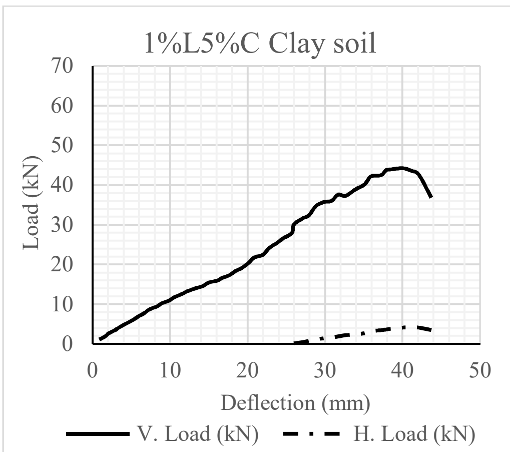
CSW5 sustained an ultimate compressive load of 35.71 kN with a vertical load displacement of 29.28 mm (Figure 4.13b). It has been recorded by Kham, Loh and Singini (2016) that RHA has a lower density as compared to pozzolanic cement. This makes the quantities of RHA to be more when batched by weight. This is disadvantageous in wall strength capacity since the extra RHA cannot be mobilized for chemical reaction which consequently occupies space within the soil matrix reducing strength gain. This could have contributed to the low compressive strength attained by CSW5.

The CSW6 curve had three sections: (i) gaps closure, (ii) load uptake and (iii) wall failure. The load capacity begun with a shallow curve until a load point of 18.80 kN was achieved (Figure 4.13c). This may have been contributed by closing of the interlocking joints. Beyond this point, the load curve gradient increased until an ultimate load (60.20 kN) was reached. In this section the wall sustained the load to its ultimate capacity, after which it experienced failure. CSW6 wall attained a higher ultimate compressive strength than CSW4. This phenomenon could be explained by the fact that since CSW6 individual blocks behaved plastically, they allowed compressional compaction thereby sustaining much higher compressive load.

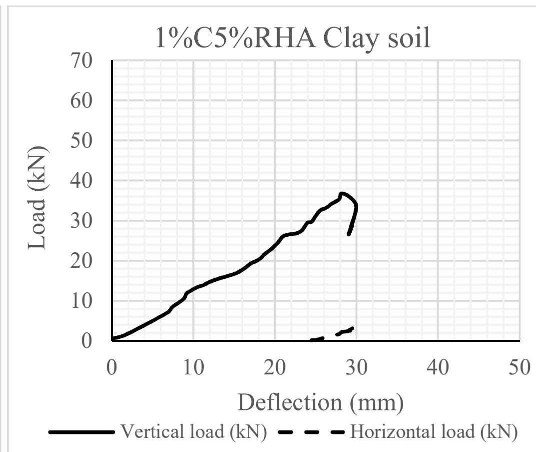
The general response of the wall panels was that there was gradual increase of load capacity before a sharp increase was experienced. This observation has been justified by Quagliarini and Lenci (2010) that when pressure is exerted, soil grains shift thus occupying the voids which exist within the material's matrix. As loading increases progressively, the soil grains are compacted and the material's density increases. Consequently, it gradually becomes stiffer and retains its ability to resist loading.

The horizontal load capacity of the walls was very low compared to the vertical load capacity. This indicated that interlocking block walls do not have adequate tensile strength. This may be due to lack of mortar bond between the units.

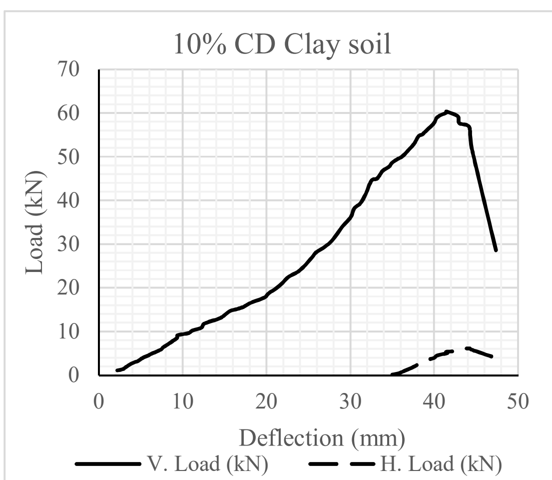
Generally, the clay soil block walls did not attain higher strengths compared to laterite soil block walls. More so, their strengths were not sufficient for construction according to the different earth construction guidelines.



(a) CSW4



(b) CSW5



(c) CSW6

Figure 0.13: Load-deflection curve for clay soil block walls

4.4. Numerical simulation model for prediction of structural failure of interlocking soil blocks

4.4.1. Prediction of the compressive strength of interlocking soil blocks and walls

Masonry compressive strength has been addressed in codes of design for mortar bonded masonry blocks. However, as a result of different performance of interlocking soil blocks due to absence of mortar layer, this research proposes alternative empirical formulae to be utilised in ISSB construction. The proposed equations predict the 28-day compressive strength of the blocks while considering the different blends of stabilizers. Since the blocks were stabilized differently, five, cases were probable considering the blends of the stabilizing agents.

Case 1: Cement and lime stabilized laterite soil

The interlocking block compressive strength (f_{cb1}) as established in this research (Equation 4.1) considered the contribution of cement and lime content in laterite soil. From laboratory results, pozzolanic cement was varied from 4.8 to 6% at intervals of 0.2 while lime varied from 1 to 5% at unit intervals (Table 3.2). The regression analysis adjusted R^2 coefficient (0.895) indicated a strong relation between the variables and the response value (block compressive strength). The equation predicts block strength with a pozzolanic cement content equal to or greater than 4.8%

$$f_{cb1} = 2.283\left(c - \frac{3l}{761}\right) - 9.995 \; for \; c \geq 4.8\% \qquad 4.1$$

where

f_{cb} – interlocking block mean compressive strength (MPa)

c – cement percentage of dry weight of laterite soil (≥4.8%)

l – lime percentage of dry weight of laterite soil

Case 2: Cement and RHA stabilized laterite soil

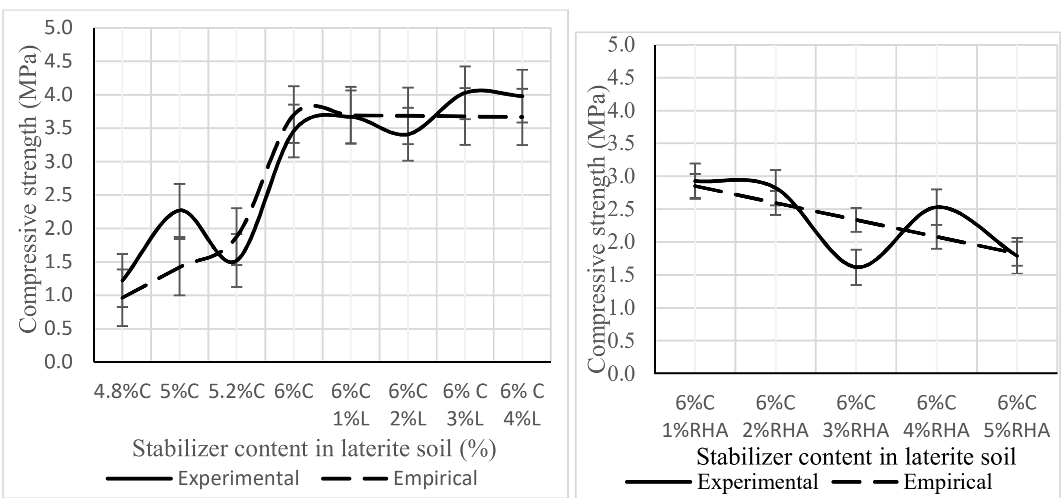
Multiple regression analysis was performed on laboratory collected data for blocks stabilized with a blend of pozzolanic cement and RHA. In this case pozzolanic cement was maintained at 6% while RHA was varied from 1 to 5% at unit intervals (Table 3.2). The empirical equation for compressive strength of blocks containing a combination of 6% cement and variation of RHA (f_{cb2}) is as shown in Equation 4.2. The RHA value of adjusted R^2 = 0.460 indicated a wide variation within the dependent variable (block compressive strength) and the independent variables (RHA and cement content). This suggests that a proportional factor need to be included in the predictive equation in order to reliably predict the compressive strength.

$$f_{cb2} = 3.109 - 0.257r \; with \; 6\%C \qquad 4.2$$

where

r – RHA percentage of dry weight of laterite soil

The best fit equation trends as predicted by Equations 4.1 and 4.2 against experimental data of ISSB are as shown in Figure 4.14. The trend in Figure 4.14(a) matches well and is in good agreement with the experimental results as compared to the trend in Figure 4.14(b). The empirical Equation 4.2 could not capture the peaks as the quantity of RHA was increased in laterite soil. From the results, it can be concluded that Equation 4.2 can essentially represent the overall compressive strength development in laterite soil blocks with RHA.



(a) Stabilized laterite soil with cement and lime (b) Stabilized laterite soil with cement and RHA

Figure 0.14: Comparison of block experimental compressive strength results with empirical equation

The formulation of the prediction functions for compressive strength of the walls considered the experimental walls to obtain the relationship between the block and the wall capacity. The characteristic compressive strength's (f_{cw}) for wall type LSW1 and LSW2 from multiple linear regression are presented in Equations 4.3 and 4.4 respectively.

$$f_{cw1} = 482.62\left(c - \frac{3l}{761}\right) - 2304.09 \qquad 4.3$$

$$f_{cw2} = 5.81\left(c - \frac{3l}{761}\right) - 26.29 \qquad 4.4$$

The compressive strength prediction function for type LSW3 obtained from the individual blocks (Equation 4.5) incorporates RHA quantity with 6% cement.

$$f_{cw3} = 1.198 - 0.097r \qquad 4.5$$

The developed empirical formulae reveal that the predicted compressive strength of interlocking blocks considers different parameters (stabilizer type, quantity and blend of stabilizers) in addition to what was adopted by Uzoegbo and Ngowi (2003). Since the dependent variable considered in this study was reliant on several independent variables, the functional output of the equations is reliable due to its consideration of multiple dependencies.

Case 3: Cement and lime stabilized clay soil

The estimation function for compressive strength of clay soil interlocking block stabilized with cement and lime (f_{cb}) is shown in Equation 4.6. The correlation coefficient (0.187) was very low indicating a large variance in the independent variables. This equation however, provides useful guide for estimation of the clay soil block compressive strength and quick prediction. The percentage quantity of lime and cement was varied from 1 to 5%.

$$f_{cb} = 2.727 - 0.107\left(c + \frac{58l}{107}\right) \qquad 4.6$$

By using the experimental data obtained on testing CSW4, Equation 4.7 was formulated which estimates the characteristic compressive strength of clay soil interlocking block masonry.

$$f_{cw4} = 0.43 - 0.013\left(c + \frac{58l}{107}\right) \qquad 4.7$$

It was inferred from Equation 4.7 that when cement content was retained at 5% and lime increased, the equation results to a constant 0.7% decrease on the compressive strength capacity of the wall.

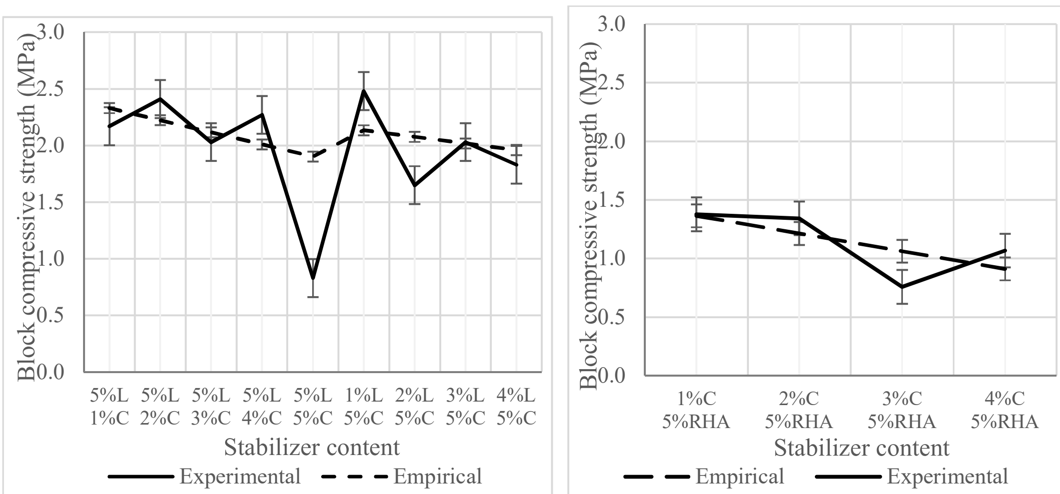
Case 4: Cement and RHA stabilized clay soil

The regression analysis of experimental data for compressive strength of clay soil blocks stabilized with cement at 5%RHA generated Equation 4.8. However, the block compressive strength (f_{cb}) can be altered when the RHA percentage is changed.

$$f_{cb} = 1.515 - 0.151c \; with \; 5\%RHA \qquad 4.8$$

Based on the experimental characteristics of type CSW5, a linear relationship between masonry compressive strength and block compressive strength is proposed as Equation 4.9. The comparison of experimental and empirical results as produced by Equation 4.6 and 4.8 is shown in Figure 4.15.

$$f_{cw5} = 0.39 - 0.304c \ with \ 5\%RHA \quad 4.9$$



(a) Stabilized clay soil with cement and lime (b) Stabilised clay soil with cement and RHA

Figure 0.15: Experimental compressive strength versus empirical equation results

The curve produced by both Equation 4.6 and 4.8 did not provide a good fit to the experimental data (Figure 4.15). Although these models offer good indicative behaviour of the block compressive strength. The block compressive strength predicted by these analytical models seem to be generally underestimated by up to a maximum of 14% of the experimental values.

