Development of Cost-Effective Earthen Building Material for Housing Wall Construction: Investigations into the Properties of Compressed Earth Blocks Stabilized with Sisal Vegetable Fibres, Cassava Powder and Cement Compositions.

A Doctoral Dissertation, Approved by the Faculty of Environmental Science and Process Engineering of the Brandenburg Technical University Cottbus and Submitted in Fulfilment of the Requirements for the Award of the Degree of Doctor-Ingenieur

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Entwicklung von preisgüstigen Erdbaustoffen für Wandkonstruktionen: Untersuchung der Eigenschafften von gepressten Erdblöcken stablisiert mit Sisalfasern, Maniokpulver und Zement

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Declaration

I, Saul Namango, hereby do declare that I have personally written this doctoral dissertation, and that I have done so only with the assistance of the literature sources and other supportive material herein contained and mentioned.

Saul Namango
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For love, patience and support of Rosemary Nabonwe, Marsha Wabuti, Juanita Namenya, Tim Asomba and Peggy Pendo.

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I thank God for the strength he gave me so as to go through this very challenging moment of my life.

Abstract

Need to develop affordable housing is necessary because of the numerous homeless people living in the developing countries; the present work is an attempt to alleviate the housing problem facing populations of these countries.

In the current investigations, a study programme illustrating the effect of various sisal, cement, cement-sisal and cassava proportions to the compressive strength, flexural strength, dry block density and porosity of compressed earth blocks (CEB) is outlined. A constant volume manual press has been used to fabricate earth blocks, at a fairly uniform pressure. The relationship of strength, block densities and porosity to reinforcement levels has been determined.

A considerable increase in strength with increasing sisal fibres, cassava powder, cement as well as cement-fibre content within certain limits is observed. Results show that sisal fibre content outside these stated limits are detrimental to the strength characteristics of compressed soil blocks. The critical sisal fibre volume for soil-sisal mix has been established. Compression and flexural strength at optimal fibre content are comparable to those of soil blocks stabilized by the already well studied conventional binders as cement; besides, these results are not recorded in literature yet. Dry block densities and porosity reflect closely on the fibre, cement, cement-fibre and cassava content. Light optical microscopy (LOM) and scanning electron microscopy (SEM) analysis have been used to verify the block morphology.

Compressed earth blocks manufactured from a limited addition of cassava powder to the soil, show improved strength. Indeed the ideal strength is above one recommended by various CEB standards. Past researchers have not documented any research related to cassava as a building material. Water vapour transmission properties of the earth blocks have been determined; values show that the earth blocks may provide better indoor air quality than conventional building materials like concrete. A simple method by which strength of earth blocks could be determined in the absence of laboratory facilities in the rural villages of Kenya and related regions has also been developed.

Use of traditional hydraulic stabilizers like cement can significantly improve the strength of compressed blocks. These additives are, however, costly; a negative factor especially for the poor rural communities of the developing nations. This research has shown that the commercial binders can be replaced by cheap material, thus, sisal vegetable fibres and cassava powder. Besides, a new building material, thus compressed earth blocks stabilised with cassava powder has been developed.

It should however, be mentioned that the roof construction should be done in such way that rain does not directly pound the compressed earth blocks when applied for building of walls.

Kurzfassung

Die Entwicklung bezahlbarer Wohnbauten ist ein wichtiger Aspekt für die Verbesserung der Situation der zahlreichen obdachlosen Menschen, die in den Entwicklungsländern leben. Einen Beitrag zur Lösung dieses Problems stellt daher das Ziel der vorliegenden Dissertation dar.

In der vorliegender Forschungsarbeit sollen die Auswirkungen verschiedener Anteile von Sisal, Zement, Zement-Sisal und Cassava auf die Druckfestigkeit, Biegefestigkeit, Trockenblockdichte und Porosität von komprimierten Erdblöcken (KEB) dargestellt werden. Zur Herstellung der Erdblöcke wurde ein Handpresse verwendet, die mit gleich bleibendenm Druck betrieben wurde. An den so hergestellten KEB wurden die Verhältnis von Festigkeit, Blockdichte und Porosität zu den Verstärkungsniveaus ermittelt.

Mit steigendem Sisalfaser-, Cassavapulver-, Zement- sowie Zement-Faser-Gehalt wird innerhalb bestimmter Grenzen eine erhebliche Festigkeitserhöhung beobachtet. Die Ergebnisse zeigen, dass ein Faseranteil außerhalb dieser angegebenen Grenzen für die Festigkeitseigenschaften der komprimierten Erdblöcke nachteilig ist. Die kritische Menge an Sisalfasern für die Erd-Sisal-Mischung wurde bestimmt. Druck- und Biegefestigkeit sind bei einem optimalen Faseranteil mit der von Erdblöcken vergleichbar, die mittels der bereits umfassend studierten, herkömmlichen Binder, wie zum Beispiel Zement, stabilisiert wurden; außerdem wurden die vorliegenden

Ergebnisse bisher noch nicht in der Literatur erfasst. Trockenblockdichte und Porosität spiegeln deutlich den Faser-, Zement-, Zement-Faser- und Cassavagehalt wieder. Es werden Analysen durch lichtoptische Mikroskopie (LOM) und Rasterelektronenmikroskopie (REM) vorgenommen, um die Blockmorphologie zu verifizieren.

Komprimierte Erdblöcke, hergestellt mit einem begrenzten Zusatz von Cassavapulver zur Erde, weisen eine verbesserte Festigkeit auf. Die ideale Festigkeit liegt faktisch über den Werten, die in verschiedenen KEB-Standards empfohlen wurden. Bisherige Forscher haben keinerlei Forschungsarbeiten in Bezug auf Cassava als Baumaterial dokumentiert. Die Eigenschaften der Wasserdampfdurchlässigkeit der gefertigten Blöcke wurden bestimmt. Die Werte zeigen, dass die Erdblöcke für eine bessere Innenraumluftqualität sorgen können als herkömmliche Baumaterialien, wie zum Beispiel Beton. Es wurde ebenfalls eine einfache Methode entwickelt, anhand welcher die Festigkeit der Erdblöcke auch ohne Laboreinrichtung in den ländlichen Siedlungen von Kenia bestimmt werden könnte. Die Baumaterialen müssen konstruktiv vor unmittelbarer Regenwirkung geschützt werden.

Der Einsatz traditioneller hydraulischer Stabilisatoren, wie zum Beispiel Zement, kann die Festigkeit der komprimierten Blöcke erheblich verbessern. Solche Zusätze sind jedoch teuer; ein negativer Faktor, insbesondere für die armen ländlichen Gemeinden in den Entwicklungsländern. Die vorliegende Forschungsarbeit hat gezeigt, dass die kommerziellen Binder durch kostengünstigere Materialen ersetzt werden können, nämlich Sisalpflanzenfasern und Cassavapulver. Ein weiteres Ergebniss der Arbeit ist die Entwicklung eines neuen Baumaterials - mit Cassavapulver stabilisierte und komprimierte Erdblöcke. Allerdings, müssen auch diese Baumaterialen konstruktiv vor unmittelbarer Regeneinwirkung geschützt werden.

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Abbreviations

BASIN	Building Advisory Service and Information Network
CaC	Cassava Stabilized Compressed Earth Blocks
CEB	Compressed Earth Blocks
CeC	Cement Stabilized Compressed Earth Blocks
CMB	Compressed Mud Blocks
CRATerre	International Centre for Earth Construction
CSC	Cement-Sisal Stabilized Compressed Earth Blocks
DIN	Deutsche Industrie Norm
GATE	German Appropriate Technology Exchange
ITDG	Intermediate Technology Development Group
LL	Liquid limit
LOM	Light Optical Microscopy
L.O.I	Loss on Ignition
OMC	Optimum Moisture content
PEB	Pressed Earth Blocks
PI	Plastic index
PL	Plastic Limit
OPC	Ordinary Portland Cement
PSB	Pressed Soil Blocks
SC	Sisal Stabilized Compressed Earth Blocks
SEM	Scanning Electron Microscopy
SKAT	Swiss Centre for Development and Cooperation in Technology and Management
SSB	Stabilized Soil Blocks

1.0 Introduction

The urgent need to develop suitable and affordable housing is born as a consequence of the fact that over one billion people in the world, most of who live in the developing nations, are either homeless or live in very poor housing (BASIN news, 2001).

Earth building is the most common method of making cheap accommodation since soil is readily available almost anywhere on the planet. Earth also called soil (Minke, 2000) and scientifically referred to as loam, is a mixture of clay, silt, sand, and sometimes larger aggregates like gravel and sand. To give an idea of how big the earth building field is, it is observed that, one third of the world's population live in a home of unbaked earth (Walker, 1998). Roughly 50% of the population of developing countries, the majority of rural populations, and at least 20% of urban and suburban populations live in earth homes (Houben and Guillaud, 1994). Unbaked earth homes in many developing nations are basically mud houses constructed by use of soil (earth). The application of earth for building of homes in different forms is well known. (Hujbers, 1987) classifies such methods as follows:

- Daub - moist mud placed between a framework of posts and poles
- Cob - the cob procedure consists of stacking earth balls on top of one another and lightly tamping them with hands or feet to form monolithic walls
- Rammed earth - continuous walls formed by ramming moist mud between movable wooden shuttering
- Adobe blocks - made by placing wet mud in forms and allowing to dry
- Compressed earth blocks (CEB) or pressed earth blocks (PEB) - made by compressing moist soil in a press.

The technique of adobe, rammed earth and compressed earth block are currently the most widespread and have to some extend been developed fairly high scientific levels. The CEB constructions have been developed as an improvement to the other methods. Past workers have shown however, that such structures still face great instability and hence durability problems; the alleviation of this problem is a major concern of the present work.

This study proposes the use of available local raw materials to improve and develop new vegetable fibre earth building materials as a means to positively impact on the shelter conditions of the resource poor countries of the developing world. It is hypothesised that a composite of earth reinforced with vegetable fibre or/and cassava as a binder component could produce a low-cost and durable wall material for housing. The more expensive cement which is traditionally added to soil for binding (stabilising) purposes could hence, in part or in whole be replaced and a new building material developed.

2.0 Statement of the Problem

2.1 Background to the Research

The genesis of this research work is the experience the author has had on the ground in a village in Kenya where he was born. The walls of mud houses made from wet soils or earth are unable to withstand harsh rainy seasons. Figure 2.1 shows the kind of cracks that appear on the walls due to extreme shrinkage. Cracks appear because the soil particles are not held together with sufficient bonding strength. Given that moisture from rainfall is the main cause of cracking and other durability problems associated with compressed earth blocks, it was important to investigate the possibility of stabilising the soil with cheap, easily available and renewable raw materials.

Past researchers, as will be surveyed in section 2.5, have shown that use of traditional hydraulic stabilizers like cement or lime or waterproofing agents like bitumen do significantly improve the strength of compressed earth blocks (CEB). These additives are, however, accompanied by increase in costs of material; this is not sustainable especially for the poor rural communities of the developing nations. It is the aim of the present investigation to show that these traditional binders can be replaced by environmentally friendly and sustainable alternatives i.e. sisal vegetable fibres and cassava powder. Figure 2.2 depicts this stated idea.

Aims and Objectives

The main purpose of this research study was to replace the relatively expensive cement as stabiliser of compressed earth blocks (CEB) through ingredients which are renewable resources in nature. A strength and therefore durability testing method, in the absence of laboratory facilities in the rural areas, was to be established; this was to be accomplished by determining a conversion function between standard laboratory tests and the proposed simple testing method i.e. loading strength was to be correlated with compressive strength; this is illustrated in figure 2.3. Of equal importance was to investigate properties of the prepared soil blocks and recommend specifications accordingly.

The prime objectives were to:

- Synthesize vegetable fibre earth wall material for housing
- Synthesize cassava stabilised earth wall material for housing
- Prove the sufficient durability of the products
- Prove the water transmission properties
- Prove the mechanical strength
- Develop an on-sight appropriate and easy-to-use testing criteria of strength.