Case 5: Cow dung stabilized clay soil

The Pearson correlation of 28-day compression strength and cow dung content was -0.564. The negative correlation suggested that an increase in cow dung in clay soil would lead to decrease in strength. Equation 4.10 estimates 28-day compressive strength of individual blocks when stabilized with cow dung equal to or greater than 5%.

$$f_{cb} = 2.115 - 0.018cd \geq 5\%CD \quad 4.10$$

Where

cd – cow dung content

The experimental results of CSW6 enabled to generate Equation 4.11 which estimates the compressive strength of masonry wall made of interlocking clay soil blocks stabilized with cow dung.

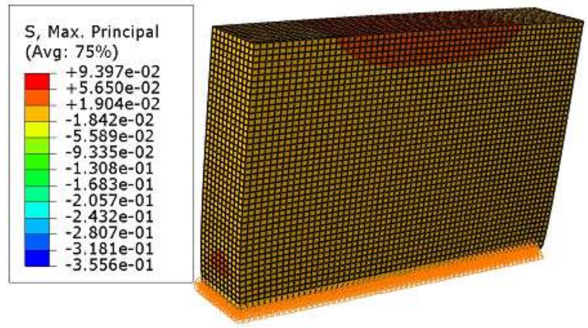
$$f_{cw6} = 1.012 - 0.00745cd \qquad 4.11$$

4.4.2. Simulation of failure modes of interlocking soil block walls using finite element

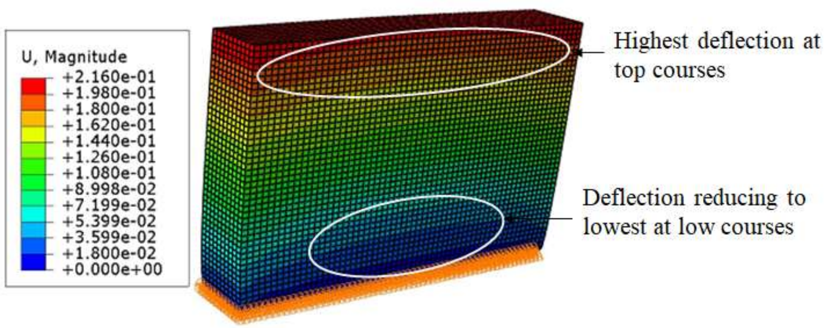
The non-linear stress-strain and failure mode behaviour of the interlocking masonry wall was simulated using the Rankine failure criterion in the Finite Element (FE) model. The simulation followed the maximum principal stress theory where failure was considered to occur once the elastic limit stress in simple tension was reached.

A good agreement was found on failure modes of experimental results and the stress distribution expressed by the FE simulation of the LSW1. The results showed that the observed experimental wall failure behaviour (Figure 4.16a) was governed by principal stresses distribution as shown by the contours in Figure 4.16b. It is observed in the FE simulation results (Figure 4.16b), that the block-load interface layer at the top central regions are subjected to maximum stress (0.94 MPa). The ultimate compressive stress recorded in experimental analysis (0.90 MPa) was however marginally lower than in numerical simulation. This finding concurred with the observation of Sadoun (2000), who found that the load carrying capacity from FE analysis of Putra Block was relatively higher than that obtained from test results. He argued that this was due to neglection of the material and geometrical nonlinearity and initial imperfection in FE modelling.

The FE simulation indicated that LSW1 allowed higher compression displacement at the top block layers than bottom layers (Figure 4.16c). The displacement at the bottom layers was higher at the corners and increased vertically upwards at the central bottom courses. These small compressive strains resulted to constraining of the blocks at this region leading to initiation of cracks as observed in the experimental wall (Figure 4.16a).



(a) Failure mode of experimental wall (LSW1) (b) Maximum principal stress distribution



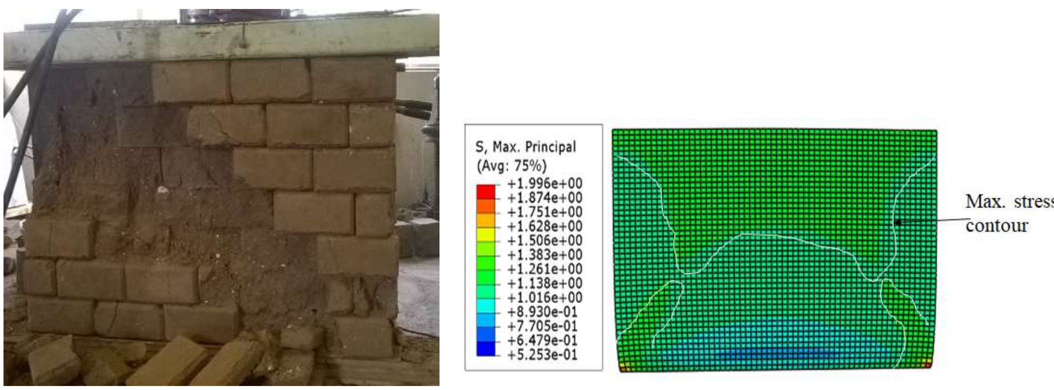
(c) Finite element wall displacement

Figure 0.16: Maximum principal stress and load displacement distribution in LSW1 masonry

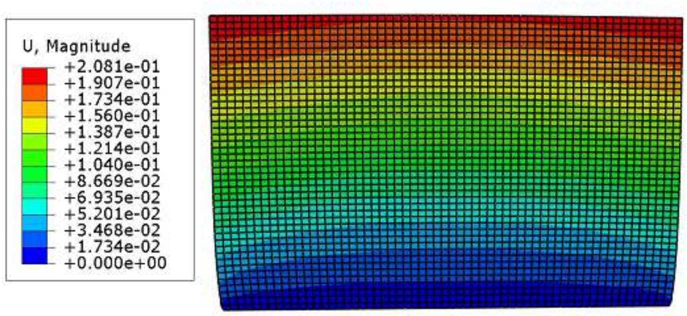
The experimental results of LSW2 depicted spalling of block debris in a diagonally stepped failure mode (Figure 4.17a). The maximum principal stress distribution from FE showed conical failure through the wall (Figure 4.17b). The maximum principal stress contour spread at an inclined angle to the central region of the middle courses of the wall, then outwards to the bottom corners. The diagonally oriented failure of the experimental wall matched the inclined contour path to the bottom corner of the wall. This observation was in line with Horri and Nasser (1986) findings. They have shown that, under axial compression, tension cracks initiate at an angle close to 70 degrees to fault orientation in brittle material. These cracks grow resulting to axial splitting. The model results indicated that maximum stresses are experienced at the top courses with blocks at the bottom central position experiencing the lowest stresses. The maximum stress recorded by analytical analysis was 1.38 MPa compared to 1.08 MPa recorded from experimental result.

The model results depict higher vertical displacements at the top courses which reduces downwards. From the results it is clear that the vertical edges of the wall deflected more than the central sections (Figure 4.17c). Compared to LSW1, the FE results indicate no change of deflection behaviour of the walls when loaded to failure. However, there is a change of failure mode from compression failure experienced in LSW1 to diagonal stepped compression in LSW2. There was also an increased stress carrying capacity in LSW2 panels.

It can be implied from these results that the compression capacity and failure mode of ISSB wall is dictated by the distribution of the maximum principal stresses on the wall which was influenced by the characteristics of the stabilizing agent used. This clearly indicates that stress distribution is influenced by composition of the constituent material (in this case, type of target material and stabilizer used) which further determines how the wall sustains the applied stress.



(a) Failure mode of experimental wall (LSW2) (b) Maximum principal stress distribution

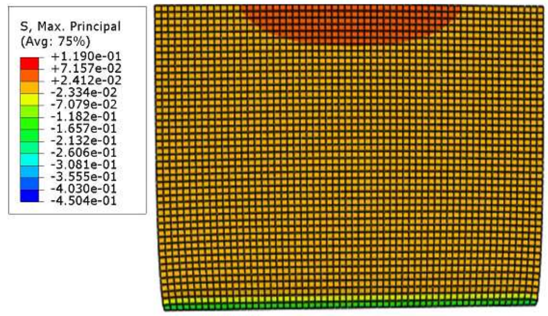


(c) Finite element wall displacement

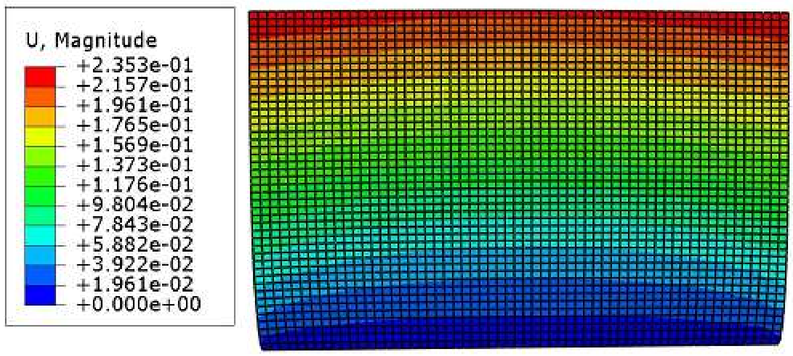
Figure 0.17: Maximum principal stress distribution in LSW2 masonry

The initiation of cracks was at the top courses in the experimentally tested LSW3. The crack widths and intensity increased as they spread to the bottom course (Figure 4.18a). As can been seen from Figure 4.18(b), the maximum compressive stress (1.19 MPa) occurred at the central top courses of the wall. Other sections of the wall experienced a uniform distribution of stresses, with compressive stresses at the bottom course. There was no vertical deformation that was recorded at the bottom curses of the wall (Figure 4.18c). This restriction of deformation on blocks may have resulted to cracking of the units as observed in the experimentally tested wall. Maximum vertical deflection of 23.53 mm was achieved on the top courses. It is noted that blocks stabilized with lime deflected the least and sustained the highest compressive stress, as compared to its RHA stabilized equivalents. Arroyo, Amaral, Romero and Viana (2013) suggested that natural soils can be deformed highly under loading than stabilized one. They further argued that volumetric compression is not experienced much due to cementation and hardening of the soil making it brittle. In this study, the degree of brittleness (as suggested by the vertical deflection) of the wall may have contributed to the mode of failure of the ISSB panel.

Overall, the FE model walls experienced less vertical deflection as compared to the experimental walls. Vertical deflection due to flattening process of the dry joint has been examined by Marzahn and Koning (2002) by placing a sheet of carbon paper in between two dry stacked blocks. They concluded that most of the deformations were caused due to the geometric imperfection at the contact surface of the dry joint. Since no imperfections were assumed in the study model, this contributed to smaller vertical deflection.



(a) Failure mode of experimental wall (LSW3) (b) Maximum principal stress distribution

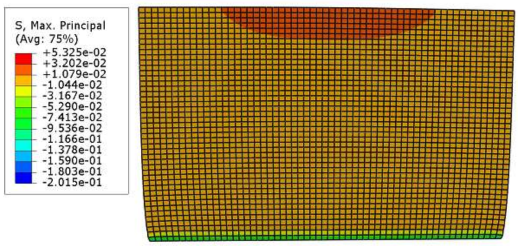


(c) Finite element model wall displacement

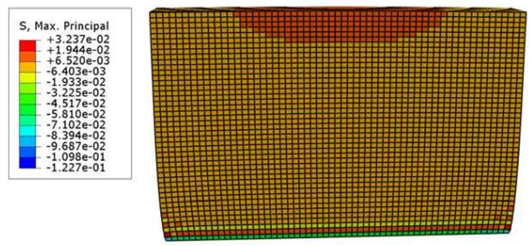
Figure 0.18: Maximum principal stress distribution in LSW3 masonry

The finite element modelling of clay soil block walls indicated a more or less similar distribution of stresses on the wall surfaces (Figure 4.19). For CSW4 and CSW6 the stress was highest at the top course and reduced to the bottom courses. The maximum stress recorded for these two walls was 0.53 MPa (Figure 4.19a and 4.19c). As shown in Figure 4.19b, CSW5 had higher stresses at the top course and the bottom course. This indicates that block walls stabilized with RHA and pozzolanic cement resits load at the point of application and along the supported zones. The maximum stress achieved (0.31 MPa) was however smaller than that resisted by the other walls.

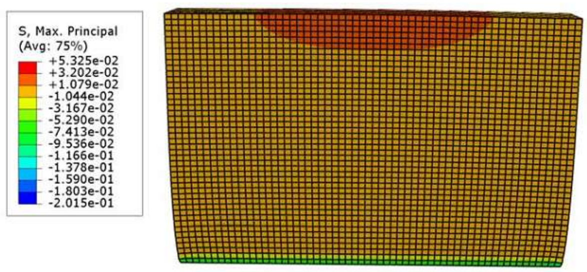
The material constitutive model adopted for the FE indicate that there is no much difference in the stress contours obtained on loading the walls. Therefore, in terms of the maximum principal stress when considering stabilized clay soil, the failure criteria of the wall may not substantially affect the global response of masonry wall by changing the type of stabilizer.



(a) CSW4 stress contours



(b) CSW5 stress contours



(c) CSW6 stress contours

Figure 0.19: Maximum principal stress distribution on stabilized clay soil walls

4.5. Social acceptability of interlocking soil block technology in Kenya

The interviews were guided by the indicative questions prepared based on the laboratory findings and research objectives. The list of interview responses by the respondents is provided in Appendix E. The Technology users and Non-technology user views were organised under their preferred walling structures for ISSB technology, their evaluation of the technology performance and the factors that are inhibiting its adoption in the Kenya construction industry (Table 4.5). The contribution of these themes to acceptability has been discussed below.

4.5.1 Preferred walling structures for ISSB technology

There was a general agreement in both the TU and NTU that the technology can be best utilised in constructing residential houses (Figure 4.20). The technology was also argued to be adequate in acting as infill material in framed structures, but not as load bearing material. Some technology users however, contradicted this opinion by suggesting that the technology can be used in constructing recreational/entertainment and institutional centres. According to them, residential house walls requires plaster work which tend to increase the cost of construction. The ISSB technology was found least applicable in construction of storey structures (Figure 4.20). Laboratory findings found ISSB to have compressive strength of the 2.5 N/mm^2. In accordance to the specification of KS 02-1070

Table 0.5: Research study themes

Theme	Opinions of respondents
Preferred walling structures for ISSB technology	The ISSB technology can be used for: - Smaller residential houses; bungalows and maisonettes; classrooms and institutional offices - Mass production of units for displaced persons - Infill in framed structures - Space partitioning - Perimeter wall construction ISSB is best suited in rural areas due to its labour-based nature. It can be conveniently used where conventional blocks are expensive to source
User evaluation of ISSB technology performance	The assessment of ISSB technology found that it has: - No difficult in construction - Natural attractive appearance – can form a key on the outer face, possibility of incorporating different coloured dyes - No visible physical deteriorating features that reduce the cost of plaster work - Connectivity problems between walls and columns when used as infill, resulting to cracking along these zones - Likelihood of breakages when mishandled - Problems of wall plumbness when high walls are done without columns - High susceptibility to water absorption on first laid courses - Tendency of peeling of plaster work when wrongly applied - Cracking if the blocks are not well aligned during stacking - High erosion of walls where roof eaves are shorter or no protection from wind driven rain - Suspicion about block interlocking mechanism; whether the blocks can sustain small vibrations or not crumble when hit by intruders
Factors affecting adoption of ISSB technology	Aspects that hinder ISSB technology adoption include: - Missing or unknown standards, Attitude - None existing framework for alternative construction materials in construction industry - Fear of change from use of conventional walling material - Inadequate specification of the ISSB technology by designers - Lack of ISSB technology demonstration projects

(1993) this strength is adequate for non-load bearing masonry. This outcome affirms the application of ISSB technology in construction of non-load bearing structures as opposed to high rise structures. Nearly 13% of the respondents were of the view that since the technology is labour intensive it can be conveniently applied in rural set up where it can also create employment. In addition, the conviction of minority NTU was that this technology can be used in constructing decent and affordable short duration occupancy houses.

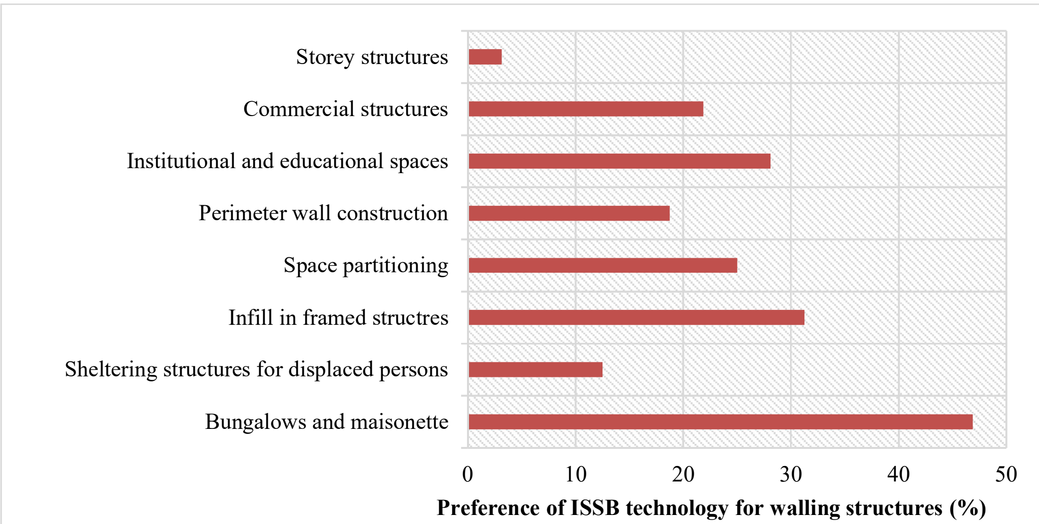
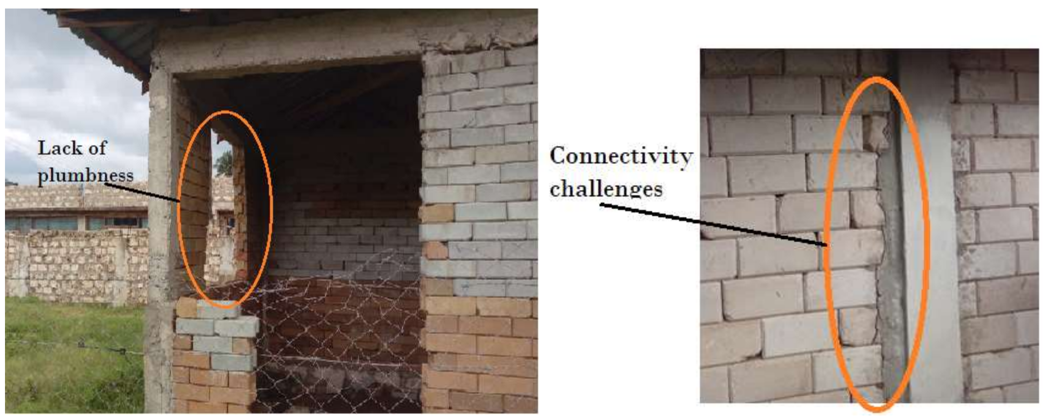


Figure 0.20: Preferred walling structures for ISSB technology construction

4.5.2 User evaluation of the ISSB technology performance

The theme of onsite performance was found to be very good since no visible physical deteriorating features have been observed for the last 4-5 years of occupancy by the TU and the NTU. It was noted by 28% of TU that the interlocking nature of the blocks provides ease of construction and the regular nature of the blocks reduces amount of plaster works. It was observed that the masonry walls were created using running bond pattern. Since interlocking blocks are regular and smaller in size as compared to conventional blocks, the running bond pattern enabled them to interlock easily. According to Jaafar, Thanoon, Najm, Abdulkadir and Ali (2006) failure of interlocking blocks occurred by splitting between the webs and the shells of the blocks depending on the type of bond pattern used. They argued that interlocking mechanism restrained the movements in horizontal and vertical directions. For load bearing construction of interlocking soil blocks, they recommended use of English running bond pattern where the performance of the walls was adequate. Their finding affirms the use of running bond in ISSB in constructing walls as practised by the technology users.

While 19% of respondents indicated block production workmanship to be the major challenge when using the ISSB technology, problem of wall plumbness was noted in the constructed houses (Figure 4.21a). Supporting this view, 38% of TU noted that columns need to be cast after constructing 10 courses high (approximately 1200 mm). This will encourage bonding of the concrete column with the blocks while also encouraging maintenance of wall plumbness. Where ISSB have been used as infill material, connectivity between the wall and other structural elements was noted by 9% of the respondents to be a challenge (Figure 4.22). This resulted to cracking along these zones (Figure 4.21b). Such challenge can be averted by toothing the block wall at points where it is to be connected to a concrete element and then fill them during concreting.



(a) Challenges of wall plumbness (b) Connectivity between blocks and column

Figure 0.21: Performance rating of the ISSB technology

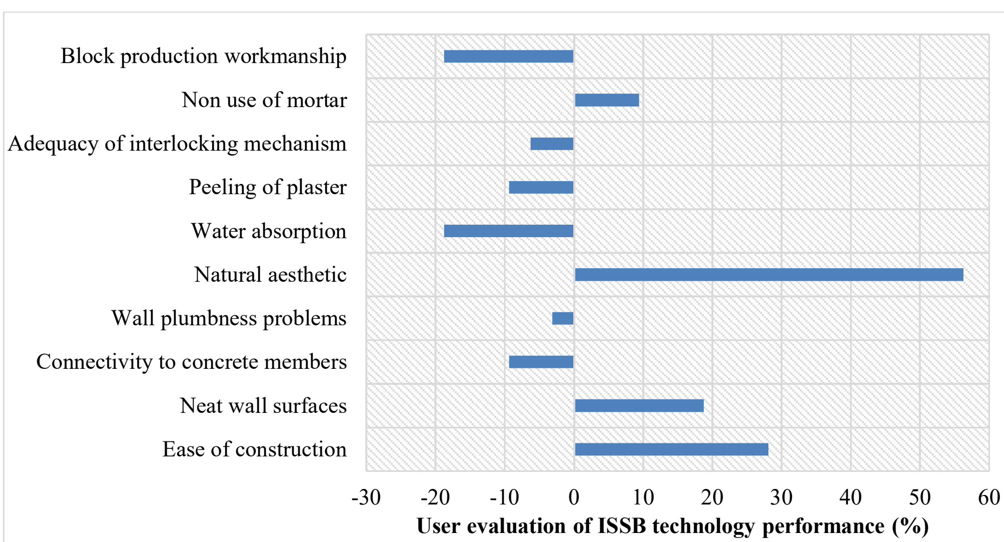
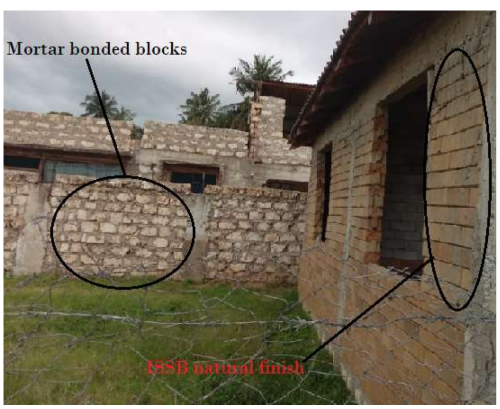


Figure 0.22: Assessment of the ISSB technology

The three most preferred qualities of ISSB are non-use of joining mortar, ease of construction and natural aesthetic (Figure 4.22). It was acknowledged by nearly all respondents that ISSB are regular hence not requiring cutting and dressing of the surfaces as compared to bush stones, thus reducing the time of construction. In addition, UN-HABITAT (2009) record that, mortar bonded masonry has mortar workmanship problems related to moving of units after mortar initial set and incompletely filing of mortar on head and bed joints. These challenges are however averted when ISSB are used (Oyawa, 2009). The construction process has also been simplified by the interlocking nature of ISSB which allows them to be dry stacked without use of mortar. Mortar bonded blocks normally leave a rough surface which may necessitate plastering as compared to a good exterior décor presented by ISSB (Figure 4.23a). The lean surfaces of ISSB and running bond pattern of the blocks creates a natural aesthetic appearance on the walls. The bevelled edges of the blocks allow them to generate a natural key on the wall (Figure 4.23b), adding to appealing appearance of the walls. This affirms Adewole (2009) finding that an aesthetically pleasing look is achieved if the ISSB are properly constructed.



(a) Wall appearance of mortar bonded blocks and ISSB (b) ISSB natural key on the surface

Figure 0.23: Natural wall appearance on mortar bonded blocks and ISSB walls

The perception that earth materials are of less durability has contributed to low preference of the ISSB technology to developers. Durability was found to be contributed by poor workmanship observed during moulding of blocks. Since the blocks require mixing of the constituent materials, it was in view of some NTU that the shortage of existing guidelines may lead developers to compromise on the ratios resulting into sub-standard blocks.

The study found that the first laid courses and those which were not protected against rain were susceptible to water absorption. 19% of the respondents associated water absorption with deterioration of the ISSB technology. The first laid courses were therefore done with natural stones or constructed on a well-drained and raised ground. In order to avoid erosion by wind driven rain, most respondents indicated that roof eaves should be made long enough to shield the blocks. Furthermore, where the blocks have been used in constructing fencing walls, a capping stone was placed at the top course to protect the blocks against rain.

Pealing of plaster was observed to occur where it had been applied on ISSB walls. Since the stiffness of cement-sand mortar is higher than that of ISSB, it may have resulted to inadequate adhesion causing the pealing of the plaster. However, to overcome this challenge, earth-based rendering materials should be applied on ISSB surfaces as recommended by ARSO: 1333 (2018).

The theme on occupational safety was based on the question: 'How safe is it to live in houses built with ISSB?' While earlier laboratory observations indicate difficult in demolishing an ISSB wall, most of the TU interviewees confirmed that they felt safe while occupying the houses. Nonetheless, 6% of the respondents were suspicious of the adequacy of the interlocking mechanism. It was in their opinion that the ISSB walls may not be able to withstand small vibration or impact caused by intruders. It has been reported by Elvin and Uzoegbo (2011) that earthquake damage to masonry walls constructed using interlocking soil blocks occurs in form of bricks shifting creating vertical gaps, splitting and cracking of a few bricks and spalling of plaster. Generally, they concluded that the structures are mildly damaged by earthquake vibrations and the houses still have structural integrity to allow occupants to exit safely. This finding asserts the view that the ISSB technology can sustain vibrations while assuring safety to the occupants.