Figure 2.1 Pictorial illustration of the research background

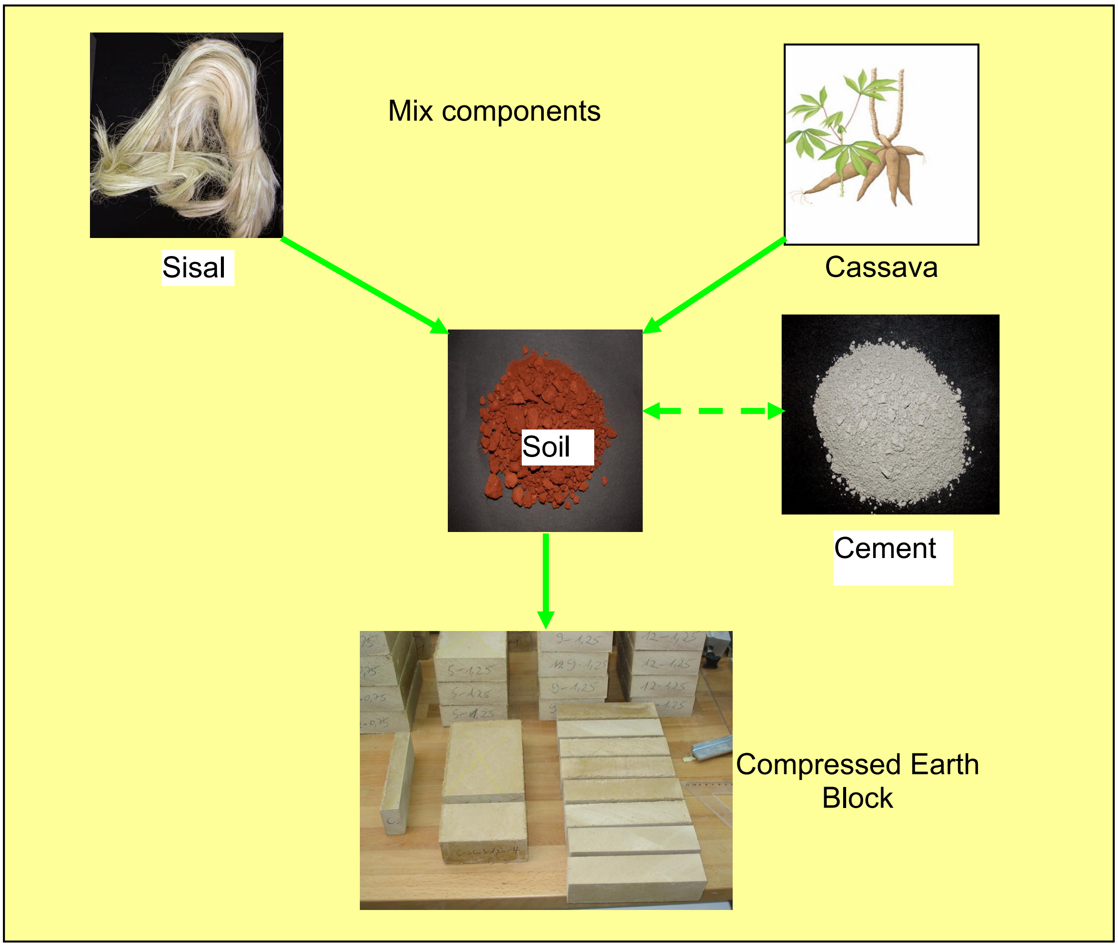


Figure 2.2 Proposed material for manufacture of compresses earth blocks

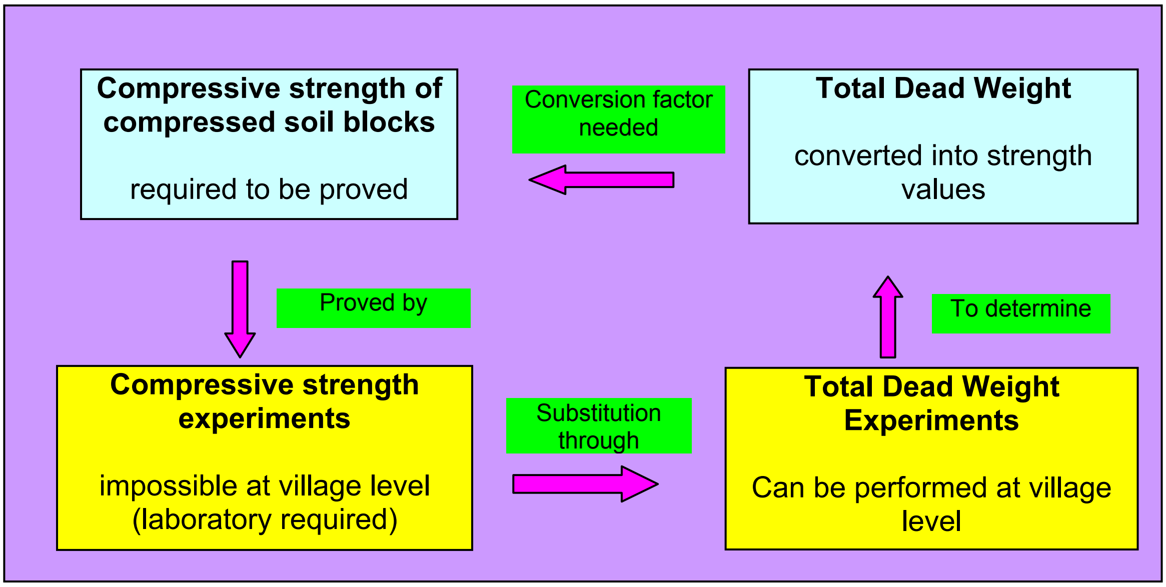


Figure 2.3 Conversion factor - Practical importance of the testing method

Hypotheses

- Indigenous raw materials, thus, soil, vegetable fibre and cassava powder found in abundance in the developing nations can be used to develop a cost-effective building material composite for housing construction

- Sisal vegetable fibres can be used to reinforce compressed soil blocks leading to increased strength and reduced shrinkage consequently improving the durability

- Cassava powder can replace cement as stabilizing or reinforcing agent in preparation of compressed earth blocks (CEB)

- It is possible to develop a simple on-sight testing method - suitable for rural areas (without laboratory) - for the building material's strength and therefore durability based on a conversion factor (function).

2.2 Motivation for the Present Study

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

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

The need to provide more housing for the worlds poor societies can not be overemphasised. Shelter is, after all, a basic requirement of human being. As concerns the developing nations, it is already recognised that the huge housing requirement cannot be met with industrially produced building materials (Minke, 2000). Indeed, 25% of the world's population does not have any fixed abode, while 50% of the urban population live in slums (Kerali, 2001). In spite of the many effort such as "Global strategy for housing by the year 2000" declaration by the UN, the shelter issue remains a major problem, and hence the need to look at possible solutions including scientific research.

It is most likely that the majority of the people in the developing world will, out of necessity, continue to live in mud (earth) houses, consequently, ways of improving on this traditionally built mud houses are a subject of concern to many researchers. Compressed earth block (CEB) construction is one of the most widely used technologies in building with earth and has been adopted as the improvement to rammed mud houses. The key future of the technology is the compression of the soil in a mould with the help of a press at a compaction effort of 2-4 MN/m^2 (Mukerji, 1994).

Although soil (earth) has been used as a building material for thousands of years, unprotected structures seldom withstand wet climates for long periods of time. Relatively new materials such as cement have meant that blocks can be made which will last for centuries, but they are too expensive for most people in developing countries. Traditionally built mud houses or ones constructed from compressed earth blocks made only of unfired earth have become a cheaper option. Attempts by past workers to improve strength of compressed earth blocks are discussed in section 2.3.

From the above discussion, it can be said that properties of soil as a building material should therefore be further studied. It is the intention of this work is to further contribute to the scientific knowledge of soil as a building material, and in particular strive to improve the strength and dimensional stability of compressed soil blocks. This should be possible by introducing sisal as well as cassava powder to the soil structure and thus replace cement or other hydraulic binders stabilising agents. An extra gain should be seen in terms of the income local population would benefit from plantation of these components.

2.3 State-of-the-Art

2.3.1 Stabilised Compressed Earth Blocks (CEB)

In accordance to (Compressed Earth Blocks, Standards, Series Technologies Nr. 11, CRATerre-EAG Basin, 1998), compressed earth blocks (CEB) are masonry elements, which are small in size and have regular verified characteristics obtained by the static or dynamic compression of earth in a mould in a humid state followed by immediate demoulding. Section 3.4 provides some insight on the use of earth presses. Compressed earth blocks are principally made of raw earth and owe their cohesion to the clay fraction within the earth. If any additive is added to the CEB in order to improve or enhance particular characteristics, then the CEB are referred to as stabilised compressed earth blocks. Additives are stabilisation products intended to neutralise the sensitivity of CEB to water. Additives may also be used to modify other characteristics such as colour or shrinkage cracks. It should be noted that some literature refer to stabilised compressed earth blocks as stabilised soil blocks (SSB), Stabibloc, Terracrete, soilcrete, pressed soil blocks (PSB) or Geocrete.

As discussed in the previous section, mud houses made only from earth face durability problems. Several possible solutions have been forwarded by past researchers in bid to add strength and add durability to the earth raw material, even in less arid conditions, thus:

- By using stabilizers that improve certain characteristics of soil
- By appropriate architecture, i.e. earth building made with suitable design
- By using bonding mortar to improve the structure
- By applying plaster and renders on the building surface.

The idea to use renders, paints or plasters on the external surface can protect the CEB or housing walls from external attack, but these are expensive materials and hence not suitable for a developing society, additionally, expansion rates between soil blocks and renders/plasters mortars are different resulting in to peeling. The use of appropriate architecture (Montgomery, 2002) is also hindered due to costs and skills required.

Application of stabilizers as a remedy to the soil instability problem or for improvement of the durability of compressed earth blocks appear, from literature survey, to be fairly widespread and most successful way of improving strength to soil. Many types of stabilizing agents are known (Stulz, 1988; Mukerji, 1994; Minke, 2000), although not much research appears to be available, the most tried ones are: cement, lime, gypsum and bitumen (mineral products), animal products, manufactured products and natural fibres (e.g. plant fibres). Earth blocks stabilized with 3 – 12 % mass of cement seem to be the most common (Gooding, 1993). As

(Spence, 1983) correctly points out, the potential of soil as a building material has been considerably underestimated, the reason being, that the enormous variety of naturally occurring soils has made specification for any particular set of properties difficult and that many soils in untreated state lack strength and dimensional stability.

Indeed, past workers have given certain amount of light on the issue of earth construction. (Fitzmaurice, 1958) was first to point out that the population is more demanding of their building materials and that stabilisation of soils normally with asphalt or cement is necessary to maintain the materials integrity when exposed to moisture. Most of the work has since then focussed on the durability of the cement-stabilised compressed earth blocks (CEB) also referred to in some literature as compressed soil blocks (CSB). Durability of a soil block structure or element can be understood as its ability to withstand or resist weathering i.e. resistance to erosion of material by rain, wind or other environmental agents (Ngowi, 1997). The basics of soil stabilisation are well covered by (Houben and Guillaud, 1994; Murkerji, 1994; Norton, 1997 and Minke, 2000) who describe the idea behind earth construction, soil stabilization, and characteristics of earth as a building material.

After Fitzmaurice forwarding the importance of CEB stabilisation, most workers have tended to develop and examine parameters that provide information on the CEB durability. Compressive strength seems, from past research, to be the yardstick for measuring durability. According to (Heathcote, 1991) blocks with a minimum dry compressive strength of 2 MPa are acceptable by most codes (Australian code, New Mexico building code and UNESCO, CRATerre). Heathcote mentions soil type (clay quantity), cement content (generally in the range of 5 – 10 %) and density of the compacted soil as the main factors controlling strength. It is suggested that the stabilisation mechanism lies in the cement forming a skeleton of hydrates throughout the voids. A proposed correlation between density and cement content for estimating compressive strength can however, at best only be approximate and can not substitute the physical testing of materials given the inherent variability in material. Although the author finds no sense in using the wet (saturated) compressive strength, he proposes in a later investigation (Heathcote, 1995), in spite of the large data scatter, that the ratio of wet to dry strength of 0.33 – 0.55 to be a suitable criterion for durability evaluation of stabilised CEB. More contradictions occur as (Walker, 1998) finds blocks with a wet/dry strength ratio as low as 0.24 to provide adequate erosion resistance.

Earlier, (Heathcote, 1994) shows that a minimum cement content exists (0.75 %) below which strength is independent of cement quantity present; he tests samples with 0 – 3.5 % cement content. By establishing that suitable blocks may be manufactured from soil with cement content as low as 0.75 %, the author contradicts other workers whose results show a value of between 5 – 12 % to be best suitable; for instance, (Walker, 1995) reports that blocks made with less than 5 % cement are often too friable to be handled. Later from survey of several works, (Walker, 1996) recognises that the clay content of the soil should be between 5 - 20 %, a cement content of 4 - 10 % and soil plasticity index of 2.5 - 30 %; see section 4.1.1 for definition of plasticity index.

Investigations by (Kerali, 2001, 2000) point out at the behaviour of blocks in terms of compressive strength, water absorption, and microstructure with respect to composition, processing methods and exposure conditions; the variables being soil type, cement content, compacting pressure, curing conditions and water/(soil + cement) ratio. The source concludes that the CEB stability can be significantly raised if: inter-granular bonding between particles is improved, voids are reduced and block water absorption is lowered. It maintains that moisture (from rain, rising damp and vapour condensation) provides the most serous factor influencing the deterioration of CEB. Results of Kerali are in agreement with those of (Walker, 1997, 1998, 2001) and (Heathcote, 1995, 2000), both who perform erosion tests on earth blocks and find erosion resistance to improve with increase in cement content, block density, surface area to volume ratio and reduction in clay content. A shortcoming of the erosion tests is that a sample passing one type of erosion test may fail another, and some are open to operator bias; a unified approach is still none existent. Erosion is also dependent on the sample geometry. Attempts by the authors to simulate impact of falling rain (spray tests) provide only approximations as they fail to take care of the difference in wind and spray velocity, raindrop size and spray drop size as well as angle of attack by rain and effect of wetting and drying in the field. Wide ranging field data should be taken as attempt to close this gap.

In another similar study, (Ozkan, 1995) attempts to improve strength and water absorption of blocks stabilised not only by cement but also by lime, bitumen and gypsum, and observes that gypsum and bitumen blocks fail the erosion test; cement & lime addition increase strength and reduce water absorption. Related experiments are performed by (Ngowi, 1997) The source notes the low durability of earth walls in some villages in Botswana (Africa) and attempts to alleviate this problem by stabilising the soils with cement, lime, bitumen and cow dung separately. As in the case of Ozkan, the bitumen as well as the cow dung stabilised blocks failed the water absorption test. Increase in lime content improved strength but, surprisingly unlike Ozkan, increased the water absorption of the blocks.

(Walker, 1997) investigates the suitability of mortars to the production of CEB, i.e. the effect of soil composition and cement content to the characteristics of CEB (compressive strength, drying shrinkage, wetting and drying durability, water absorption and mortar consistency). The source establishes that compressive strength, drying shrinkage and durability improve with increase in cement content but is inhibited by increase of clay content in the soil. Water absorption and retention rise with increase of clay.

The block compaction as a parameter influencing the durability of earth blocks is also documented. Moisture content and compaction delay as factors affecting quasi-static compression of cement stabilised soil blocks are examined by (Gooding, 1993). The source attempts to establish a relationship between compaction pressure, cement content and compressive strength, and records better strength with increasing pressure, a fact that provides an improved water protective measure to the blocks. The same author (Gooding, 2000) looks at compressive strength as related to dynamic compaction. The following variables are considered: water content, compaction energy, mixing delay and compaction method. He underlines that this compaction method provides better block densification than static compaction at equivalent applied pressure. (Montgomery, 2002) investigates, in a Ph.D. thesis, the process, production and performance of dynamically compacted cement-stabilized soil blocks as against those compacted by static means. Observing that moisture is the most critical variable, the author establishes that dynamic compaction provides the blocks with a 3 - 5 MPa 7-day wet compressive strength, what is 40% higher than the compacted by quasi-static method.