4.5.3 Factors affecting adoption of ISSB technology

The adoption of ISSB technology was described by most interviewees as relatively low. It was emphasised (by TU and NTU) that the most contributing factors were: lack of awareness, missing or unknown standards of ISSB technology, fear of change from conventional materials, and negative attitude towards earth material (Figure 4.24).

There has been advocacy of conventional materials with aim of using stronger and prestigious material. Similarly, Tyrel (1996) argues that pressure from modernization has contributed to neglection of promotion of traditional construction methods and materials. Since the blocks are made of soil, some developers have a feeling that ISSB is reversing the progression of such trend. Awareness and exposure of the technology to developers has also been reported by Hadjri, Osmani, Baiche and Chifunda (2007) to be lacking. As reported in Figure 4.24, lack of awareness (56%) hinders the most to adoption of ISSB technology. The TU pointed out that deliberate campaign awareness should be carried out supported by construction of demonstration projects. Besides documentation of the ISSB technology advantages, there is need to develop a framework for its use on different construction sites so that home owners can be able to experience and see its performance. Conversely, the respondents opined that alternative stabilizers should be applied to enable the ISSB to be much cheaper and easily made in areas where pozzolanic cement is expensive. More so laterite soil should be substituted by other target materials like crusher quarry dust and corral stone dust which are considered as waste material after quarrying activities to be used as substitute materials. This will encourage production of ISSB in regions where the existing soil is not ideal in the production of ISSB.

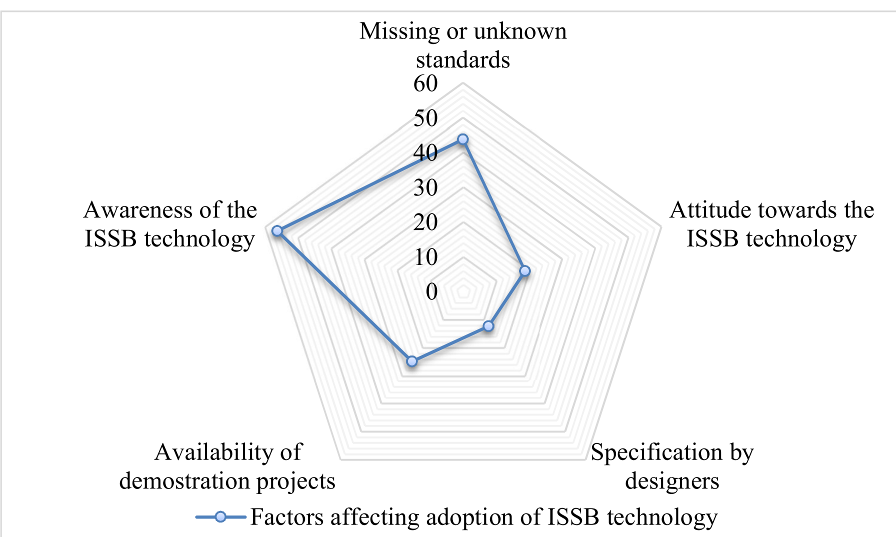


Figure 0.24: ISSB technology adoption index

The training of construction designers in Kenya has majorly been towards use of conventional materials. However, in Nigeria it was Bobbo, Ali, Garba and Salisu (2015) recommendation that earth construction techniques should be incorporated into the educational curriculum. This was to facilitate training of designers and ultimate production of codes of designs. The lack of trained personnel coupled with unclear code of standard for the ISSB technology has led to its little specification by the designers for consideration by the clients. This finding concretized Burnet (2007) observation that lack of standards has made earthen construction to be regarded as unapproved and un-regulated material. The present adoption has therefore been left to the premise of the current procedure which is based on experience, previous use and knowledge gained on site.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were drawn from this research work;

5.1.1 Conclusions for objective one

(1) The improvement of the physico-mechanical properties of the interlocking blocks in terms of compressive strength, water absorption and durability is a positive aspect of the stabilizers. An optimum of 3% lime in laterite soil stabilized with 6% pozzolanic cement exhibited the highest 28-day compressive strength, with a highest reduction of 24-hour water absorption obtained through addition of 1%RHA. Overall, compressive strength and increased resistance on abraded material of laterite soil blocks is optimally achieved with lime but water resistance is best achieved with rice husk ash stabilization.

(2) Lime performs better in clay soil stabilization when used together with cement as stabilizer. Maximum abrasion resistance in clay soil blocks, however, can be achieved with cow dung stabilization.

5.1.2 Conclusions for objective two

(1) A mix of lime and pozzolanic cement stabilized laterite soil walls failure is characterised by multiple cracks occurring in vertical direction and spalling of block debris due to horizontal loading. Replacing lime with rice husk ash, causes laterite soil walls to develop cracks through its individual blocks mostly at the bottom layers of the wall.

(2) A blend of Rice husk ash and pozzolanic cement stabilized laterite soil blocks leads to compressive strength (1.14 N/mm^2) higher than recommended value of 0.2 N/mm^2 for storey structures.

(3) Clay soil block walls stabilized with a mixture of lime and pozzolanic cement mixture fail by splitting of individual blocks in a diagonal direction, with the failure concentrated in less restrained parts of the wall. Alternatively, use of rice husk ash and pozzolanic cement in clay soil stabilization lead to blocks that lack cohesiveness character and easily disintegrate when loaded. However, cow dung

stabilized clay soil walls accommodate considerable vertical load defection and fail by compression crushing. Generally, the load-deflection curves of loaded ISSB walls can be divided into three distinct parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure.

5.1.3 Conclusions for objective three

(1) Multiple regression analysis empirical formulae correctly estimated the compressive strength of laterite soil block walls stabilized with a blend of lime and pozzolanic cement. However, the multiple regression equations only represent the overall compressive strength development in laterite soil blocks stabilized with rice husk ash-pozzolanic cement blend.

(2) The finite element modelling of clay soil block walls indicated that the failure mode is characterised by post-damage-crack initiation which controlled the evolution of the failure surfaces on the individual walls. Finite element results showed concentration of stress on the top courses and the middle central courses. This led to higher vertical displacements at the top courses reducing downwards to the lower courses.

(3) Total behaviour and failure pattern of ISSB masonry is influenced by the type of stabilizer used on the target material which dictates the stress distribution and vertical displacement of the masonry. Finite element modelling results indicated a diagonally stepped failure mode is experienced in more brittle masonry assemblage while cone failure mode occurs in less brittle masonry assemblage.

5.1.4 Conclusions for objective four

(1) Interlocking stabilized soil block technology is best suited for construction of non-load bearing walling structures such as residential houses, perimeter fencing walls and partitioning of buildings. The desirable features of interlocking stabilized soil block technology include: non-use of mortar, ease of construction and good aesthetic value.

(2) Interlocking block connectivity with concrete members, wall plumbness and block production workmanship are main hinderances to adoption of the interlocking soil block technology.

5.2 Recommendations

The study recommends that:

1. To achieve higher compressive strength in cement stabilized laterite soil, lime should be added, however, rice husk ash should be blended to enhance durability.
2. A combined system of constructing columns and ISSB masonry should be adopted to enable blocks connectivity with fresh concrete and achieve wall plumbness. The interlocking stabilized soil block walls should also be constructed on foundations built with natural stones and protected against wind driven rain.
3. To aid specification of interlocking stabilized soil block technology, clear codes of standards prescribing workmanship and construction guidelines should be developed.
4. Future studies should consider improving reliability of multiple regression equations through development of a proportional constant.

5.3. Contribution to knowledge

Performance of interlocking soil block walls has not been completely understood well in relation to its properties. This work has shown that a blend of pozzolanic cement and lime or rice husk ash improves the durability properties of interlocking stabilized soil blocks. This also leads to an improvement of the failure resistance of the overall masonry wall. This study established that a combined system of columns and interlocking stabilized soil block masonry should be adopted during construction.

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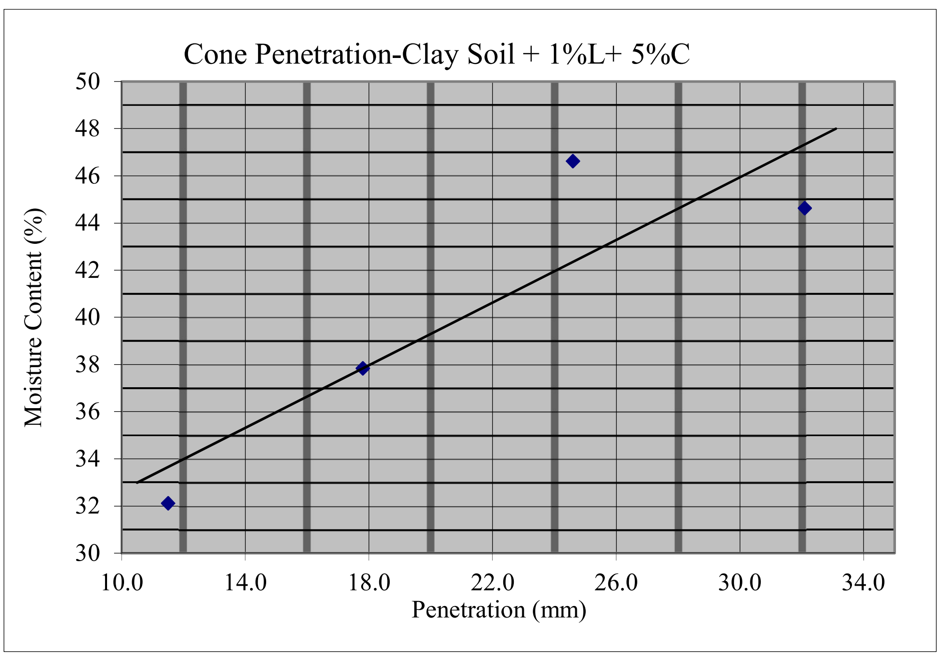
APPENDIX

Appendix I – Soil properties

A1: Stabilized clay soil Atterberg limits

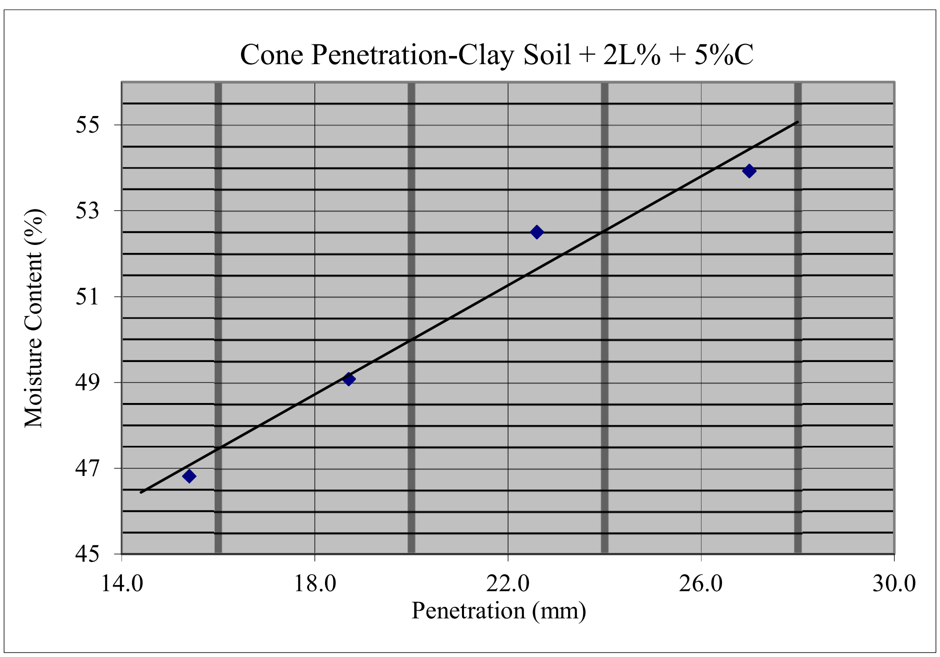
					2/16/2017	
Specimen No	**Clay soil + 1% lime + 5% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**	**1**	**2**
Penetration (mm)	11.5	17.8	24.6	32.1	xx	xx
Tin No	8A	3A	4A	12A	6A	10A
W_t of Tin + Wet Soil, m_a (g)	10.14	9.01	11.4	16.3	6.39	6.16
W_t of Tin + Dry Soil, m_b (g)	9	8	9.5	12.9	6.17	5.96
W_t of Tin only, m_c (g)	5.45	5.33	5.51	5.28	5.46	5.30
Moisture Content (%)	32.11	37.83	46.62	44.62	30.99	30.30
					30.64	

Linear Shrinkage %		
Lo (mm)	139.7	139.7
Shrinkage (mm)	10.6	10.6
Shrinkage (%)	7.59	7.59
	7.59	