Another durability factor recorded in literature is the flexural bond strength. (Walker, 1995) investigates soil characteristics and cement content on dry density, compressive strength, flexural strength, durability and drying shrinkage. The source produces an empirical relationship equation 2.1 between flexural strength and compressive strength. A large scatter in the data is however, reported and hence eq. 2.1 may not be a substitute for direct testing.

$$\text{Flexural Strength} = \frac{1}{6} * \text{Compression Strength} \tag{2.1}$$

(Rao, 1996) looks at the effect of mortar composition, strength and moisture to the flexural bond strength of the CEB. The source notes, as was the case with Walker, an increase in the flexural bond strength with rise in the CEB cement content and compressive strength; and establishes an optimum CEB moisture content above which the flexural bond strength falls off sharply. It asserts that flexural bond strength is a good measure of the blocks durability. (Walker, 1999) considers the flexural bond strength (using bond wrench method) as an indicator of CEB durability. Flexural bond strength (< 0.1 MPa) is noted to be a function of CEB compressive strength, clay and moisture content. The same author (Walker, 2001) attempts to examine the durability of CEB by use of the pullout tests, i.e. asses bond of steel rebars embedded in rammed earth. The pullout bond resistance is shown to be a function of compressive strength, bar type and bar length. Steel bar reinforcement is likely to be an expensive undertaking in poor economies, besides, steel may promote the corrosion phenomena.

The influence of steam curing is hardly available in literature. The effect of steam curing at 80° C as well as lime content on the wet strength (saturated strength) of lime (and fly ash) stabilised blocks is from (Reddy, 2002) evaluated. The source observes increase of strength with increasing steam curing period (6 - 12 hours), lime content (6 - 14% mass) and lime & fly ash content (0 - 50% mass). Pozzolanic reactions between clay minerals and lime or fly ash are speculated to be responsible for strength gain.

2.3.2 Natural Fibre Reinforced Compressed Earth Blocks

The use of natural fibres as a building material poses a special challenge to science and technology. Their use can, whilst alleviating the housing problem, assist (Swamy 1990) to save energy, conserve scarce resources and protect the environment.

Although research data is not quite abundant, some workers have documented the issue of using natural fibres as stabilising or reinforcing agent in earth construction. In discussion on kinds of stabilizers (Stulz, 1988) recognises straw (wheat, rye, barley, etc) and plant fibres (sisal, hemp, elephant grass, coir and bagasse) as an important category of stabilizers but provides no much scientific findings. Accordingly, such fibres check cracking in soils with high clay contents and increase insulating properties, adding however, that excessive use should be avoided due to possibility of increased water absorption. (Rigassi, 1995) observes that fibres create an omni-directional fibres network which improves tensile and shearing strength and reduce shrinkage. The author states further, without forwarding research data, that although fibres are commonly used to reinforce adobe, they are incompatible with CEB compression process as they render the mix elastic. (Minke, 2000) agrees with Rigassi and notes that adding fibres such as animal or human hair, coir, sisal, agave, bamboo and straw may help to reduce shrinkage ratio; the reason being that the relative clay content is reduced and some of the water is absorbed by the fibre pores. Additionally, appearance of cracks is reduced as the mixture binding force is raised by the fibres. The author presents a study on linear shrinkage as a function of fibre (coir, flax straw and rye straw) type and amount but avails no further scientific results. Tests with sisal are also not available.

In work entitled seismic strength of CEB, (Vergas, 1986) observes increase in compression strength of CEB on addition of 0.5-8,0% by weight, 100 mm long straw and explains this by the sewing action of the CEB-mortar interface from straw fibres, i.e. controls micro-cracking produced by drying shrinkage. (Filho, 1990) reinforces adobe with sisal and coconut fibres; the investigation brings to surface the problem of high water absorption rates of the fibres-a phenomenon that may be detrimental to the blocks on drying. The author tries to circumvent this by application of water-repellent agents. However, addition of 4% sisal improves the brittle behaviour of the adobe blocks.

(Olivier, 1995) performs so far the most comprehensive study of sisal reinforced earth blocks, and claims that the weak point is the interface between earth mortar and earth blocks. The source attempts to improve the interface by reinforcing the compressed earth blocks as well as the earth mortar with sisal fibres and describes, quantifies and evaluates the advantage of sisal use. An increase in cohesion (improved compressive & tensile strength) is observed. Plasticizer addition increases shear stress and reduces amount of water to be used. In a more recent related study, (Eko et. al., 2001), reinforces soils with a mixture of cement and sugarcane bagasse vegetable fibres. The study uses 5 to 10% cement by weight and 5 to 15% bagasse fibres by volume. An improvement in the 28-day unconfined compressive strength with increasing cement content up to a maximum of about 5MPa is recorded. The increase in fibres volume is, however, found to be detrimental to strength development.

2.3.3 Cassava Stabilised Compressed Earth Blocks

The possibility of using powder from Cassava (Manioc) as either a reinforcing agent or a stabiliser for earth blocks is not recorded in literature. (Minke, 2000) reports that the compressive and bending strength of earth can be improved by addition of starch and cellulose, and that, these additives reduce the binding force and increase the shrinkage level. The source does not specify the starch type neither does it provide any research support. Cassava powder as stabilizing agent for soil (cassava-soil mortar) is, however, already used by individuals in some villages in Kenya and Uganda.

2.4 Justification of the Present Study

Compaction of a suitable soil-stabiliser mixture can provide a relatively cheap raw building material. Stabilised blocks offer a wide range of advantages. They maximise use of local materials, low levels of energy required for production, simple production and construction methods and good thermal and acoustic properties. Their application is however, hindered by lack of test procedures and performance criteria. Requirements for, among others, compressive strength, tensile and flexural strength, durability, drying shrinkage, dimensional tolerances, dry density and water absorption may differ from region to region and should therefore be tested and documented appropriately.

Sections 1 and 2 above show on one hand the need to improve the housing situation of the poor countries, and on the other hand, the role earth construction plays; they expose the inadequate research in this area. Several questions are as a consequence left open. Lack of standard performance criteria and adequate guidelines for CEB production are quite apparent from the above sections. Most of the estimations and correlations can only be approximate and may apply to a particular soil. Measurements should be taken in each study case to assign any specifications. Rain patterns, intensity, drop angle and temperature changes-important for laboratory and field correlations-may for instance, not be the same for Australia and Kenya. Not much effort has been put in the direction of developing new building materials. CEB parameters considered seem to reoccur, one worker after the other, without much strive to create new ones or harmonise them. It is imperative that effort be put in both the direction of improving the existing materials as well as developing new ones; (Griffin, 1995) agrees with this view. Literature in general supports this opinion as it recognises that earth material forms a good case for a scientific study.

Natural fibres thus, sisal as well as cassava are abundantly found in the developing nations. They are cheap and could provide not only the required raw material for shelter, but also some income for the people. No research is recorded, documenting use of cassava as a binding component for soil although the very low income villagers are putting it in use; it was imperative to have a study carried out. This was the goal of the present research.

3.0 Soil, Natural Fibres and Cassava Powder as Building Materials

3.1 Soil as a Building Material

3.1.1 Soil Composition

This section consists of a brief overview of soil and its composition. Soil is a loose material of varying thickness, which supports vegetation and bears humanity and its structures (Houben and Guillaud, 1994). Soil is the result of underlying parent rock under the influence of a range of physical, chemical and biological processes related to bio-climatic conditions and to animal and plant life. The present project limits itself to aspects of soil directly relevant to application of soil in manufacture of soil (earth) blocks for housing walls.

Depending on the parent rock and climatic conditions, soil appears in infinity of forms possessing an endless variety of characteristics. It is therefore imperative to determine the properties of soil before applying it as a construction material. Chapter 4, section 4.1.1 examines these properties relevant to the present dissertation and how they were determined.

Soil is made up of several substances, thus gaseous, liquid and solid substances. The gaseous constituents, which include nitrogen, oxygen and carbon dioxide, fill up the voids within the soil and are considered of negligible relevance to the present research. The liquid ones are water soluble organic acids and mineral compounds; they are also assumed to be of insignificance value to this work, for they are unlikely to affect the quality of compressed earth blocks. The solid fraction of the soil is made up of two parts; organic matter which occur as a result of decomposition of plant and animal matter and mineral constituents resulting from dissociation of parent rock. Organic matter is of low mechanical strength and may negatively affect the quality of soil if found in high concentrations. The influence of the organic matter, found normally in the surface horizon of the soil, on the quality of soil blocks is discussed in section 4.1.1.4 under the loss on ignition parameter. The mineral component represents the greater part of the soil; they are mainly stones (pebbles), gravel, sands, silts and clay. These components contain silicas (quartz), silicates (mica, feldspar) and limestone.

Depending on the predominant part, the soil texture can be divided into

- Organic soils
- Gravel soils – are fragments of the parent rock and consist of particles in the range from 2 to 20mm; the relevant characteristic of gravel to CEB is that it limits the capillarity and shrinkage of soil

- Sandy soils - consist of particles in the range from 0.06 to 2mm; made up mainly of silica or quartz, low water absorption of sand surfaces limits swell and shrinkage. They are inactive chemically, clean sand particles do not exhibit cohesive attributes, and being non-absorbent, they are little influenced by changes in moisture content
- Silty soils- consist of particles in the range from 0.002 to 0.06mm; similar to sand particles only smaller; Silt provides stability to the soil by increasing internal friction and possess a limited amount of cohesion due to inter-particle water films operating on a higher specific surface
- Clayey soils- consist of particles smaller than 0.002mm; these are hydrated alumino-silicates with high susceptibility to swelling and shrinkage. The importance attached to this colloidal fraction is associated with the electrical charges which the particles carry on their surface.

3.1.2 Clay Mineral Composition

A brief overview of the clay composition and structure is given in this section. The importance of clay component lies in the fact that clay particles are responsible for cohesive character of soil and that cohesiveness is of prime importance to the strength characteristics of CEB. Clay particles are only visible under microscope; each particle is coated by a film of water, held by surface tension. It is this water which binds particles together (Norton, 1997).

(Ogunye, 1997) states that the atomic structure of clay minerals consists of two fundamental building blocks i.e. tetrahedral of silica and octahedral of alumina, see figure 3.1b. The {[SiO4]4-} tetrahedron, has one silicon atom equidistant from oxygen or hydroxyls. A silica tetrahedron sheet is formed from a series of tetrahedral which are arranged in a sheet-like hexagonal structure so that the oxygen atoms at the basal corners of the tetrahedral are in a common plane, with each shared between two in a tetrahedral. These sheets have a chemical make-up which varies according to the type of clay, degree of hydration and spacing; the spacing between the sheets is between 7 and 20 Angström (Houben and Guillaud, 1994).

In general some sheets are made of silica (atoms of silicon surrounded by oxygen atoms) and others are made of alumina (aluminium atoms surrounded by oxygen atoms and OH group). In some cases, the base is made of Si and Mg or Si and Fe, and not just Si or Al. Thus the silica tetrahedron sheet may be viewed as a layer of oxygen in the base and a layer of hydroxyls at the tips of the tetrahedral. In the octahedral unit the atoms of aluminium, iron or magnesium are equidistant from six oxygen or hydroxyls. Different clay mineral groups are formed as a result of the bonding together of two or more molecular sheets, see figure 3.1a. The three main clay minerals are kaolinites, illites and montmorillonites. The soils used for this investigation are found, as would be seen in section 4.1.1.5, however it deemed necessary to briefly look at the other two main soil minerals for purpose of comparison.

Kaolinite

It is principally formed as an alteration product of feldspar and muscovite as a result of weathering under acidic conditions and it is non-expansive in nature. Kaolinite is mainly found in considerably weathered, well-drained soils and is common in the tropics. It is composed of a single silica tetrahedral sheet and a single alumina sheet combined in a unit which forms a repeat layer with the general formula $n[Al_2Si_2O_5(OH)]$, see figure 3.1b and figure 3.1c. The distance between sheets is constant at 7 Angström and the thickness of the crystal is between 0.005 and 2μm, see figure 3.1d. The charges within the structure are balanced, i.e. there are no charges on the lattices due to substitutions within the lattice. Kaolinites are considered to be the most stable clays from the engineering point of view, (Ogunye, F. O, 1997).

The hydrogen bonds between the elemental sheets are sufficiently strong to prevent water molecules and other ions from penetrating, hence the lattice is considered to be non-expanding lattice the effective surface area to which the water molecules can be attracted is restricted to the outer faces. It is for this reason that the plasticity, cohesion and shrinkage and swelling properties of kaolinite are low compared with other silicate clays. The theoretical composition is 46.54% for SiO_2, 39.50% for Al_2O_3, and 13.96% for H_2O. Very limited substations of iron and/or titanium for aluminium occur, and such substations are restricted to poorly crystalline kaolinite. The type of mineral composition is significant to soil when used as a building material; this is related to shrinkage levels experienced by earth blocks, see section 6.5.

Ilite (mica clay)

Ilite develops due to the weathering of feldspars, mica, and ferro-magnesium silicates. The process of its formation is favoured by an alkaline environment; illite are non-expansive lattices. It has a 3-layer structure, see figure 3.1e, mainly aluminous octahedral layer between two mainly silicaceous tetrahedral layers. Mg or Fe ions may replace Al ions in the aluminous layer, and Al ions may substitute Si in silica layer. The distance between sheets is 10 Angström and the thickness of the crystal is between 0.005 and 0.05μm.

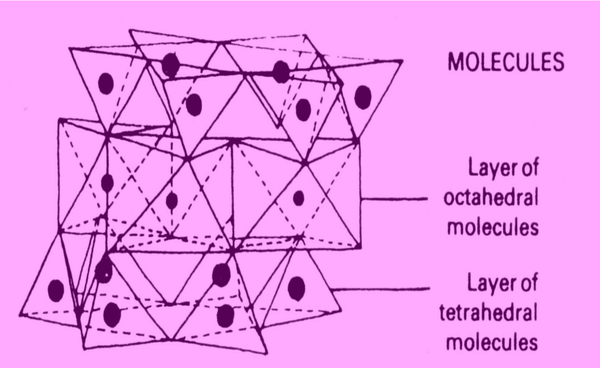


Figure 3.1a Clay molecules

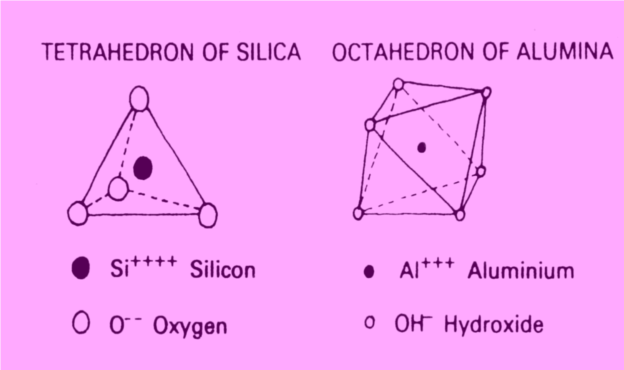


Figure 3.1b Silica and Alumina

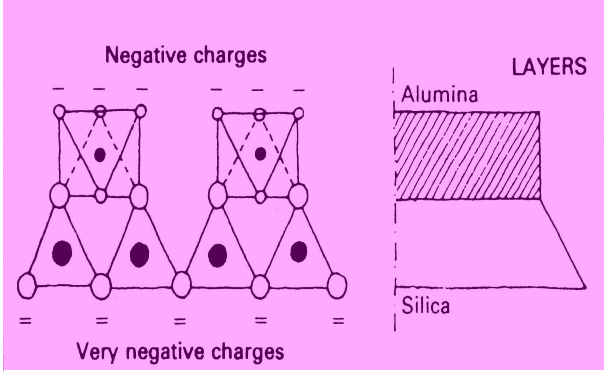


Figure 3.1c Layer arrangement

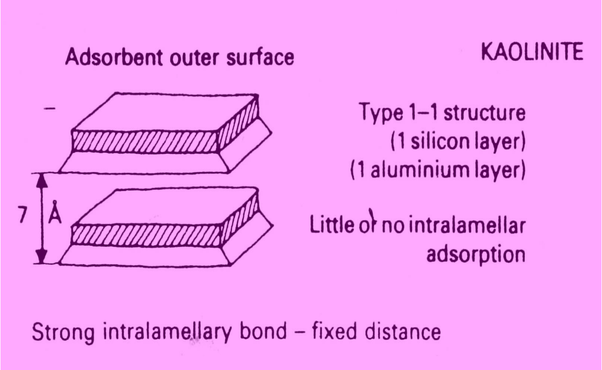


Figure 3.1d Kaolinite

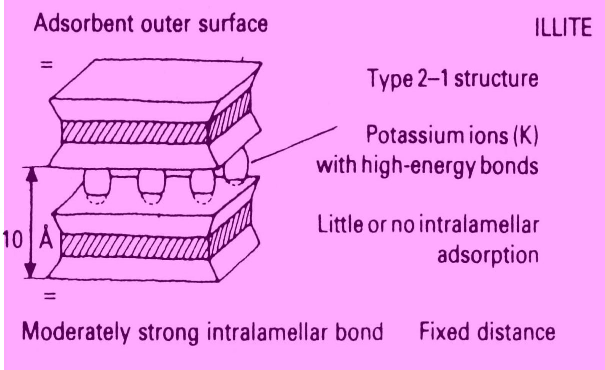


Figure 3.1e Illite

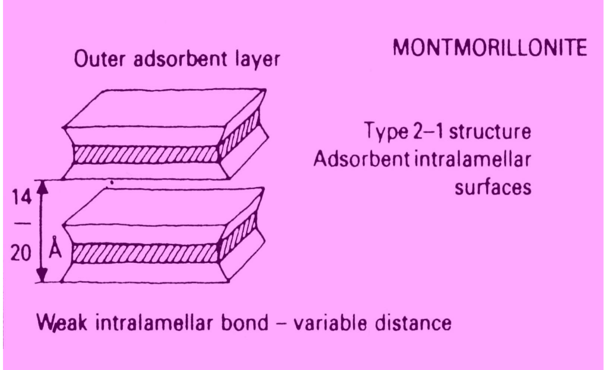


Figure 3.1f Montmorillonite

Montmorillonite

Montmorillonite forms when basic igneous rocks, in badly drained areas, are weathered. An alkaline environment favours formation of montmorillonite minerals. They have expansive lattices, i.e. it has swelling ability in a moist environment and notable cation exchange properties. The weak bonding between the layers accounts for why montmorillonite can readily absorb water into the interlayer spaces in its sheet structure. The structure of montmorillonite is similar to that of illite, see figure 3.if, but substitution takes place in the octahedral alumina layer, thus, Al ions may be replaced by Mg, Fe, Mn Ni etc. The distance between the sheets ranges from 14 to 20 Angström. Thickness of the crystal layers lies between 0.001 and 0.12 µm.

Advantages of Soil as a Building Material

The advantages of soil (earth) as building material (Stulz, 1988) can be given as follows:

- availability in large quantities
- low or no cost
- easy workability i.e. no special equipment is required
- suitable for construction of most parts of a building
- fire resistance
- high thermal capacity i.e. maintains moisture balance,
- low processing energy input (1% of a produced equivalent cement concrete unit)
- unlimited reusability of the non-stabilized soil
- sustainable resource (unlimited resource used in its natural state).

A traditionally built mud (earth) house or the use of compressed earth blocks made only of unfired earth, displays (Stulz, 1988) however, certain weakness due to:

- Extensive water absorption
- Poor resistance to abrasion and impact
- Low tensile strength
- Low acceptability amongst some social groups.

3.2 Natural Fibres as Building Materials

3.2.1 Classification of Fibres

According to (Nilsson, 1975) fibres are generally classified as natural and synthetic (man-made). Natural fibres, which are of more interest to this study, can be further split up in to vegetable, animal or mineral fibres. Sisal, whose scientific name is *agave sisalana*, belongs to the vegetable sub-group known as leaf fibres. Further categorization of fibres is illustrated in figure 3.2. (Nilsson, 1975) provides a comprehensive discussion on the type and uses of fibres; this dissertation, however, limits itself to sisal vegetable fibres.

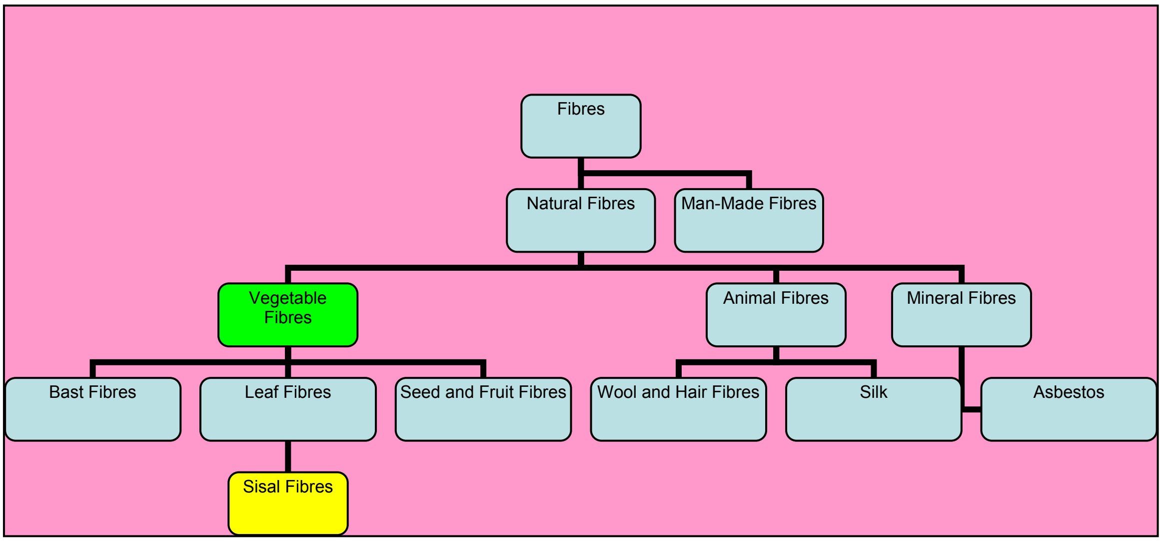


Figure 3.2 Fibre family tree (Nilsson, 1975)

3.2.2 Sisal Vegetable Fibres

Sisal vegetable fibres are the focus of the present study, in that they are used as reinforcing agent for the compressed soil blocks. Attempts are therefore made in this section to provide some information about sisal. It is the most important of the group of hard fibres, which includes New Zealand flax and Manila Hemp (Yayock et. al, 1988). Sisal is essentially a plant of the tropics and subtropics and production benefits from temperatures above 25°C and plenty of sunshine. Sisal is essentially a commercial crop hardly ever grown by small-scale farmers except as hedges. This crop requires large scale production to justify the use of expensive machinery required. The greatest demand for sisal is (Rehm et. al., 1991) for the long fibres (>90cm long) used for ropes and binder twine. Approximately 25% of the fibres are shorter (flume tow and tow fibre), and these are used for padding, mats and stair carpet, also for paper and building panels; sisal is also used to make ropes, sacks and bags of various types as well as marine cordage.

World Production

According to (Rehm et. al., 1991) sisal occupies 6th place among fibre plants, representing 2% of the world's production of plant fibres (plant fibres provide 65% of the world's fibres). The world's largest producers are Brazil 52% (199,000t), Mexico (12%), Kenya 10% (40,000t), Tanzania 9% (28,000t) and Madagascar 5% (20,000t). There are significant exports only from Brazil (65,000t), Kenya (31,000t), Tanzania (18,000t) and Madagascar (9,000t).

Origin and Cultivation

As per details given by (www.nnfcc.co.uk/crops/info/sisal.htm) sisal originated from Yucatana Peninsula in Mexico, grows best in a hot climate and may be grown in the humid and sub-humid lowland tropics. It is a perennial succulent which, with good growing conditions forms an inflorescence after 6 - 9 years after having produced 200 - 250 leaves, and then dies. Leaves average 120cm in length and are arranged spirally around the thick stem. The leaves are 75% schlerenchyma bundles. The root system is shallow but extends up to 3.5m from the stem. As a cactus, Agave plants survive and produce a marketable product in infertile arid regions which in many cases would otherwise be unproductive. Because it is a labour intensive crop it offers at least stability for a large rural population. A sisal plantation is shown in figure 3.3.

Figure 3.3 A plantation of sisal vegetable (Rea Vipingo)

50 leaves, each weighing up to 1 kg may be cut per plant per year. The ripest lower leaves are cut first and this continues periodically over the next four years. On average, over the first 4 years, two cuttings are made annually. In following years only one cut is made per year, until the flower stalks begin to develop.

Propagation of sisal is by means of bulbils which appear on the flower stalk, or by suckers growing around the base of the plant. A sisal plant produce up to 4000 bulbils compared with less than a quarter of this number of suckers, hence bulbils are preferred for propagation (Yayock et. al., 1988). Only large bulbils should be selected for planting. Bulbils are first planted into nursery beds at spacing of 25-30 cm apart in rows 50 cm apart. The bulbils are allowed to grow to about 40 cm or until they are about 9-12 months old, after which they are transplanted to the field. At this time the bulbils have good roots (Yayock et. al, 1988). The growth of bulbils is improved by mulching sisal nurseries with grass, paper or polythene. Mulching with partially rotted sisal gives best results (Webster et. al., 1980). Transplanting takes place preferably at the beginning of the rainy season. A recommended planting pattern in the field is a series of double rows 60 cm apart with a 2.5 m alley between pair of rows. Plant spacing is at 75 cm, giving a population of about 25000 plants per hectare. Alternatively plant can be spaced 1 m apart in 3 m rows (Yayock et. al, 1988). The crop should be kept weed-free and annual legumes such as beans may be cultivated between rows to suppress weed growth and limit erosion.

Harvesting and Processing

A process of decortication is used to extract the fibre from the leaf tissues. Leaves are crushed and beaten by a rotating wheel set with blunt knives, so that only fibres remain. All other parts of the leaf are washed away by water. Decorticated fibres are washed before drying in the sun or by hot air. Proper drying is important as fibre quality depends largely on moisture content. Artificial drying has been found to result in generally better grades of fibre than sun drying. Dry fibres are machine combed and sorted into various grades, largely on the basis of the previous in-field separation of leaves into size groups (Yayock et. al., 1988). After the fibre extraction 95 - 96% of the leaves' weight still remains, this is used as fertiliser, or the dried pulp as a fuel for methane production.

Sisal Fibres as a Soil Stabiliser

The use of sisal vegetable fibres in reinforcing compressed earth blocks as per the investigations of past researchers has been briefly described in section 2.3.2. The use of sisal is however, not well documented. Research appears to focus more on straw. (Houbon et.al., 1994) states that straw can be regarded as a structural reinforcement agent and that it allows an increase in compressive strength of at least 15% compared to non-reinforced materials. Fibre reinforced soil blocks can withstand high stresses, thus, whereas non-reinforced blocks crack in bits, fibre-reinforced blocks stay in one piece. The most important property of fibres in earth blocks is that facilitate improvement in tensile strength. The role of fibres in compressed earth blocks according to this source is as follows:

- Hinder cracking upon drying by distributing tension arising from shrinkage of clay throughout the bulk of the material
- Accelerate drying because they improve drainage of moisture
- lighten the material, reducing the bulk density and improving insulating properties,
- Increase tensile strength

(Filho et.al., 1990) has investigated the mechanical properties of sisal fibres relevant to application of sisal as reinforcement agent. With the use of 500mm long sisal fibre, the source finds a tensile strength of 470 N/mm^2 and stress at failure of 1.6 %. The source uses a tensile testing machine with a maximum capacity of 200N; the load applied at a speed of 1mm/sec. These results are similar to the one forwarded by (Mukerji. K, Satyanaryama, K.G., 1984), who report a tensile strength of 560 N/mm^2 and stress at failure of 4.2 %. A range of 330 – 820 is N/mm^2 and 1.0 – 5.8% strain is reported by (Mawenya, A.S., in Appropriate Building Materials for Low Cost Housing, African Region, Proceedings of a Symposium, Ed. Spon, F.N., Vol. I, Nairobi, Kenya 7-14 Nov. 1983).