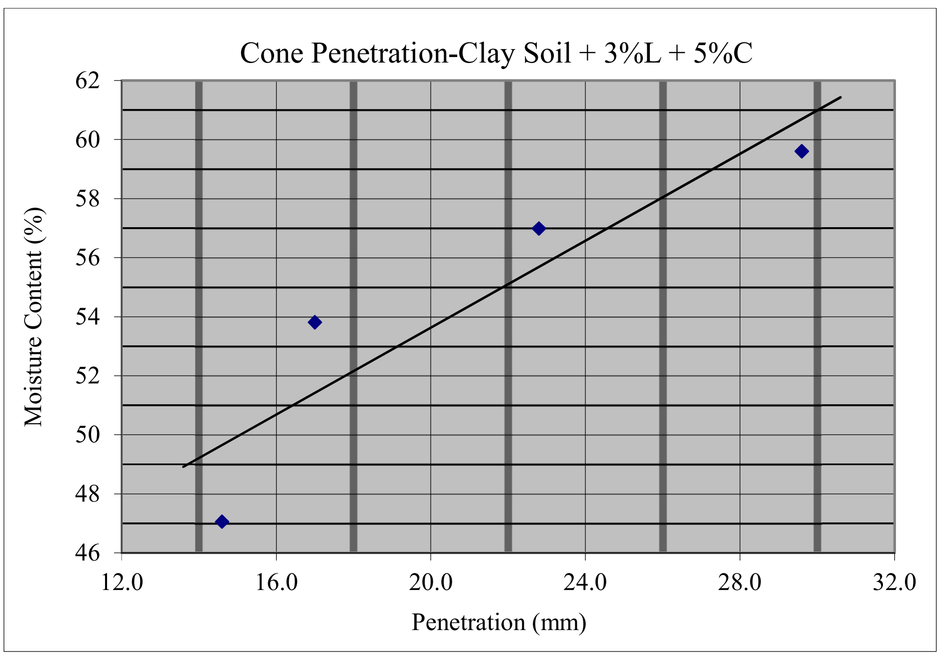
					2/16/2017	
Specimen No	**Clay soil + 2% lime + 5% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**		
Penetration (mm)	15.4	18.7	22.6	27.0		
Tin No	24	2	25	14		
W_t of Tin + Wet Soil, m_a (g)	17.5	14.18	17.6	18.09		
W_t of Tin + Dry Soil, m_b (g)	14.93	12.59	14.8	15.07		
W_t of Tin only, m_c (g)	9.44	9.35	9.42	9.47		
Moisture Content (%)	46.81	49.07	52.50	53.93		
					non-plastic	

Linear Shrinkage %		
Lo (mm)	139.6	139.6
Shrinkage (mm)	9.4	9.4
Shrinkage (%)	6.73	6.73
	6.73	



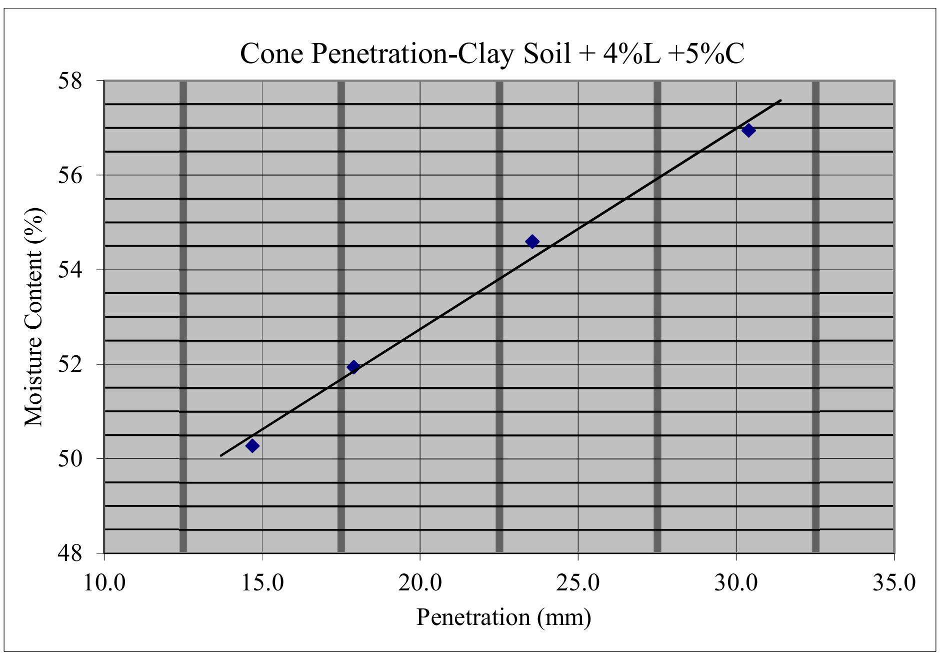
					2/16/2017	
Specimen No	**Clay soil + 3% lime + 5% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**		
Penetration (mm)	14.6	17.0	22.8	29.6		
Tin No	28	5	9	15		
W_t of Tin + Wet Soil, m_a (g)	13.43	13.58	16.6	19.07		
W_t of Tin + Dry Soil, m_b (g)	12.15	12.17	14	15.44		
W_t of Tin only, mc (g)	9.43	9.55	9.45	9.35		
Moisture Content (%)	47.06	53.82	56.99	59.61	**non-plastic**	

Linear Shrinkage %		
Lo (mm)	140	140
Shrinkage (mm)	11.1	11.1
Shrinkage (%)	7.93	7.93
	7.93	



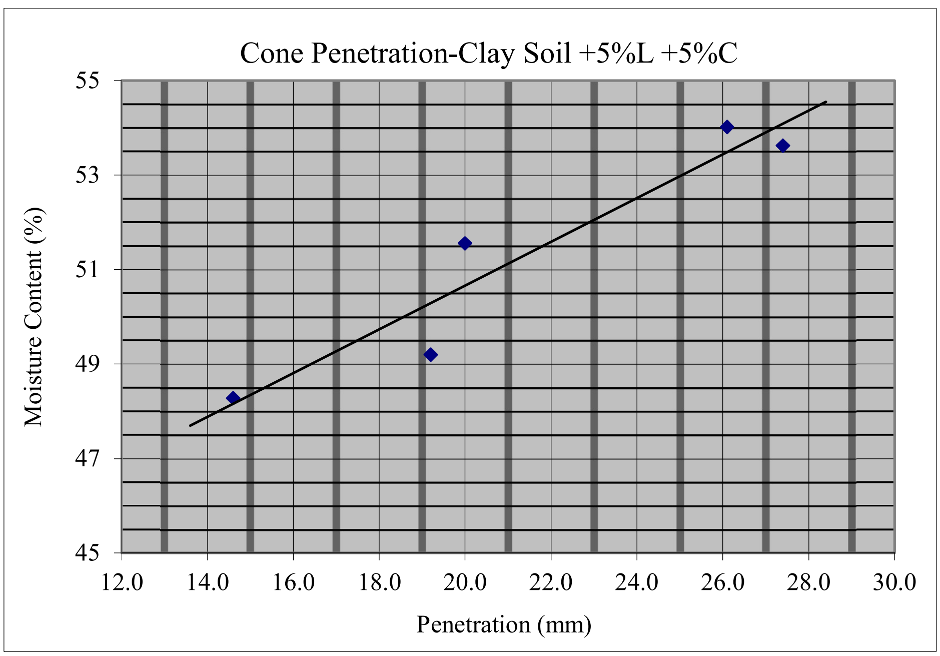
					2/16/2017	
Specimen No	**Clay soil + 4% lime + 5% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**		
Penetration (mm)	14.7	17.9	23.6	30.4		
Tin No	4	12	5A	11A		
W_t of Tin + Wet Soil, m_a (g)	15.11	18.8	15.3	14.55		
W_t of Tin + Dry Soil, m_b (g)	13.24	15.58	11.8	11.27		
W_t of Tin only, m_c (g)	9.52	9.38	5.51	5.51		
Moisture Content (%)	50.27	51.94	54.59	56.94	**non-plastic**	

Linear Shrinkage %		
Lo (mm)	139.9	139.9
Shrinkage (mm)	10.3	10.3
Shrinkage (%)	7.36	7.36
	7.36	



					2/17/2017	
Specimen No	**Clay soil + 5% lime + 5% cement**					
Type of Test	**Liquid Limit**					**PL**
Test Run No	**1**	**2**	**3**	**4**	5.00	
Penetration (mm)	14.6	19.2	20.0	26.1	27.4	
Tin No	12A	11A	3A	8A	6A	
W_t of Tin + Wet Soil, ma (g)	12.61	11.1	13.6	13.7	15.42	
W_t of Tin + Dry Soil, m_b (g)	10.22	9.26	10.8	10.81	11.94	
W_t of Tin only, m_c (g)	5.27	5.52	5.35	5.46	5.45	
Moisture Content (%)	48.28	49.20	51.55	54.02	53.62	**non-plastic**

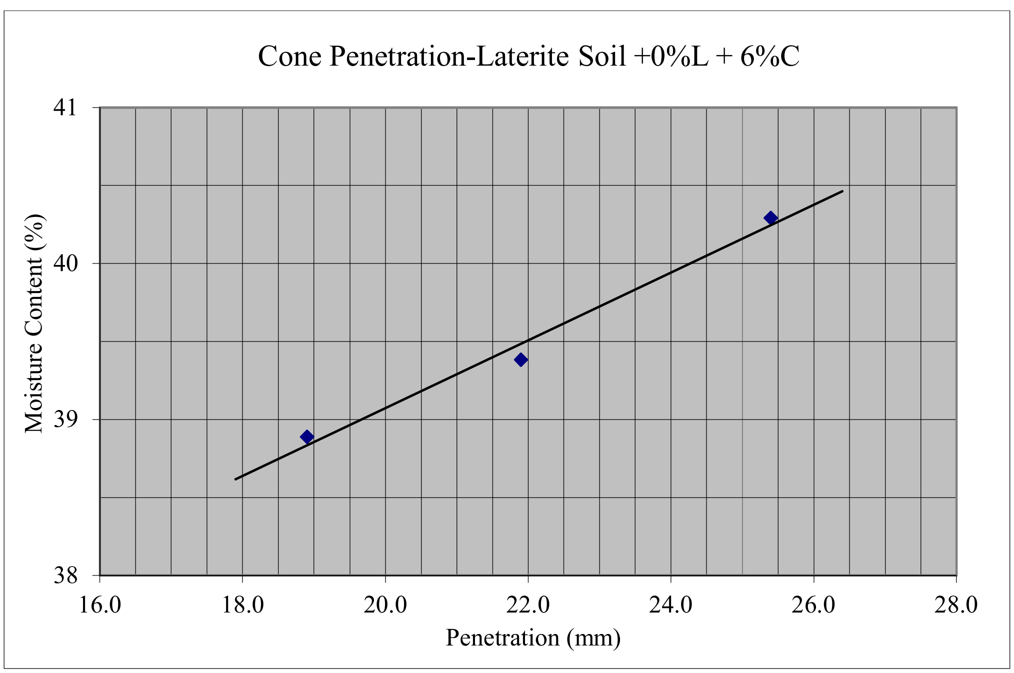
Linear Shrinkage %		
Lo (mm)	139.9	139.9
Shrinkage (mm)	7.3	7.3
Shrinkage (%)	5.22	5.22
	5.22	



A2: Stabilized laterite soil Atterberg limits

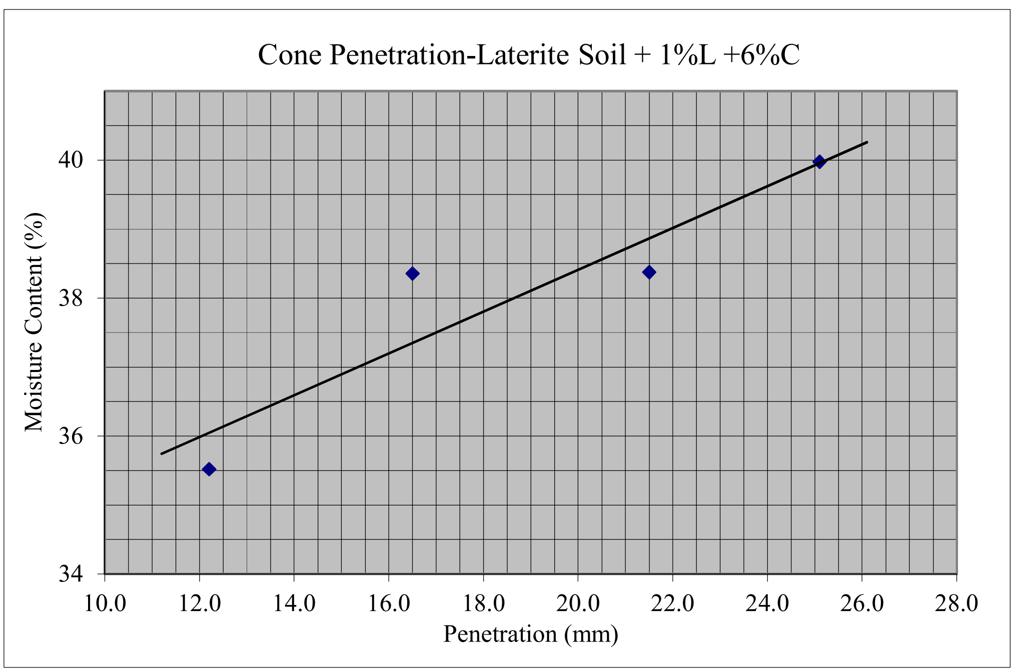
					2/20/2017	
Specimen No	**Laterite soil + 0% lime + 6% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**	**1**	**2**
Penetration (mm)	18.9	21.9	25.4		xx	xx
Tin No	9A	5A	8A		12.00	12.00
W_t of Tin + Wet Soil, m_a (g)	11.97	15.04	15.09		11.13	11.13
W_t of Tin + Dry Soil, m_b (g)	10.15	12.35	12.33		10.72	10.72
W_t of Tin only, m_c (g)	5.47	5.52	5.48		9.41	9.41
Moisture Content (%)	38.89	39.39	40.29		31.30	31.30
					31.30	