These results confirm the fact that sisal vegetable fibres are in possession of properties that would significantly enhance the durability properties of compressed earth blocks. The choice of sisal fibres as a reinforcement agent in the present project is based on the knowledge stated in this and in the past two sections.

3.3 Cassava Powder

3.3.1 Cassava Plant Origin and Cultivation

Cassava (English speaking Africa, Thailand, Sri Lanka), is also known as manioc (French-speaking Africa), manioca, yucca (Latin America), mandioca or aipim (Brazil), tapioca (India, Malaysia), kaspe (Indonesia), manihot, mandica and sweet potato tree. It is an important food crop in the tropics where it is grown for its starchy, tuberous roots, figure 3.4. The roots which are the most valuable portions of the plant grow in clusters of 4 – 8 at the stem base. The number of tuberous roots and their dimensions vary greatly among the different varieties. The roots may reach a size of 30-120 cm long and 4-15 cm in diameter, and a weight of 1-8 kg or more.

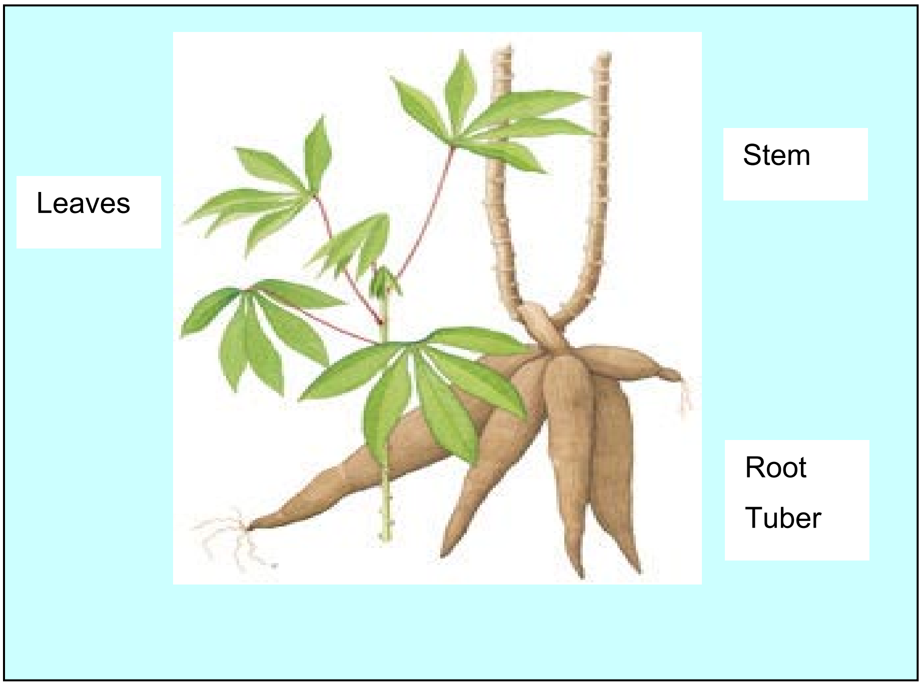


Figure 3.4 Cassava plant

According to (http://www.fao.org/docrep/X5032E/x5032E01.htm#Acknowledgments) the cassava plant, flowering shoots shown in figure 3.4 and 3.5, is a perennial that grows under cultivation to a height of about 2.4m. The large, palmate leaves ordinarily have 5 - 7 lobes borne on a long slender petiole. They grow only toward the end of the branches. As the plant grows, the main stem forks, usually into three branches which then divide similarly.

The roots or tubers radiate from the stem just below the surface of the ground. Feeder roots growing vertically from the stem and from the storage roots penetrate the soil to a depth of

50-100 cm. Male and female flowers arranged in loose plumes are produced on the same plant. The triangular-shaped fruit contains three seeds which are viable and can be used for the propagation of the plant.

Figure 3.5 Cassava plantation

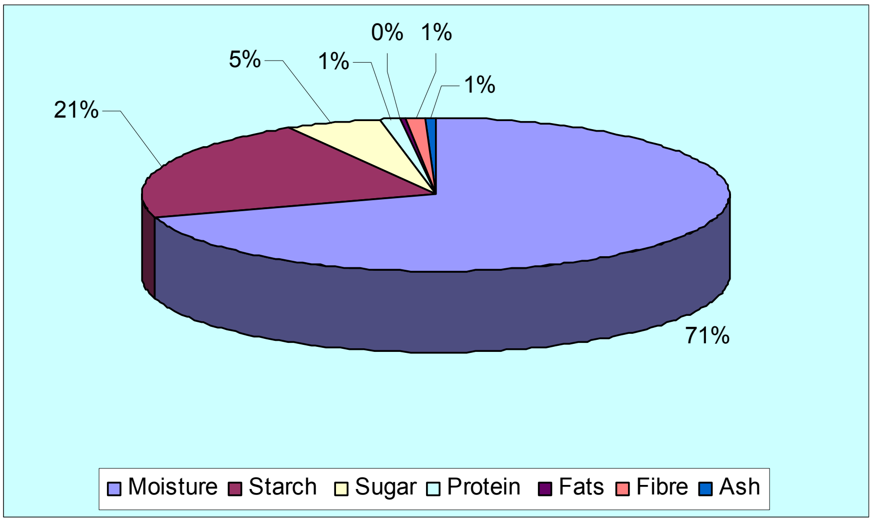


Figure 3.6 Composition of cassava flour

The peel consists of an outer and an inner part, the former comprising a layer of cork cells and the phellogen. The cork layer, generally dark-coloured, can be removed by brushing in water, as is done in the washers of large factories. The inner part of the peel contains the phelloderm and the phloem, which separates the peel from the body of the root. The texture of the transition layer makes it easy to loosen the whole peel from the central part, thus facilitating the peeling of the roots. The outer layer varies between 0.5 and 2 percent of the weight of the whole root, whereas the inner part of the peel accounts for about 8-15 percent. Generally in ripe roots this is about 2-3 mm thick. Starch content of the peel is only about half that of the core. Composition of cassava flour (powder) is presented in figure 3.6.

Origin and Cultivation

Cassava was unknown to the Old World before the discovery of America, (http://www.fao.org/docrep/X5032E/x5032E01.htm#Acknowledgments). There is archaeological evidence of two major centres of origin for this crop, one in Mexico and Central America and the other in north eastern Brazil. The first Portuguese settlers found the native Indians in Brazil growing the cassava plant. It is believed that cassava was introduced to the western coast of Africa in about the sixteenth century by slave merchants. The Portuguese brought it later to their stations around the mouth of the Congo River, and it then spread to other areas. Cassava cultivation increased after 1850 in the east African territories as a result of the efforts of Europeans and Arabs who were pushing into the interior and who recognized its value as a safeguard against the frequent periods of famine. In the Far East, cassava was not known as a food plant until 1835. In about 1850 it was transported directly from Brazil to Java and Singapore. During the period 1919-41 about 98 percent of all cassava flour was produced in Java, but during the Second World War Brazil increased and improved its production. Now grown throughout the tropical world, cassava is second only to the sweet potato as the most important starchy root crop of the tropics. The cassava plant has been classified botanically as Manihot utilissima Pohl

Because it grows easily, has large yields and is little affected by diseases and pests the areas under cassava cultivation are increasing rapidly. The plant is grown for its edible tubers, which serve as a staple food in many tropical countries and are also the source of an important starch. In parts of the Far East during the Second World War many people survived on cassava roots, and in Africa it was a principal food source for workers in mining and industrial centres.

It is now grown widely as a food crop or for industrial purposes. In many regions of the tropics cassava occupies much the same position as white potatoes do in some parts of the temperate zones as the principal carbohydrate of the daily diet. The industrial utilization of cassava roots is expanding every year. In the early decades of this century, cassava was held responsible for the rapid exhaustion of forest clearings, but later experiments in many parts of the tropics showed that it is not a soil-depleting crop.

Since the Second World War, a more balanced appraisal of the crop has developed. More scientists, agriculturists and sociologists have become aware of its importance in developing countries, where it is most commonly produced. In many countries emphasis is being placed on research for the improvement of production and utilization of cassava crops. However the use of cassava powder in building industry is undocumented; investigations carried out in this work show that this is possible, see section 6.4.

Cassava Powder as a Soil Stabiliser

The use of cassava as a stabilisor for soil blocks is unrecorded in literature. The only similarity that appears to exist is the use of casein (middle fraction of the protides of milk). (Schneider et al., 1996) suggests that the improved water proof ability of soil blocks made with casein may simply be, because the its proteins fill up the pores in the clay matrix thus stopping the movement of water by capillary action and reducing the ability of clay to swell. No concrete research findings are catalogued in the available literature.

The choice of cassava powder as a possible stabilising in this dissertation is based on the observation that the powder mixed up with water produces a sticky product. It is then assumed that this sticky product could be used as a binder for soil particles, section 6.4 provides further details.

3.4 Earth Stabilization for Production of Compressed Earth Blocks A Historical Perceptive

According (Rigassi, 1995) the compressed earth block (CEB) is the modern descended of the moulded earth block, more commonly known as the adobe block. The idea of compacting earth to improve quality and performance of moulded earth blocks is, however, far from new, and it was with wooden tamps that the first CEB were produced. This process is still used in many developing countries. The first machine for compressing earth may have appeared in the 18th centaury. In France, Francois Cointeraux, invented “new pise” (rammed earth) and designed the “crecise” a device derived from a wine press. It was not until the beginning of 20th centaury that the first mechanical presses, using heavy lids forced down into moulds were designed. However, the turning point in the use of presses and in the way CEB were used for building came only with effect from 1952, following the invention of the famous CINVA-RAM press designed by engineer Raul Ramirez at CIVA centre in Bogoto Columbia. Later there appeared new generation of manual, mechanical and motor-driven presses leading to the emergence today of a genuine market for the production and application of the compressed earth block. Production technology and application of CEB in construction has since continued to improve. Research centres have developed sophisticated body of knowledge making this technology today the equal of competing construction technologies.

In spite of all these developments and although earth is the oldest building material and soil constructions exist in almost all developing countries much research is still needed to improve soil technologies due to instability in wet conditions (low cost technologies in Kenya, 1996). It is the purpose of this doctoral research project, as already mentioned, to provide solid scientific contribution to the body of knowledge associated with the use of earth as a building material.

Stabilization Methods Definition and Objective

Stabilization, according to (Product information, GATE, 1994), is a technical process, the object of which is to neutralize or at least restrict the detrimental behavior of the clay present and thus reduce the natural sensitivity of the soil to water, which leads to a loss of strength and cohesion. According to (Kenya standard specification for soil blocks, 1990), stabilisation is done for the purpose to improve the natural durability and strength of a soil by the addition of other materials. (Rigassi, 1995) records that the goal of stabilisation of soil is to lend it properties which are irreversible in the face of physical constrains. (Houbon, 1994) notes that stabilization of soil implies the modification of the properties of a soil-water-air system in order to obtain lasting properties which are compatible with a particular application. (Norton, 1997) states that the purpose of stabilization is to permanently improve a soil, either by increasing its strength or by reducing the variations in cohesion and size caused by changes in moisture content, by reducing the erosive effect of water on the surface, or by combinations of these.

Various groups of stabilizers can be classified according to the way they act on clay plates, described in section 3.1.2. A simplified classification of additives is shown in the table 3.1 (Mukerji, 1991) below. It should be mentioned that no single method of stabilization precludes the use of another; on the contrary, the most durable earth blocks result from a rational use of several stabilization methods.

Table 3.1 Stabilization methods

STABILIZATION METHODS					
Stabilizer		**Nature**	**Process**	**Means**	**Principle**
Without Stabilizer			Mechanical	Compaction	Creation of a dense material, blocking pores and capillarity
With Stabilizer	Inert Stabilizer	Minerals	Physical		
		Fibers		Reinforcing	Creation of isotropic matrix, opposing any movement
	Physico-Chemical Stabilizer	Bonding and Water Repellent	Chemical	Cementation	Formation of an inert matrix, opposing any movement
					Formation of stable chemical bonds between clay crystals
				Water Proofing	Coating of soil particles with an impermeable film and filling pores and ducts
				Water Repelling	Maximum elimination of water absorption and adsorption

This dissertation focuses mainly on the application of natural fibres (i.e., sisal vegetable fibres) which are categorized, as observed from table 3.1, to be inert in nature. Their way of stabilization is physical through reinforcement. The principle by which they improve the durability of compressed earth blocks is by creating isotropic matrix with the soil particles. The type of stabilization or reinforcing agent applied in the present dissertation is the cassava powder; it is assumed that this is a physio-chemical type of stabilizer which uses the principle of cementing soil particles.

Other types of physio-chemical stabilizer are cement, lime, bitumen etc. These have been well researched on as indicated in section 1.2 and well documented by (Mukerji, 1991; minke, 2000; Norton, 1997; Houben 1994); it is not the intention of this dissertation to duplicate these research findings, but rather confine to areas that are less documented in literature.

4.0 Experimental Material and Equipment

The scope of this chapter limits itself to description of materials and equipment used to produce the specimen block samples. Various tests have been carried out on experimental materials, thus clay, cassava and sisal in order to determine their physical properties. Although section 6.0 is dedicated to discussion of the bulk of results from the present study, section 4 provides some results of the basic but useful properties of the material characterisation. Attempts have also been made to provide some information about the equipment that was most fundamental for the success of this work.

4.1 Experimental Material

Earth, sisal fibres, cement and cassava powder are the raw materials that have been used for this study. Earth or soil, considered suitable for manufacturing compressed earth blocks, has been taken from Bautzen near Görlitz in Germany. Portland cement, type CEM I 32.5R, was manufactured in the Czech Republic. Sisal vegetable fibres used to reinforce the earth blocks and cassava powder required for stabilisation of the blocks originated however, from Kenya. The other material used to moist the above stated materials was tap water. These raw materials used for preparation of samples as well as the variables in the raw mix are shown in Tab. 4.1 and figure 4.1.