Linear Shrinkage %		
Lo (mm)	140	140
Shrinkage (mm)	7.7	7.7
Shrinkage (%)	5.50	5.50
	5.50	



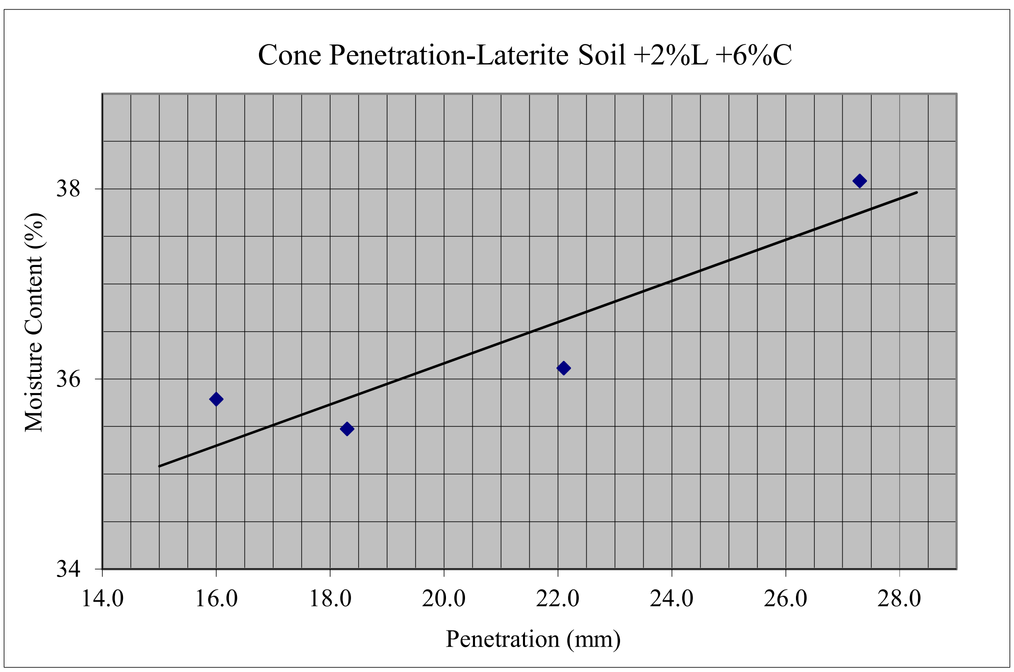
					3/17/2016	
Specimen No	**Laterite soil + 1% lime + 6% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**	**1**	**2**
Penetration (mm)	12.2	16.5	21.5	25.1	xx	xx
Tin No	14	10	4	8	9.00	9.00
W_t of Tin + Wet Soil, m_a (g)	14.88	14.46	17.03	20.25	11.79	11.79
W_t of Tin + Dry Soil, m_b (g)	13.47	13.11	14.95	17.18	11.28	11.28
W_t of Tin only, m_c (g)	9.50	9.59	9.53	9.5	9.40	9.40
Moisture Content (%)	35.52	38.35	38.38	39.97	27.13	27.13
					27.13	

Linear Shrinkage %		
Lo (mm)	139.9	139.9
Shrinkage (mm)	8.35	8.35
Shrinkage (%)	5.97	5.97
	5.97	



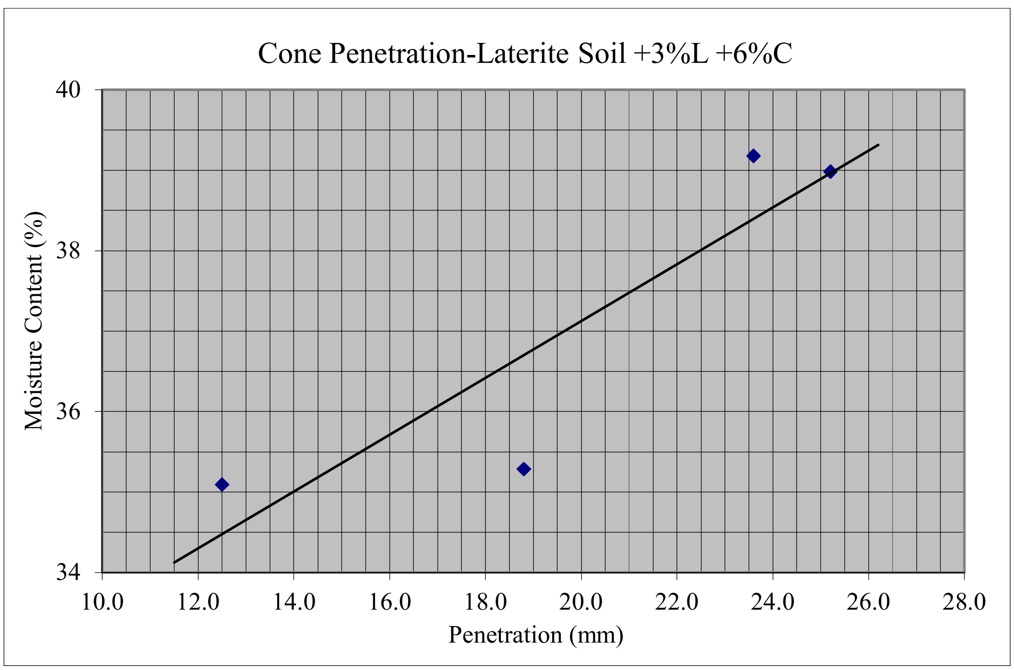
					3/17/2016	
Specimen No	**Laterite soil + 2% lime + 6% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**	**1**	**2**
Penetration (mm)	16.0	18.3	22.1	27.3	xx	xx
Tin No	15	28	5	12		
W_t of Tin + Wet Soil, m_a (g)	13.2	18.69	16.05	20.02		
W_t of Tin + Dry Soil, m_b (g)	12.18	16.26	14.32	17.08		
W_t of Tin only, m_c (g)	9.33	9.41	9.53	9.36		
Moisture Content (%)	35.79	35.47	36.12	38.08		
					non-plastic	

Linear Shrinkage %		
Lo (mm)	139.7	139.7
Shrinkage (mm)	6.15	6.15
Shrinkage (%)	4.40	4.40
	4.40	



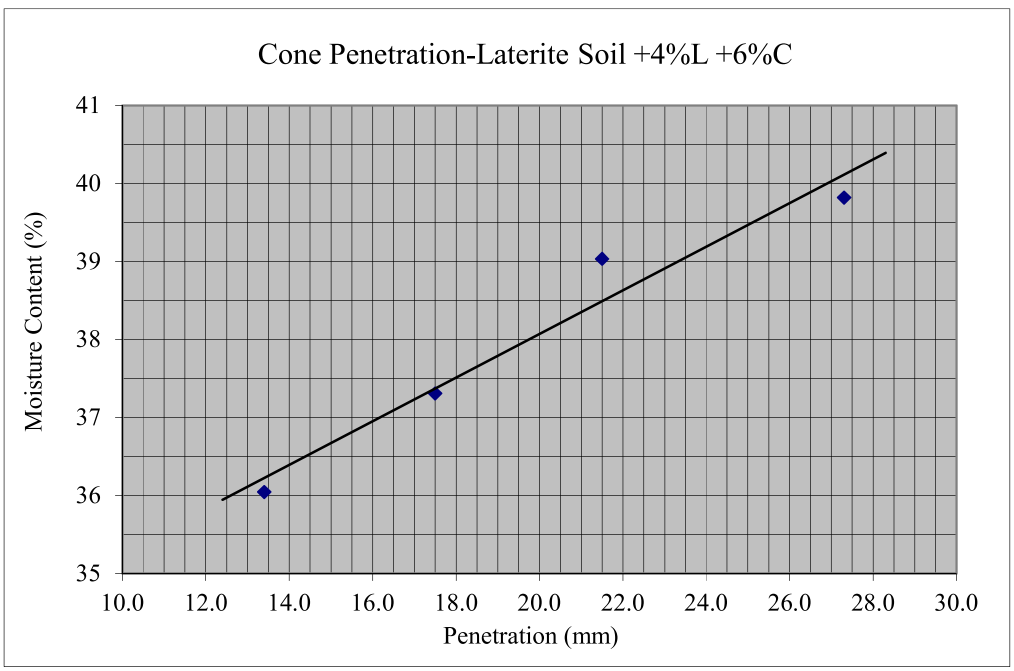
					3/17/2016	
Specimen No	**Laterite soil + 3% lime + 6% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**	**1**	**2**
Penetration (mm)	12.5	18.8	23.6	25.2	xx	xx
Tin No	7A	4A	5A	12A		
W_t of Tin + Wet Soil, m_a (g)	9.8	12.95	14.66	13.49		
W_t of Tin + Dry Soil, m_b (g)	8.67	10.96	12.09	11.19		
W_t of Tin only, m_c (g)	5.45	5.32	5.53	5.29		
Moisture Content (%)	35.09	35.28	39.18	38.98		

Linear Shrinkage %		
Lo (mm)	140	140
Shrinkage (mm)	8.1	8.1
Shrinkage (%)	5.79	5.79
	5.79	



					3/17/2016	
Specimen No	**Laterite soil + 4% lime + 6% cement**					
Type of Test	**Liquid Limit**				**Plastic Limit**	
Test Run No	**1**	**2**	**3**	**4**		
Penetration (mm)	13.4	17.5	21.5	27.3		
Tin No	11A	8A	10A	9A		
W_t of Tin + Wet Soil, m_a (g)	10.56	13.54	15.4	13.09		
W_t of Tin + Dry Soil, m_b (g)	9.23	11.35	12.57	10.92		
W_t of Tin only, m_c (g)	5.54	5.48	5.32	5.47		
Moisture Content (%)	36.04	37.31	39.03	39.82		

Linear Shrinkage %		
Lo (mm)	139.9	139.9
Shrinkage (mm)	6.85	6.85
Shrinkage (%)	4.90	4.90
	4.90	



Appendix II – Interlocking stabilized soil block properties

B1: 24-hour water absorption by blocks

24-hour water absorption					
CLAY SOIL					
Sample	Block	Mass 1 (gms)	Mass 2 (gms)	% water absorbed	Comments
1	5%CD	8684.5	10600	No measurement	Crumbled in water
2	5%CD				
1	10%CD	8624.5	10200	18.27	Blocks had an intact shape
2	10%CD	8520	10000	17.37	
				17.82	
1	15%CD	8362	10074	20.47	crumbled into bigger pieces
2	15%CD		10900		
1	20%CD	7863	11700	48.8	Blocks bulged but they could
2	20%CD	7991.5	12300	53.91	be lifted out of water and
				51.36	the corners were not broken
1	5%C	9376	10000	No measurement	An irregular shaped block
2	5%C	8564	none		was achieved with pieces
					spalled off
1	5%C1%L	9226.5	10449	13.25	edges crumbled only
2	5%C1%L	10750.5	12400	15.34	
		10596	12500	17.97	
				16.66	
1	5%C2%L	9392.5	none	No measurement	
2	5%C2%L	9396.5	none		
1	5%C3%L	10090.5	10900	8.02	Blocks had cracked severally
2	5%C3%L	9819	11400	16.1	but could be lifted out of water
				12.06	
1	1%C5%L	8770.5			Disintegrated in water and
2	1%C5%L	9439	13500	43.02	were disfigured
1	2%C5%L	9757	none	No measurement	Blocks completely disfigured
2	2%C5%L	9867	none		and disintegrated in water
1	3%C5%L	8983.5	none	No measurement	
2	3%C5%L	10368.5	none		

Sample	Block	Mass 1 (gms)	Mass 2 (gms)	% water absorbed	Comments
1	4%C5%L	9642	None	No measurement	The blocks completely disintegrated in water and could not be weighed
2	4%C5%L	9504.5	None		
1	5%C5%L				
2	5%C5%L				
1	5%CD6%C	9453.5	10777	14	Cracks at the surface
2	5%CD6%C	9436	10845	14.93	
				14.47	
1	10%CD6%C	8700.5	10500	20.68	no cracks at the surface and the block was intact
2	10%CD6%C	8635	10400	20.44	
				20.56	
1	15%CD6%C	9079.5	None		
2	15%CD6%C	9205	10943.5	18.89	
1	25%CD6%C	8083	None	No measurement	block disintegrated
2	25%CD6%C	8039	None		

B2: Abrasion resistance of clay soil blocks

CLAY SOIL BLOCKS				
Block	Sample	Weight before	Weight after	% abrasion
5CD6C	1	9741.5	9470.5	2.78
	2	9707.5	9571.5	1.40
				2.09
10CD6C	1	8264	8142	1.48
	2	7466	7267	2.67
				2.07
15CD6C	1	8019.5	7895.5	1.55
	2	7822	7619.5	2.59
				2.07
25CD6C	1	6970	6807.5	2.33
	2	7210	7059.5	2.09
				2.21
5CD	1	8684.5	8592	1.07
	2	8925.5	8870.5	0.62
				0.84
10CD	1	8111	7822.5	3.56
	2	6910.5	6531	5.49
				4.52
15CD	1	8118.5	8047.5	0.87
	2	8090.5	7968	1.51
				1.19