Tab. 4.1 Raw materials for sample preparation

Experimental material			
Item	**Type**	**Effect/Means**	**Process**
Sisal	Natural fibres	Reinforcement	Physical
Cassava	Starch	Bonding	Chemical
Portland Cement	Mineral	Cementation	Chemical
Soil	Clayey material	Compaction	Mechanical

Indeed, soils differ from country to country and even region to region. In fact it is for this reason that no universal standards for soil as a building material exist. It is important to note, however, that although these differences in soil type exist, this has not hindered scientific work to advance data on soil as construction element to be generated by various workers. The decision to use soils originating from Germany and not Kenya was based not only on the on the economic factor but also because preliminary investigations on texture of various soil samples from different sites showed that the Salzenforst-Bautzen soils (from “Sand und Kiesgrube Schneider) were close to those found in the western region of Kenya from where the author hails.

Figure 4.1 Experimental material

4.1.1 Earth Preparation and Characterization

Full blocks were fabricated using soil collected from the town of Bautzen in Germany. In order to obtain initial uniform moisture content, the soil was stored in the open at a room temperature of 22 °C at a relative humidity of 65 – 70% for five months before being broken down and passed through a 2 mm sieve. Several past researchers have recommended the ideal sieve size; (Webb & Lockwood, 1987) prefer 5-6 mm sieve; (Houbon and Guillaud, 1994) recommend 10-15 mm.

The procedure applied in preparation of soil prior to block manufacture is shown in the scheme in figure 4.2. After drying, the soil is crushed and passed through a sieve of 2 mm, figure 4.3. The soil has been, through crushing and sieving, prepared with particular care, in order to ensure that the stabilizer or reinforcing agent could be uniformly distributed throughout the material.

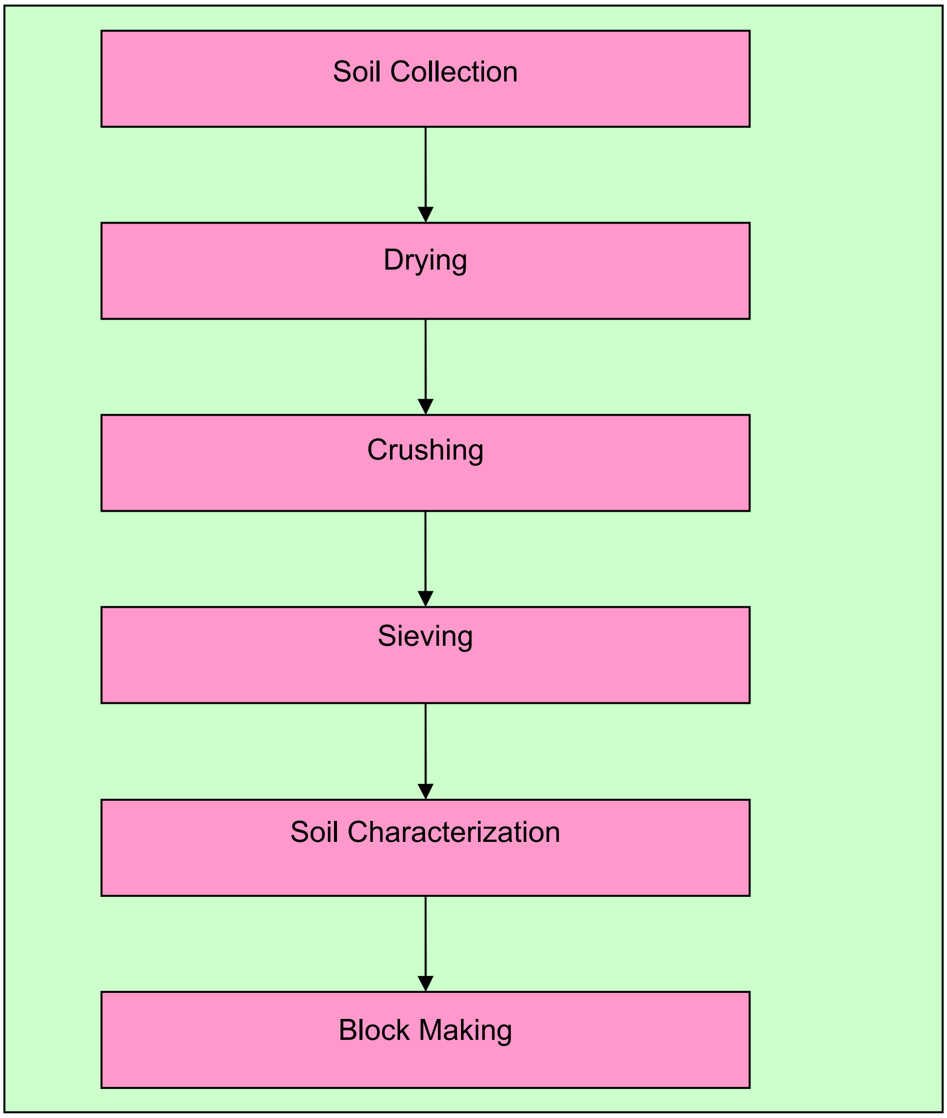


Figure 4.2 Soil preparation flow chart

In order that the stored soil can dry out more evenly, it was thinly spread over polythene paper and regularly raged through, thus turned over several times. The change in colour at different layers helps to determine to which extend the soil has dried out. Dark complexion shows presence of moisture. The process of regular raging also provided the means by which impurities in the soil, e.g. papers leaves, polythene and non-soil stone boulders, shown in figure 4.4, were separated and eliminated from soil.

Figure 4.3 Sieving an earth sample

Figure 4.4 Impurities in earth sample

Many researchers in the area related to soil science, geology and agronomy have written volumes of literature concerning soil properties, identification and characterization methods. It is not the purpose of this doctoral project to go deep into this area. It is however, necessary to mention a few of the methods or identification tests whose results can help understand if a given soil sample is appropriate as a building material. According to (Houben and Guillaud, 1994) such tests can be divided in to indicator and laboratory tests. The indicator test which include visual and manual do not form part of this work; this is because experimental tests provided data that was sufficient for finding out suitability of the soil sample as in building. The indicator tests, which are normally done at a relatively low cost and which are very suitable for people practicing in the rural areas, are well documented by (Rigassi, 1995).

As mentioned in section 3.1, soil appears, depending on the parent rock, in infinity of forms possessing an endless variety of characteristics. This section examines the properties relevant to the present dissertation and how they were determined. Indeed, soils must not only be classified, it is also of great significance to establish their attributes or properties before selecting them for use as construction materials. In order to establish the category of the soil sample, the following physical characteristics of the sample were determined before block making process commenced, thus, particle size distribution, plasticity index (Atterbergs limits), optimal moisture content, organic matter, chemical composition and mineralogical composition. These are depicted in figure 4.5.

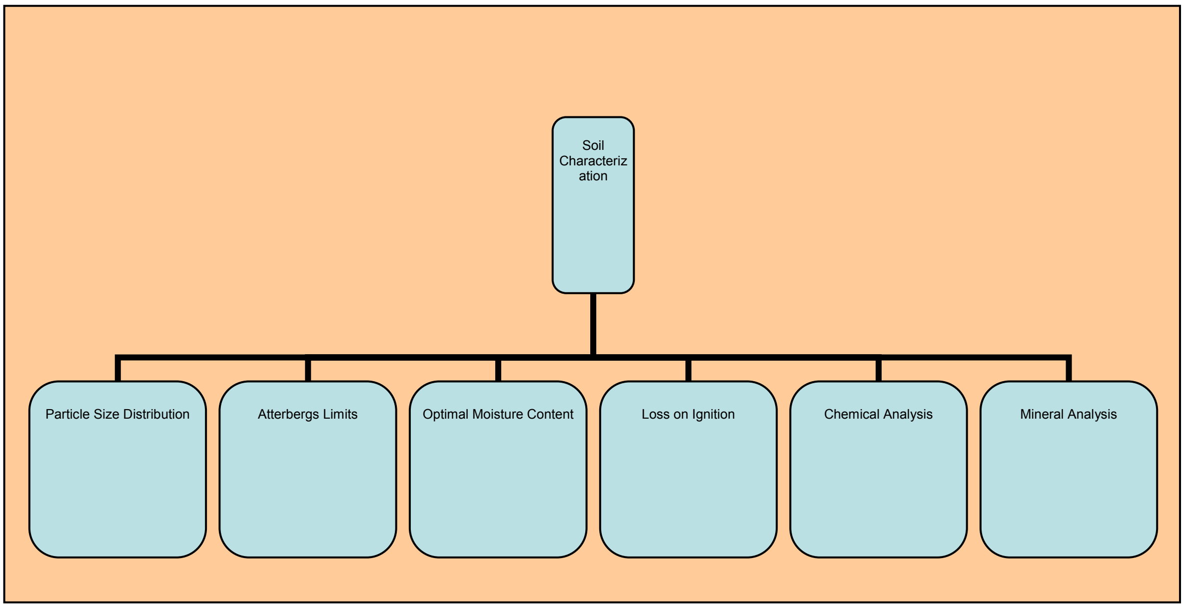


Figure 4.5 Soil characterization tests

4.1.1.1 Particle Size Distribution

The particle size distribution was established by sedimentation using the German industrial standards (DIN 18 123); results are illustrated in table 4.2. The results indicate that the clay proportion (20%) is within the recommended limits required for production of compressed soil bricks. The clay presence is important in the sense that, clay is responsible for the bonding effect amongst the soil particles. The soil also contains sufficient amounts of course fraction, i.e. 20% sand by proportion, this amount is sufficient to limit shrinkage of blocks when drying out, (Minke, 2000), refer also to section 6.5.

The Kenya standards recommend that the soil grains should be less than 6mm in size while the silt and clay content should exceed 10%. (Walker, 1996) states that clay contents of between 5% and 20% are considered suitable for earth block production.

Table 4.2 Atterberg limits, sedimentation results, loss on ignition and optimum moisture content of soil sample

S. No.	Item	Quantity, %
1	**Grading**	
	Gravel Fraction	0.0
	Coarse Sand Fraction (0.6 – 2 mm)	0.0
	Medium Sand Fraction (0.2 – 0.6 mm)	2.0
	Fine Sand Fraction (0.06 – 0.2 mm)	18.0
	Coarse Silt Fraction (0.02 – 0.06 mm)	32.0
	Medium Silt Fraction (0.006 – 0.02 mm)	22.0
	Fine Silt Fraction (0.002 – 0.006 mm)	6.0
	Clay Fraction (≤ 0.002 mm)	20.0
2	**Atterberg Limits**	
	Liquid Limit (LL)	28.9%
	Plastic Limit (PL)	18.3%
	Plasticity Index (PI)	10.6%
3	**Optimum Moisture Content (OMC), %**	14.0%
4	**Los on Ignition (LOI), %**	2.138%

4.1.1.2 Atterberg Limits (Plasticity Index)

The consistency of clay in the soil relative to its moisture content varies according to its mineral and chemical composition (Norton, 1997). This consistency which can be weakly referred to as plasticity, refers to the ability of soil to submit to deformation without elastic failure characterized by cracking or disintegration. The range of consistency or plasticity is expressed through the so called Atterberg limits (Minke, 2000). The liquid limit (LL) defines the water content on the boundary between the liquid and plastic stage. The plastic limit (PL) is the water content as a percentage at the boundary of the plastic and semi-solid state. At LL, soil starts to manifest a certain resistance to shearing; at PL, the soils stops being plastic and becomes brittle. The plasticity index (PI) is the difference between LL and PL. PI determines the range of plastic behaviour of the soil. The greater PI becomes, the greater the swell when soil is moistened and its shrinkage when it dries. For the present work, the soil's sample Atterberg limits were determined according to (DIN 18 122). The obtained PI of 10.6%

indicates, according to (Voth, 1978), that the soil sample lies within the range or category of silty and clayey type, table 4.3. (Rigasi, 1995) suggests PI of 5 to 25 and LL of 20 to 50; that would imply according to this standard that the soils used in this project are silty in nature.

Table 4.3 Plasticity index of soils (after Voth, 1978)

Type of soil	LL, %	PL %	PI = LL - PL
Sandy	10 – 23	5 – 20	5
Silty	15 – 35	10 – 25	5 – 15
Clayey	28 – 150	20 – 50	15 – 95
Bentonite	40	8	32

4.1.1.3 Optimal Moisture Content

The optimum moisture content is said to be that water content in the soil with which a maximum dry density can be obtained at a given amount of compacting energy (Norton, 1997). If the moisture content is too high the soil may swell and the pressure of the compacting equipment will be dissipated by the water trapped between particles (Rigassi, 1995). If on the other hand, the moisture content is too low, the particles will be insufficiently lubricated and it will not be possible to compact the soil to its minimum volume. Optimum moisture content, also referred to as optimum water content, was determined in this project by use of the procedure as provided in (DIN 18 127). In this particular case a value of 14.0% was established. The compaction, with a proctor hammer, was performed on samples with varying water contents and the densities established. A Proctor curve, passing through these various densities, depicts the optimum water content at its maximum.

(Minke, 2000) notes that OMC does not necessarily lead to maximum compressive strength since other factors like the soil workability and binding force (dependent on clay content) are more decisive. The source suggests that the so called OMC be taken as minimum water content in practice. For the present work, the obtained OMC content formed a basis upon which several pre-experiments were performed with water levels above OMC; results of the pre-experiments helped to establish that 17% water content provided the best compressive strength; this value has also obtained or used by other researchers as would be shown in section 2.5.

4.1.1.4 Loss on Ignition (LOI)

Soils with great LOI value are unlikely to be suitable for compressed block production. Large number of organic particles would prevent the clay part, which is responsible for cohesion, from direct contact with other soil parts. The Kenya standard specifications for soil blocks recommend that the loss on ignition should be less than 12%; (Houben, 1989; Walker, 1995) suggest that amounts exceeding 4% would already affect soil characteristics. This source reports that organic matter is likely to trigger acidic reactions in the soil leading to corrosive attack of other minerals in the soil. The organic component in the soil was assessed according to (DIN 18 128). A value of 2.138% was obtained for the soil sample; accordingly with reference to LOI, this soil was suitable for block making.

4.1.1.5 Chemical Analysis of Soil

By application of Roentgen diffractometry (X-Ray fluorescence analysis) method (Philipps-Diffractometer PW1050 equipment) it was possible to establish that the soil sample contains the following 3-layer clay minerals: Mica, swelling clay minerals (Montmorillonite) and Chloride, table 4.4. The clay mineral present is therefore predominantly montmorillonite. The non-clay minerals present are Silica and Feldspar.

Table 4.4 Mineral composition of sample soil

S. No.	**Bautzen Soil**					
		Non-Clay Minerals		**Clay Minerals**		
1	Mineral Type	Silica	Feldspar	Chloride	Montmorillonite	Mica
2	Mineral Content, %	51	16	8	8	16

Chemical composition of sample soil sample is shown in table 4.5. As expected, quartz represents the highest fraction of the soil sample, i.e. almost 70%. The Kenya standards suggest that the combined amount of alumina oxide silica oxide and iron oxide should be greater than 75%; the soils applied for the present work contained 92.94% hence these soils were seen to be suitable for block production.

Table 4.5 Chemical composition of sample soil

S.No.	Type and Quantity of Element, %								
1	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**SO_3**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
2	0.84	0.87	13.37	69.93	-0.17	3.69	0.72	1.11	9.64

4.1.2 Sisal Fibres

Sisal vegetable fibres were imported from Kenya. The initial length of sisal fibres, shown in figure 4.6, varied from 0.9 – 1.2 m. In order that the moisture content reflects that of the soil sample, the fibres were kept in the open space in laboratory just as was the soil sample. In this way the initial moisture content of sisal and soil were expected to be the same.

Figure 4.6 Sisal vegetable leaves and fibres

Sisal Fibres Dimensions and Density

Sisal vegetable fibres were cut to an average length of 3 – 10 mm. Choice of these length was based on pre-experiments, results (not part of this write-up) had shown that fibre length of over 15 mm caused balling and therefore difficulty in attaining uniform fibre distribution within the soil. The thickness of the sisal fibres as determined by a scanner from IST Ltd Switzerland, with a resolution of 2400 [dpi], is shown in table 4.6. The density of sisal fibres was, on the other hand, determined with the help of a pycnometer, and found to be 1.30g/cm^3.

Table 4.6 Measurement limits of sisal thickness

	Dimensions, µm	Median, µ m	±
Thickness, µm	128.38	122.19	73.41

4.1.3 Cassava Powder Characterization

Particle size, Chemical analysis and Density

Particle size of cassava powder was determined by scanning a sample with a scanner from IST Ltd Switzerland at a resolution of 2400 [dpi]. It was found to lie between 1 µm and 50 µm. By use of X-Ray fluorescent analysis (Spectrace 5000), the chemical composition of cassava powder was established; results are presented in table 4.7 and figure 4.7. As expected, the cassava powder is basically a starch with a carbohydrate content of 98.48%.

Table 4.7: Chemical composition of cassava powder

	Others									Carbohydrates
Element	**Na**	**Mg**	**Al**	**Si**	**P**	**S**	**Cl**	**K**	**Ca**	
Content, %	0.50	0.05	0.05	0.07	0.11	0.05	0.05	0.88	0.06	98.48

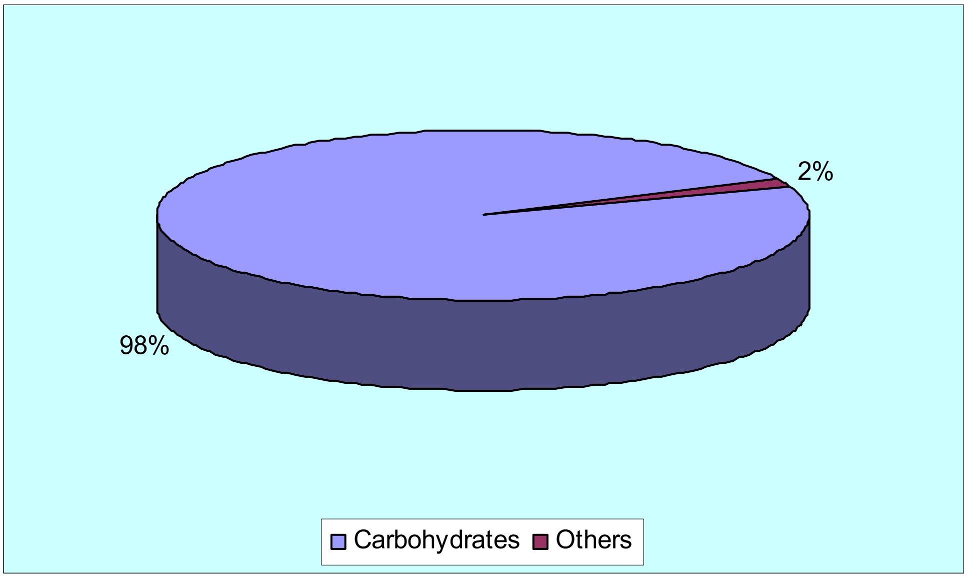


Figure 4.7 Chemical composition of cassava powder

Scanning electron microscopic analysis was used to study the cassava powder internal structure. The micrograph of the sample, shown in figure 4.8, confirms the presence overwhelmingly of starch (carbohydrates) molecules in the cassava powder. The density of cassava powder was, on the other hand, determined after 20 Ton compaction and was found to be 1.32 g/cm^3.

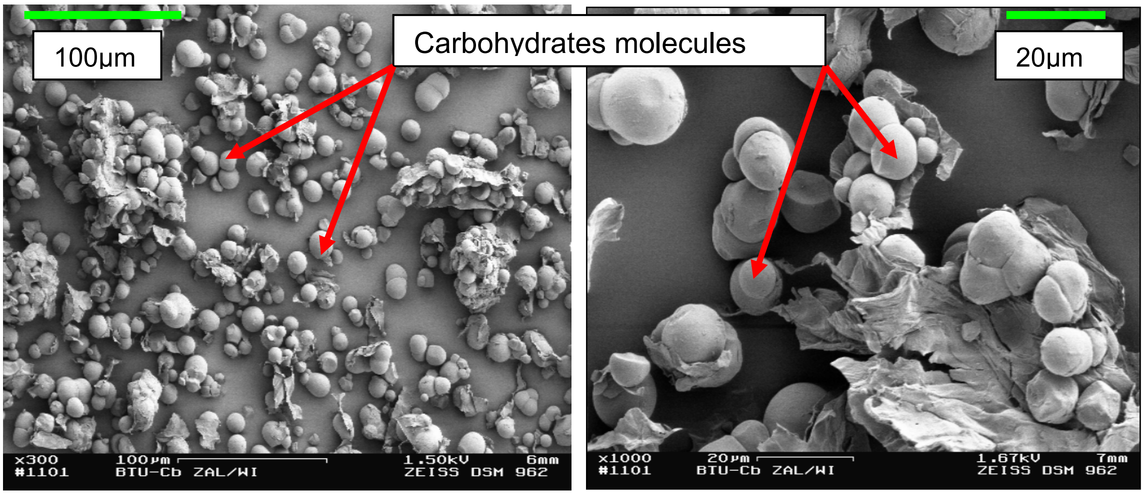


Figure 4.8 SEM image of cassava powder sample

4.2 Experimental Equipment

This section contains a brief description of the important equipment used in the present work. This included, among others, the soil crushing apparatus, block making press, block cutting equipment and the apparatus for mechanical strength determination.

4.2.1 Soil Crushing Machine

The purpose of crushing the soil was to reduce the agglomerates to a particular size suitable for block manufacture. Past research has shown that soil particles of smaller size (less than 10 mm) provide better bonding during block making. (Houben 1994) notes that the finer element must not be allowed to form nodules with a size of more than 10mm; the presence of 50% nodules with a size of greater than 5mm could cut the compressive strength by half. The wet soils collected from an open site were mainly bound together by the initial natural drying process in the laboratory hall. After this initial dying period, the soils were held together in lumps of approximately between 10 to 100 mm in diameter. Such lumps would not be conducive for mixing with other ingredients.

Fgure 4.9 Soil crushing process

The soil grinding apparatus are shown in figure 4.9. Below the rotating knives mounted on a hub was a sieve 2 mm in size. The undersize had therefore a maximum diameter of about 2 mm. The crushed soils were then spread over a polythene sheet and allowed to undergo the secondary drying process for a period of 4 weeks.

4.2.2 Block Making Press

A manually operated constant volume press borrowed from “artifact gGmbH” of Glücksburg, Germany, shown in figure 4.10, was used for fabrication of compressed earth blocks. Although it was not possible to measure exactly the compaction pressure, numerous past researchers have indicated that such a single acting ram press is capable of developing pressures of between 2 – 4 MN/m^2. The press used in this investigation produces full blocks with nominal dimensions of 230 mm (length) 110 mm (width) and 90 mm (height).

The “Balram” block press made entirely of steel consists of a double mould box with mould cover (lid) on to which a toggle locking lever is rolled. This is connected via a yoke to a piston below the mould box, which has a moveable base plate fixed to a piston. The soil mix is filled in the moulds with the lever arm in the horizontal position. The mould lid is then closed and secured by the lever toggle. When the lever arm is pushed down, the piston moves upwards, thus, compressing the soil between the base plate and the lid. In order to eject the compressed earth block, the lever is released to horizontal position, the lid opened and the lever arm pushed downwards. The whole unit is mounted to a metal base board so that stability is provided during the operation process.

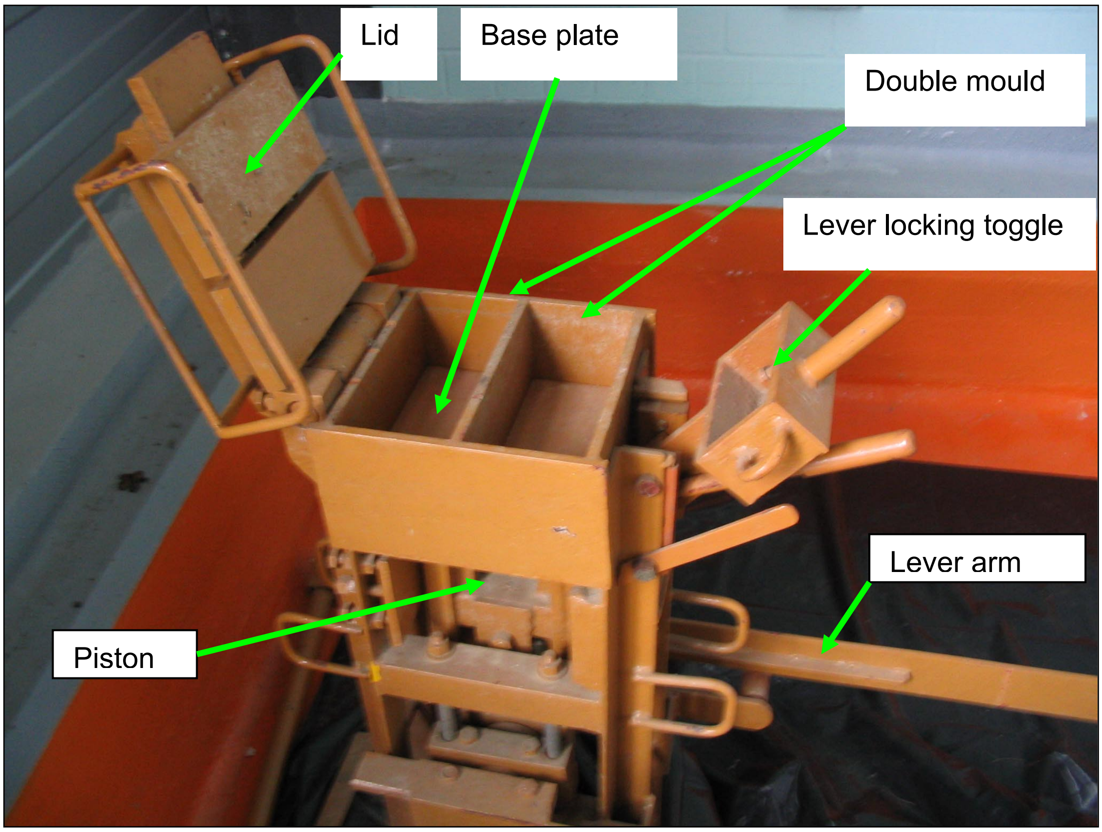


Figure 4.10 “Balram” Block press “artefact gGmbH Glücksburg”

4.2.3 Block Cutting Equipment

The equipment available for testing of both compressive and tensile strength, required prisms of the size 160 mm (length) 40 mm (width) and 40 mm (height). These smaller scale blocks were obtained by mechanically cutting the full blocks in a diamond coated rotary power saw. Because of the diamond coat, it was possible to cut through the full bricks of size 230 mm (length) 110 mm (width) and 60 mm (height) with high precision and without the risk of breakages, see figure 4.11.

The power saw operating at a speed of between 1000 – 3000 rotations per minute produced cut surfaces that were that appeared well leveled straight. Such surfaces are required for better results; especially in determination of compressive and flexural strength where the measuring equipment is surface sensitive. The rotary power saw model “WOCO-TOP 300-A2”, shown in figure 4.11, is manufactured by Conrad Apparatebau GmbH. Sample of compressed soil blocks and the cut samples are illustrated in figure 4.12, with the dimensions shown 4.13 and 4.14.