20CD	1	9245	9145.5	1.08
CONTROL	1	8287.5	8048.5	2.88
1L5C	1	9425.5	9284	1.50
	2	9310.5	9161	1.61
				1.55
2L5C	1	7620	7488	1.73
	2	8036.5	7926.5	1.37
				1.55
5L5C	1	9657	9541	1.20

B3: Abrasion resistance of laterite soil blocks

LATERITE SOIL + CEMENT + LIME				
Block	Sample	Weight before	Weight after	% abrasion
6C	1	11000.5	10936.5	0.58
6C1L	1	11011.5	10958	0.49
6C2L	1	11197.5	11160	0.33
6C3L	1	10623.5	10580	0.41
6C4L	1	10677.5	10648.5	0.27
LATERITE SOIL + CEMENT + RHA				
Block	Sample	Weight before	Weight after	% abrasion
5RHA	1	10777	10715	0.58
	2	10661	10445.5	2.02
				1.30
6C5RHA	1	10719.5	10630	0.83
	2	10508.5	10145.5	3.45
				2.14
6C4RHA	1	10851	10814.5	0.34
	2	10978	10921.5	0.51
				0.43
6C3RHA	1	11610	11558.5	0.44
	2	11364.5	11331.5	0.29
				0.37
6C2RHA	1	10951	10927	0.22
	2	11128	11102	0.23
				0.23
6C1RHA	1	11105	11053	0.47
	2	10773.5	10719	0.51
				0.49

Appendix III – Guidelines on using stabilizers

	Target soil: **Laterite**				
	Mix proportions for optimum				
Stabilizer blend	Compressive strength	Water absorption	Abrasion resistance	Walling use	Remarks
6%C	*				
6%C2%L	*	*	*	√	Adequate compressive strength with good abrasion resistance
6%C3%L	*				
6%C1%RHA		*			
6%C2%RHA			*		RHA improves on abrasion resistance
	Target soil: **Clay**				
5%C1%L	*	*		√	Adequate compressive strength; susceptible to weathering
2%C5%RHA			*		
10%CD		*	*	√	Wall will inhibit water absorption and resist abrasion

Appendix IV – Participant consent form

JOMO KENYATTA UNIVERSITY

OF

AGRICULTURE AND TECHNOLOGY

Consent Form for Participation in a Research Study

Social Acceptability of Interlocking Soil Block Technology in Kenya

My name is Isaac Fundi Sanewu, a doctoral student at Jomo Kenyatta University of Agriculture and Technology. You are invited to participate in a research study whose purpose is to evaluate the social acceptability of interlocking soil block technology in Kenya's construction industry. The research is for educational purpose and may give useful information in developing affordable and acceptable building technology. You have been selected as a potential respondent in this research due to your knowledge of the interlocking soil block technology. You are not required to write your name on this questionnaire and your identity will not be revealed. Your participation will involve responding to the questionnaire and oral interview questions. There is no right or wrong response only your most sincere response is required.

Please confirm that you have read the above information and accepted to participate in the survey by signing the following consent form.

Consent

I have read the above information and understand that the survey is voluntary and that confidentiality and anonymity are guaranteed to me as a participant. I therefore hereby accept to participate in the survey.

Participant's signature………………… Date……………………………………

Appendix V – Interview schedule responses

Category one (Users of the technology)

Participant

1. *What type of houses are done using this technology*

For smaller residential houses including bungalows and maisonette.

The technology is mostly used for residential and not commercial buildings

It has also been used as infill unless proven to carry heavy loads. This is because the blocks are thought to have low compressive strength. They are therefore not common in construction.

The blocks can be used for low cost housing both at urban and rural areas. The technology can be conveniently used in construction of:

- Residential houses
- Class rooms
- Institutional offices

2. *In comparison to conventional walling materials, how can you rate ISSB technology performance?*

They are economical. Conventional blocks present challenges in cutting them, and consumes time in transporting them to the site of works

Conventional blocks require cement to join them hence, adding on the cost of construction

ISSB have natural appearance and are appealing on the surface

3. *What are the challenges of ISSB?*

Quality control in making the blocks at the manufacture level

Connectivity between walls and beams and columns when used as infills. This results to cracking along these zones

It is challenging to introduce whoop irons in the walls

It has challenges when exposed to weather (water, sunshine, etc.)

4. *What makes the ISSB technology not to be easily adopted in construction industry?*

- Developers have fear of change from what has been used over a long period of time
- People need to be informed about the technology
- People exposure to the technology in lacking
- Perception

5. *What attractive feature of ISSB that led you to its use?*
   - Appearance, its aesthetic value
   - Lightweight
6. *What feature need to be improved in the ISSB?*
   - Its durability
   - Compressive strength
   - Educate people on the technology
   - Production of different designs and shapes

Participant

1. *How will you say is the performance of ISSB?*

The performance is encouraging since there are no repairs carried out for the last four years of occupancy.

The blocks are cheaper and easy to maintain

2. *From your experience with this kind of technology, which kind of houses will you suggest to be constructed using ISSB?*

Residential houses, not commercial structures. Extra excavation may be required when doing commercial buildings to achieve a better foundation.

3. *What are the visible deteriorating features of ISSB?*

The first laid courses are susceptible to water absorption if stagnant water is left for a long time. The structure should be built on a raised ground floor and the area well drained.

4. *What should be done to improve on performance of ISSB?*

More cement should be used to make the blocks harder. An alternative stabilizer should be considered to improve strength and durability of the blocks.

Composition of the soil to be improved: a better target soil should be used.

(*Observed: blocks made by marram were better than red clay soil*)

5. *What attractive attributes does ISSB have?*

Affordable – the raw materials are easily available and the labour is affordable

The shape of the blocks is regular. They interlock without use of mortar and the structure can be occupied with or without internal plaster

6. *What makes the technology not to be adopted highly by developers?*

- Fear of unknown
- Enough information is lacking among developers

7. *How safe is it under a ISSB structure?*
   - The house is safe
   - There have no reported cases of burglary due to unpacking of the blocks.

General comments

Durability of the blocks to be improved

Better composition of constituent materials

There is need of awareness campaign to be carried out

Participant

1. *What type of houses can be built with ISSB?*

Single storey houses or bungalows

For high rise structures, different material should be considered since the thickness of ISSB is bigger increasing loading on the structure.

The technology is also sensitive to poor proper control which if not well executed could lead to failure

2. *Where can this technology be used?*

The technology is generally labour based. Due to this it can fit well in rural areas as opposed to urban where the trend is mostly mechanization. This leads to creation of employment in the rural set up.

3. *What are the qualities that lead to adoption of ISSB?*
   - Appearance (good aesthetic) – in construction most clients consider appearance of building as a first attribute before considering structural strength.
   - Low cost – one can save up to more than 30%
   - Colouring – it is possible to incorporate coloured dyes to enhance the appearance of the blocks.
4. *What attributes should be added to improve on the technology?*
   - Improve on durability – durability has been the major concern. Where blocks are used in walls exposed to rain, without adequate veranda, the walls once rained they tend to be eroded.
   - External finishes should be improved to enhance durability of the blocks.

- Improving the compressive strength: according to the Kenyan construction standard, the minimum strength for infill blocks is 2.5N/mm^2. For the ISSB to be used as load bearing walls, the strength should be improved to about 7N/mm^2 in order to equally compete with other conventional blocks.
- The connectivity between ISSB and concrete frames should be improved. Soil is more dense than normal blocks, therefore for them to be used in framed structures it will require special design in order to accommodate any additional loading.

Example: in constructing JKUAT hall 7 it was suggested that ISSB to be used in constructing the walls. However, this lead to jacketing of columns in order to carry the extra load introduced by ISSB.

The behaviour of ISSB and reinforced concrete as a composite material needs to be further studied.

5. *Why is the adoption rate of this technology low?*
    - Attitude: traditionally, construction was done by use of mud. Since the blocks are made of soil, developers have a feeling that it tends to reverse the progression of technology towards use of stronger and prestigious materials.
    - Kenyans are slow in accepting changes – besides the technology being used in other countries, Kenyans are sceptical in accepting a new technology.
    - Standards are missing – the designers are not ready to use a material that has no well-known standards. The training of designers has only been towards use of conventional materials. The training curriculum need to capture alternative materials so that the designers would not find challenges in specifying their use to the clients.

General comments

More need to be done to produce ISSB of good strength

We should re-look on stabilization since it is not adequate of the target oil materials. A good stabilizer should be established which can enhance bonding to improve on the mechanical properties.

Participant

1. *What kind of structures can be constructed using the ISSB technology?*
    - It is mainly used for residential use
    - It is also well suited as infill material and as wall portioning but not as load bearing walls in framed structures.
2. *What features make the ISSB to be adopted?*

- Easy of construction – the interlocking nature of the blocks makes the construction first and time saving.
- The block surfaces are neat which reduces the cost of plaster work
- They can be moulded on site, making them to be easily controlled on workmanship
- The transportation cost is low since they can be produced on site
- It is not easy to get regular shaped bush stones as compared to ISSB. The bush stones have to be cut and shaped which add to their cost.

3. *What are the deteriorating features of the ISSB?*
    - When the blocks are not well cured, the plaster work tend to peel off due to quick absorption of the water by the plaster paste
    - They experience a lot of breakages when mishandled.
    - When used as external wall, they absorb water making the surface dump which affects plastering.
    - Some blocks are not well made from the mix proportions.
4. *What features should be improved in ISSB?*

There is no legal framework for alternative materials in the construction industry. There is no building code which exists that provides adoption of the alternative materials. This has led to the current procedure which is based on experience, previous use and knowledge gained on site.

The workmanship needs to be controlled to enable production of regular and uniform units.

5. *How safe are houses built with ISSB?*

It is just a perception that ISSB houses are not safe. Safety and security is in the mind. If they are done well, they are safe.

General comments

ISSB is a good material which can save on time and ideal for mass production like in office block portioning.

Engineers need to develop guidelines and standards for alternative materials for use in the construction industry.

Participant

1. *What type of houses can be constructed using this technology and where can they be located?*
    - The technology provides ease of construction and it was used in constructing JKUAT Technology House ground floor.

- Around Juja, the blocks are however not viable since the readily available Ndarugu blocks makes them appear expensive.
- They can be used in places where there are no block quarries.

2. *What are the attractive features in ISSB?*
   - Once you construct with ISSB their two faces are lean and at the interlocking point they make a natural key decoration.
   - On the inner side there is no much plaster work compared to conventional blocks whose sides are not regular.
3. *What are the challenges of constructing using ISSB?*

Moulding of the blocks – where manual machines are used, the number of blocks produced per day is very low to be used in a big project. This may require a lot of manual laborers. It may then restrict it to implementation of smaller projects.

4. *What are the deteriorating features of ISSB walls?*
   - For Ndarugu blocks, one has to been keen on quality of blocks produced from the to layers of the quarry, since they are weak on compressive strength. However, for ISSB one should check on the mix because the blocks which are moulded without a proper binder result into disintegration when drying or when they absorb water. Also, when moulding them, too much water increases their shrinkage.
   - The roof eaves have to be bigger enough to protect the walls from splashing rains
   - When the blocks are properly done, they have no major challenges.
5. *What attributes should be improved on ISSB?*
   - The mix should be improved with a balance between cost and required strength.
   - Alternative binders should be sourced to make them cheaper.
   - Different types of soils (murram, Ndarugu quarry dust, etc.) can be added to improve in qualities and colour
6. *What is the cost of ISSB?*

It will depend on the location where they are used. If they are used near block quarries, their cost will not be favourable as compared to when used in regions far from quarry sites.

7. *How safe will you be under an ISSB house?*
   - It is safe since the blocks are joined to other structural members. Safety will depend on how the wall is constructed.
   - The wall absorbs shock once it is bunged.

General comment

The block making machine should be mechanized so that to improve its productivity.

Participant

1. *What type of houses can be constructed using this technology?*

They can construct storey structures and perimeter walls. The blocks are similar to coral blocks in terms of their performance.

The blocks can be moulded in different mixes for building house walls and those for doing perimeter walls (fencing walls). However, for house walls the compressive strength is supposed to be higher.

2. *How safe is it to live under houses build with ISSB?*

The house is very safe. Once you are in that house, you will feel safe just like in any other house.

3. *What the good attributes in this technology?*
   - They are cheap, there is no usage of cement during joining of the blocks.
   - The walls have a very pleasing natural finish
   - Very fast in wall construction (they take short time in construction)
4. *What are the challenges of this technology during construction?*

During construction, the plumbness can be challenging when you do high walls without columns. One need to do 10 courses high and about 10 feet long before casting a column. Otherwise the wall will not remain in plumb.

5. *What is the cost of ISSB as compared to conventional walling material?*

It is less costly as compared to conventional coral blocks. The coral blocks are very expensive due to high buying price and transportation cost.

6. *Why is the adoption rate of the ISSB very low?*

May people are lacking awareness about them.

The technology is relatively new in the Kenya construction market and people have not fully embraced it.

7. *What should be done in order to increase its adoption amongst developers?*

Demonstration houses should be constructed so that developers would have the benefit of seeing how it is carried out and check its performance.

General comments

- Blocks moulded using coral stone dust (*Kifusi*) seem to produce smooth surfaces and a produced a cling sound when hit with a metal.
- The columns should be done after constructing the wall up to a height of about 1200mm before proceeding with the stacking of the blocks. This will encourage bonding of the concrete column with the blocks and also encourage maintenance of the wall plumbness.

Participant

1. *What type of house can be constructed using the ISSB technology?*

Commercial buildings used as recreational/entertainment centres. For residential houses, it may require the walls to be plastered.

2. *What are the attractive attributes of this technology?*
   - Have a good interior décor. Where they have been used, there is no need of placing a wall paper.
3. *What are the challenges of this technology?*

It doesn't have much challenge since it doesn't get rust along this coast line where there are high concentrations of salt. However, it has some problems during hacking to place electrical wiring and plumbing pipes.

4. *Why is the adoption rate low?*
   - Lack of awareness.
   - The technology has also not been used in many construction projects.
5. *How safe is it to stay in a house built using ISSB?*

It is safe. The blocks are tightly packed and it is not very possible to unpack them once the top beam is in place.

Participant

1. *What kind of houses can be constructed using ISSB?*

They can be used for both residential and commercial use

2. *What are the construction challenges faced when using ISSB?*

If the blocks don't have adequate cement content, they tend not to be durable. However, with good soil and proper cement their performance is good.

3. *What are the good qualities of ISSB?*
   - The house walls are attractive
   - The blocks don't use cement when interlocking

- The interlocking of the blocks is very easy. They are interlocked up to the lintel level before doing a ring beam.

The houses done with ISSB have a good interior conditions (have a controlled temperature)

4. *What are the deteriorating features in ISSB houses?*
    - The house needs to be occupied otherwise it deteriorates.
    - The roof eaves if are shorter, they allow wind driven rain to splash on the walls, causing them to be eroded.
5. *What should be done to improve the qualities of ISSB?*
    - The structural stability should be improved so that even if dropped they cannot break
    - Their water absorption should be reduced
6. *Why are the ISSB not used much by developers?*

In Taita-Taveta county, the moulding machines are not very many

Participant

1. *What are the best applications of ISSB?*

They are best used as infill for framed structures

2. *What are the attractive qualities of ISSB?*

When polished they look attractive in their natural appearance

The block sizes are equal allowing good finishing

3. *What are the deteriorating features of walls constructed using ISSB?*

If right soil is used, they are very durable

No cracking unless poor workmanship

4. *What makes the ISSB not to be adopted by developers?*

They are not in Taveta due to availability of natural stones which are relatively cheap.

The code of standard is also missing, making the developers sceptical using them.

5. *How safe are occupants living in ISSB houses?*

When the structure is well designed, they are safe.

When the blocks have been interlocked to construct the walls, it is very difficult to unpack them.

General comments

The size of the blocks can be considered to be increased din order to reduce the cost of production.

Awareness on performance of ISSB should be enhanced for developers to appreciate them.

Participant

1. *What type of houses can be constructed using ISSB?*

Institutional buildings. They can be easily maintained in those set ups due to availability of knowledge of the technology

2. *What qualities of ISSB are desirable as compared to other walling materials?*

They are light in weight than conventional blocks.

They produce good thermal effect to the occupants in the house

When they are made using a good binder, they sustain a high compressive strength

3. *What are the deteriorating features that can be identified in ISSB walls?*

The bottom part of the wall experiences spalling effect. They tend to behave as if they have been over stressed

They also absorb a lot of water

4. *What features should be added to improve on the ISSB qualities?*

Consider using plastics material in order to reduce weight and water absorption

A better compacting effort should be employed to produce a denser block and increase their compressive strength.

5. *What is hindering the adoption of this technology?*

To construct a structure, the blocks are required in mass which has not been well achieved

The culture of developers to be used to conventional construction materials has made this technology to be fully adopted by them.

The binders used are expensive

Government and other development agencies have not constructed many demonstration projects to depict the performance of this technology in different regions of the country.

6. *How safe are occupants in houses constructed using ISSB?*

Once they understand the behaviour of the wall, they will feel safe.

Presence or absence of mortar in masonry have no much effect when the load is purely applied axial loads. More so the interlocking key is adequate to provide the structural stability of the walls.

General comments

Experts should develop a standard to aid in adoption of this technology. Users may misuse the technology and lead to compromise on quality of the blocks.

Category two (Non-technology users)

Participant

1. *What type of houses do you think can be constructed using this technology?*

Since the technology is new, most people prefer constructing residential houses using it

It seems to be more adopted in residential as opposed to commercial because developers are concerned of safety when it comes to commercial buildings.

However, this has been aggravated by lack of awareness of the technology leading to development of negative attitude towards it.

2. *Where are these houses likely to be located?*

Mostly in rural areas: this is because it is easier to construct semi-permanent houses in the rural regions

The technology can however be adopted in towns when one wants to cut on construction cost.

3. *What features of ISSB do you really like?*
    - They are cheaper
    - Durable as compared to other walling materials like timber. Timber is prone to destruction by termite, harsh weather and very susceptible to fire.
4. *What qualities of ISSB you would suggest to be improved?*
    - Aesthetic value – have varied colours, texture, etc.
    - Awareness to developers
    - Flexibility of the blocks: can they be used to construct other structural elements besides walls?
5. *What are the deteriorating features that can be identified in ISSB?*

Cracking if not properly aligned during stacking

Variation in workmanship – some are poorly done

Varied performance under acts of nature – performance under earthquakes, flooding, Will they allow water to seep through if submerged under water? This may require a good interior finishing to avoid water seepage.

6. *How is the cost comparison to other wall construction materials?*

The ISSB are much cheaper – there is no transportation to the site of works as compared to the conventional materials.

There are many risks associated with quarrying of conventional blocks (cave in of quarries, flooding of quarries)

7. *Do you think houses built with ISSB are safe?*

When you get in a house built with ISSB and has good internal finishing you will not even feel that it is unsafe. If they are well done they are be safe.

The following general concerns were noted:

Is there a guided ratio to mix the constituent materials?

How is the production controlled, since developers can abuse it by adopting shortcuts? Is there a standard which is existing to control its production?

Ndarugu machine cut blocks are already made, therefore its control is not a problem as compared to the ISSB which an individual has to mould them.

They government should have a policy/standard to enable the adoption of this technology

It was noted that there has to be a <u>balance between cutting down construction cost</u> vs <u>control of performance of the material</u>.

Participant

1. *Compared to conventional masonry, where can the ISSB be used as a substitute?*

Construction of smaller projects

In provision of low-cost houses in case of mass production to displaced persons. This is convenient since conventional construction is a little expensive.

Availability of conventional wall blocks can be expensive when location of the construction site is considered.

Concrete blocks are also expensive due to the high cost of cement. However, the adoption rate of the ISSB is still low.

2. *What qualities of ISSB need to be improved?*

Standards are missing which would address structural strength.

There is no much involvement of the industry actors

Perception – the ISSB is considered a cheaper material “not to satisfy construction industry requirements.” This has contributed to a negative perception about its durability.

Develop a code of practice and create awareness campaign or framework

Specification of materials is lacking – more so to the designers (architects, civil engineers, etc.). the designers are not specifying the use of this blocks in different projects. This has been contributed by lack of code of standards.

The designers also need to be assured of the performance of the technology in order to aid them in specifying the blocks to clients.

Workmanship needs to be standardized

The qualities and benefits of the blocks need to be told in order to encourage their uptake by many developers.

3. *What features would you suggest to be added to the ISSB?*

Standardization/specification documents.

Awareness to the construction industry actors. The level of awareness is low.

4. *What are the deteriorating features that can be identified in ISSB walls?*

This can be viewed in terms of function – the position where the blocks have been used.

Example: if they are used as exterior walls, what is their degree of dampness? What are their thermal properties?

5. *How safe are structures built with ISSB?*

Safety is not guaranteed because:

Suspicious of the block bonding. This lead developers to question how is it easy or difficult to unpack the blocks from the wall?

How many stories can someone be able to construct suppose they are considered as load bearing blocks?

General comments:

A clear standard should be developed to enable specification by designers to clients

Question about; do they last? Do they have adequate strength? How strong are they? Should be addressed through campaign awareness.

Participant

1. *What type of houses can be constructed using ISSB technology?*

It is used in residential houses.

From where I have seen it used, the developer bought the interlocking block making machine for production of the blocks. He used the blocks to construct rental units.

2. *What are the challenges that were experienced when using the blocks?*

There was lack of skilled labour; at that time there were no trained personnel to use the machine and ratios of the soil.

The material on site were also not very good for the production of the blocks that made few blocks to be produced per day.

3. *What qualities of the blocks can make you use them for your construction?*

The house is still strong 4-5 years down the line.

I can then use them on a small commercial structure.

4. *What should be done so that the uptake can be increased?*

Big developers should be advised to use the technology in order to convince many people that the technology is adequate

The technology should be used in many other places for developers to experience its performance

The aesthetic of the blocks need to be improved with varied colours and sizes.

5. *What are the deteriorating features that you have observed in the constructed walls?*

There are no visible physical deteriorating features for the last 5 years of the structure.

The walls of the house didn't absorb water, though the soil in that site have good drainage. However, on a different location where a similar house has been done on a swampy place, did not absorb too much water. There was no challenge of paint peeling as well.

The performance on site of the ISSB is almost similar to that of conventional walling materials.

6. *What is the cost of ISSB as compared to conventional materials?*

He didn't have an idea on the cost but from what he has been informed, the technology is cheaper than conventional walling materials.

7. *Will you feel safe living under an ISSB house?*

No. This is because no one has provided a proof of consent that ISB can withstand small vibrations. How will the wall behave if it is hit by intruders?

Though from where the blocks have been used he has not heard of any reported cases of burglary though unpacking of the blocks.

General comments

The technology needs more marketing and training of users.

The technology should be used widely and people encourage to live in houses constructed using the technology so that it can demystify the fears.

There are no standards that have been shared for the use of the technology.

Participant

1. *What type of houses can be constructed using ISSB technology?*

It is used in residential houses.

This is because residential houses are continuously occupied which then provides security to them. If it is used in isolated places, the house can easily be broken in.

2. *Where is the technology best suited in application?*

In rural areas since the raw materials are easily available.

In urban areas – due to rural urban migration coupled with low income, the technology will assist in providing decent and cheap houses. In addition, the risks of fires in informal settlement will be highly reduced if this technology is used, since earth will not enhance spread of fire.

3. *What are the attractive attributes of this technology?*
    - Natural attractiveness
    - Modern construction achieved through earth
    - Interlocking gaps of the blocks introduces aesthetics
4. *What are the deteriorating features of ISSB?*

When scrubbed by hard substances on the un-plastered surfaces (or animals shedding themselves against rain) they tend to be weathered.

5. *Why is the adoption rate low?*

Awareness about the blocks is low.

6. *What is the safety of persons living under houses constructed sing ISSB?*

They are safe. The blocks cannot be unpacked, however their resistance to impact force might be questionable.

Participant

1. *What type of structures can be built using ISSB?*

Commercial buildings. This is because they provide a cheaper material to start off your business.

2. *What qualities of ISSB are good?*

They have an attractive finishing

3. *What features need to be improved in ISSB?*

Development of design standards

The thickness of the blocks should be reduced to enable minimal weight

4. *Why are ISSB not being adopted in major construction of structures?*

Culture of developers to use conventional materials

Lack of knowledge about the technology

5. *What are the identifiable deteriorating features of ISSB structures?*

Erosion of surface by wind driven rain. However, they don't experience too much cracking

6. *How safe are occupants in ISSB structures?*

They are safe since other structures are constructed with iron sheets and people leave in them. Interior finishing of the walls improves their safety.

General comments

The ISSB are cheaper way of construction

They also enable faster construction

Appendix VI – CINVA-Ram press machine manufacturer information

The CINVA-Ram block press consists of a mould box in which a slightly moist soil mix is compressed by a hand-operated toggle lever and piton system. The machine has a tare weight of 60 kg and employs a maximum compacting pressure of about 2 MN/m^2. The all-steel machine produces blocks 210 mm long 210 mm wide and 90 mm thick

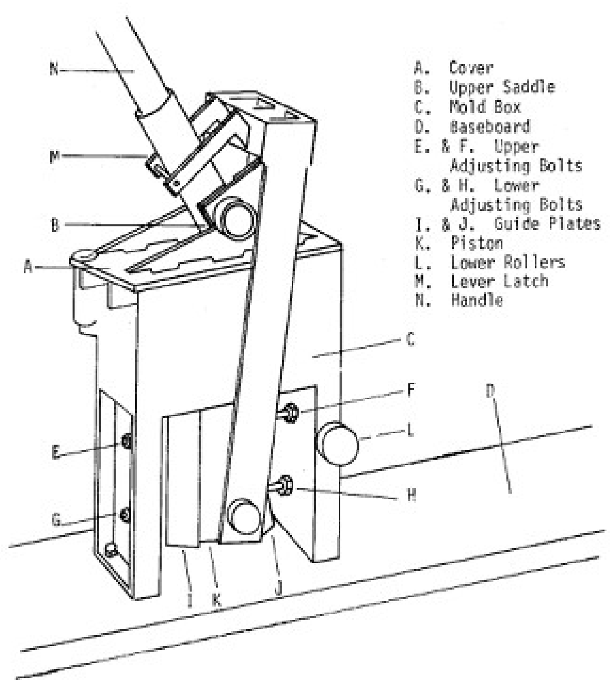


Figure F1: The CINVA-Ram block press machine