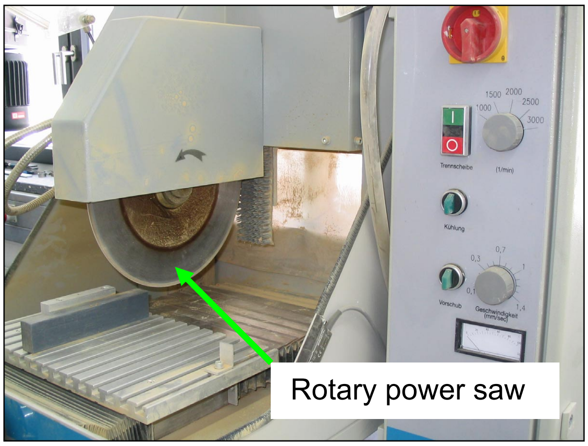


Figure 4.11 Block cutting equipment
“Conrad Apparatebau GmbH”

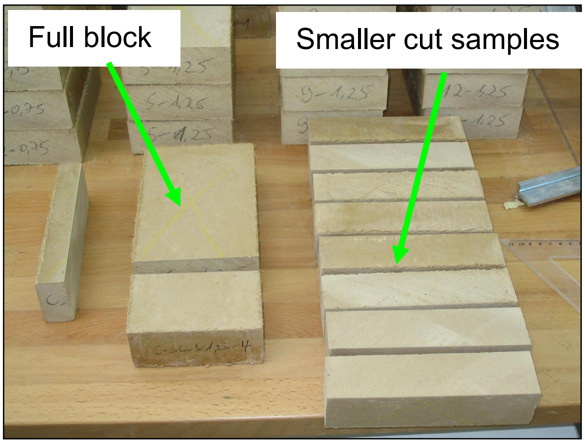


Figure 4.12 Full and cut blocks

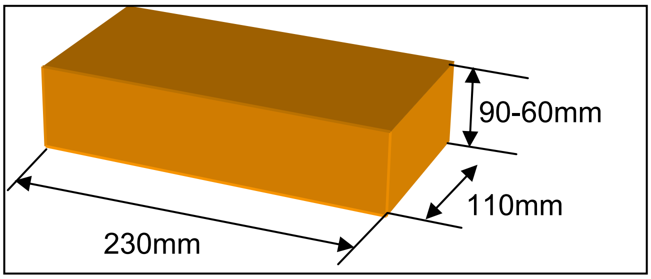


Figure 4.13 Full blocks

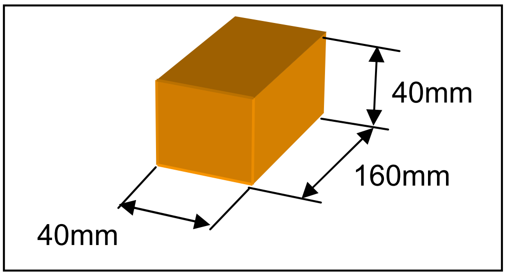


Figure 4.14 Cut blocks

4.2.4 Flexural and Compression Testing Apparatus

For determination of compressive strength, each specimen was loaded in a TONIVERSAL-TONITECHNIK hydraulic press at a rate of 1.5 N/mm^2/s. the cut blocks were placed centrally between the lower and upper sides to provide for uniform distribution of the of the compressive force. The flexural strength was conducted by **uniaxial** point loading on TONIVERSAL-TONITECHNIK hydraulic press at a rate of 0.05 kN/s

4.2.4 Water Vapour Transmission Properties Equipment

This apparatus are, for ease of understanding, described in section 6.7

4.2.5 Theoretical Block Density Equipment

For easy flow of experimental write-up, the method used to determine the theoretical block density is discussed in section 6.1.2.2

5.0 Experimental Procedure

5.1 Production of Stabilized Earth Blocks

5.1.1 Preparation Methods

Preparation towards block production, after the input materials have been treated as per chapter 4, involved mixing the dry ingredients, addition of water to sufficient workability, block pressing or compaction and curing of the freshly manufactured compressed blocks. These are crucial steps towards producing blocks which, on one hand, would have comparable parameters and on the other hand, would possess acceptable durability criterion. A great experimental error would occur if these steps are not executed with care, in other words, they should be processed as uniformly as possible. The preparation was done in such a way that the methods were consistent with the Kenya standard specification for soil blocks. Past investigations do not particularly the record the ideal way of mixing soil and sisal vegetable fibres. Pre-experiments were therefore done, as part of this work, for the purpose of finding out the best method to perform this action; results of pre-experiments are not included in this write up.

5.1.2 Mixing

Mixing of cassava, cement, sisal or sisal-cement in soil was done manually by hand on a wheelborough in a dry state. Proportioning of soil to the stabilizers as well as water was done by weight and not by volume. The soil-stabilizer mix was to be as homogeneous as it was possible in order to attain uniform or comparable results; the mixing (dry mixing) was therefore, thoroughly done before wet mixing with water to sufficient workability. Addition of about 3% water above the optimum moisture content provided a composition that would gain adequate block density on drying. In all cases, 17% water was used. In the case where both cement and sisal were used (see section 5.2), cement was first added to the soil by spreading over evenly and mixed thoroughly. Sisal fibres were then spread over the soil-cement mixture and diligently mixed through, the same applied for cassava powder, figure 5.1.

Addition of water to the dry ingredients was done using a spray and not poured over the soil. The spray produces droplets of water across the whole surface resulting in a uniform moisture distribution. Care was taken to break up any lumps formed. In order to ensure uniform distribution of input elements within the mix, only amounts or quantities sufficient to fill up the double mould were mixed in each batch. Mixing of huge amounts is more difficult and could be a source of experimental error.

Figure 5.1 Soil-fibre manual mixing

About 14 minutes were required to mix about 8 kg of soil and the respective stabilizing or reinforcement ingredients. The period between wet mixing and pressing was made as short and as equal for all batches as possible. This is because the wet mixture starts to dry up, resulting in moisture content that would be insufficient for producing blocks with ideal density. In case of cement presence, this is additionally necessary because the hydration of cement commences almost immediately. Mixing of ingredients is followed by the filling of the mould.

5.1.3 Pressing

The three stages towards pressing were as follows: mould filling, moulding (compaction) and demoulding. Pressing also known as compaction or compression, is an operation which consists in compressing the material in a confined space known as a mould using a static or dynamic mode (Compressed Earth Blocks, Standards, Series Technologies Nr. 11, CRATerre-EAG Basin, 1998). Oil was used to clean up the mould in every instance before filling. This ensured that the compacted block could easily be removed without the danger of surface pilling. Oil had no other observed effect to the block. Immediately the soil composite and ingredients were thoroughly mixed and water added to appropriate consistency, the mould was filled, the lid appropriately closed and blocks compacted by banging the press lever 10 times. The compression mode, in this particular case, was pressure transmitted by displacing the base plate onto the bed face also known as the lid, see diagram of the press in section 4.2.2.

Filling of the moulds is a short but significant step. The mould was filled in two layers. After each layer, the corners were pressed using fingers. This ensures that the bottom or lower corners are stable. The filling of the mould was done in such a way that equal amounts of the mix by volume were used; this was achieved by having the mix filled in all cases up to the upper brim of the mould. That meant effectively filling the last layer such that it stands above the height of the mould sides and then scrapping off up to the mould height. Blocks produced from same compositions were generally of equal density and dimensions; **refer to appendix A**. Figure 5.2 illustrates the filling and compaction procedure as undertaken in this investigation.

Figure 5.2 Block pressing process

The initial dimensions (length and width) of the blocks remained constant, In other words, these dimensions corresponded to those of the mould. The block height differed slightly in each case, these was due to the practical inability to keep the compression pressure exactly the same. The blocks were labeled appropriately as indicated later in table 5.1.

As expected, the compression ratio (see details in section 6.5) would differ depending on which ingredients had been added to the soil, apart from the pressure exerted during compaction. The pressure was therefore kept as constant as possible. Where cement was used as the stabilizer, compaction ratio would be lower than the situation where sisal fibres, a combination of cement-sisal or cassava have been used as reinforcing agents. This would be, understandably, because of the different pore system or quantity occasioned by the respective reinforcing or stabilizer type.

5.1.4 Curing

Great care was taken in removing (demoulding) the still wet blocks in order to avoid breakage; particularly to the block edges. The weights of the wet blocks (also known as green blocks) were constantly taken to be sure that no great variations occur. The heights were also occasionally taken as a way to monitor and evaluate the block manufacturing process, see section 6.5 on compression ratio.

The sisal as well as the cassava reinforced compressed blocks were extracted from the press and air dried in the open in the laboratory for a period of 28 days before being tested. The temperatures in the laboratory were about 22°C. The cement and sisal-cement blocks were cured under polythene sheeting for 14 days and moistened daily to allow for complete hydration of cement then left in the open to dry for another 14 days before testing for mechanical strength. With the green blocks covered by a polythene paper, moisture (and therefore relative humidity of about 100%) required for cement hydration was kept continuously present.

5.2 Experimental Design

5.2.1 Block Making Programme

This chapter provides a description of the experimental design for the tests carried out in the laboratory. It is already well established that in the final analysis, a block made only of unfired earth still displays certain weaknesses due to the following factors: its excessive water absorption, its poor resistant to abrasion and impact, its low tensile strength, see section 3.1.4

Therefore and as already stated earlier in section 2, the idea behind this present work was to manufacture compressed soil blocks reinforced or stabilized so that the mechanical strength would meet the recommended standards as would be illustrated in section 6, and consequently, such that the manufactured blocks would be suitable for house construction. Figure 5.3 shows the input combinations for the produced blocks.

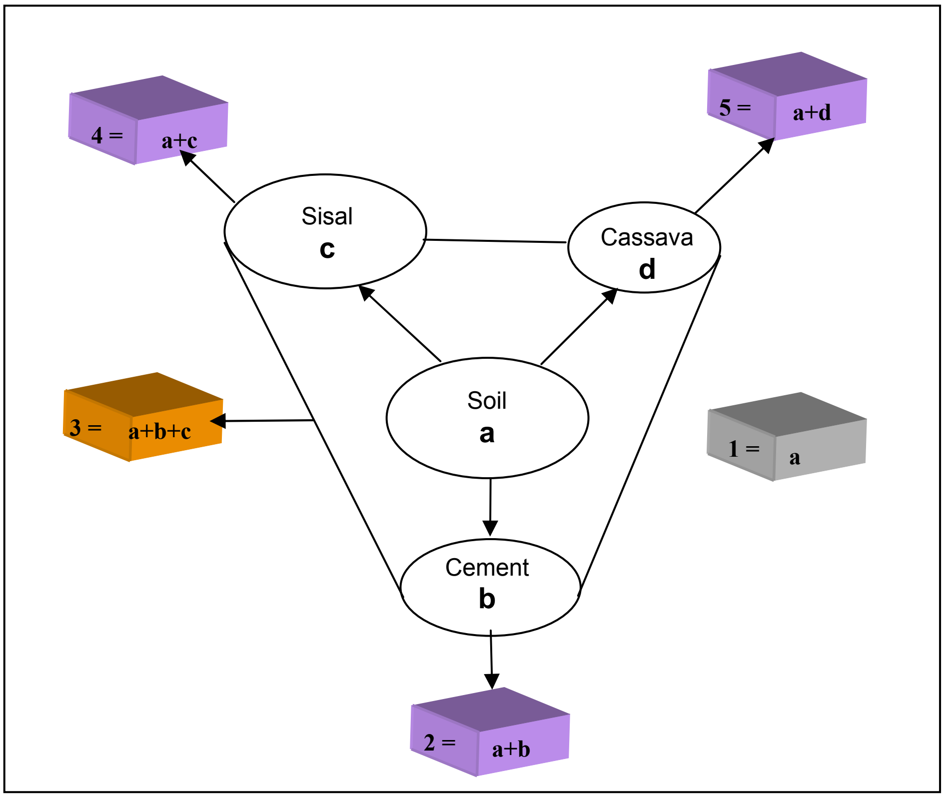


Figure 5.3 Block making combination

The procedure undertaken in the earth block making exercise is illustrated in figure 5.4. The following types of compressed earth blocks were prepared in this study:

- Unreinforced compressed earth blocks
- Sisal-reinforced compressed earth blocks
- Cement-stablised compressed earth blocks
- Sisal-cement reinforced compressed earth blocks
- Cassava stabilized compressed earth blocks.

Durability criteria and therefore practical performance of the pressed blocks is influenced by the production input variables. For the purpose of this study, the following input variables were used:

- stabiliser type
- stabiser amount
- reinforcement type
- reinforcement amount

Like it is usual, some variables had to be fixed while varying others. The type soil used in this dissertation was a fixed input variable hence all the block specimens were manufactured using soil of the same kind. Curing conditions and compaction pressure were the two process variables that were kept as constant as it could have been practicable. It would be understandable; however, that the pressure applied in the process of manual pressing will slightly differ from one case to another. In order to minimize the number of experiments but at the same time obtain prime characteristics and relationships, the experimental design was done with great care.

Addition of sisal, cement or sisal-cement to soil was done in ratios by weight of dry soil. In the first batch, pressed soil blocks were made without cement stabilisation or sisal reinforcement. In the second batch, compressed bricks were made by reinforcing the soil with 0.25, 0.5, 0.75, 1.0 and 1.25% sisal fibres; choice of these limits are discussed later in this section. Portland cement in the following proportions: 5%, 9% and 12% was used for stabilisation in the third batch; choice of the cement quantities was based on literature survey outlined in section 2.5. The fourth batch involved the use of both sisal and cement as shown by item 5 in table 5.1. In the final case, the blocks were made after the soil had been stabilised with 1.5%, 2.5%, 4%, 5% and 7% cassava powder.

Choice of cassava quantities was initially based on trial and error, given that use of cassava as an earth block stabiliser is unrecorded in literature.

The summary of the sample fabrication compositions are shown in table 5.1. In total 24 mixtures were used. For every mixture, 8 full blocks were fabricated. Each of the 8 full blocks is then cut into 2 smaller size samples. From these full blocks, 512 smaller specimens were derived or obtained, table 5.1. For each test, 8 samples were used and a mean value computed.

Mixing of cement, sisal or sisal-cement in soil was done by hand on a wheelborough in a dry state. The mixing was thoroughly done before water was added to sufficient workability. Addition of about 3% water above the optimum moisture content provided a composition that would gain adequate block density on drying see description earlier in section 5.1.2.

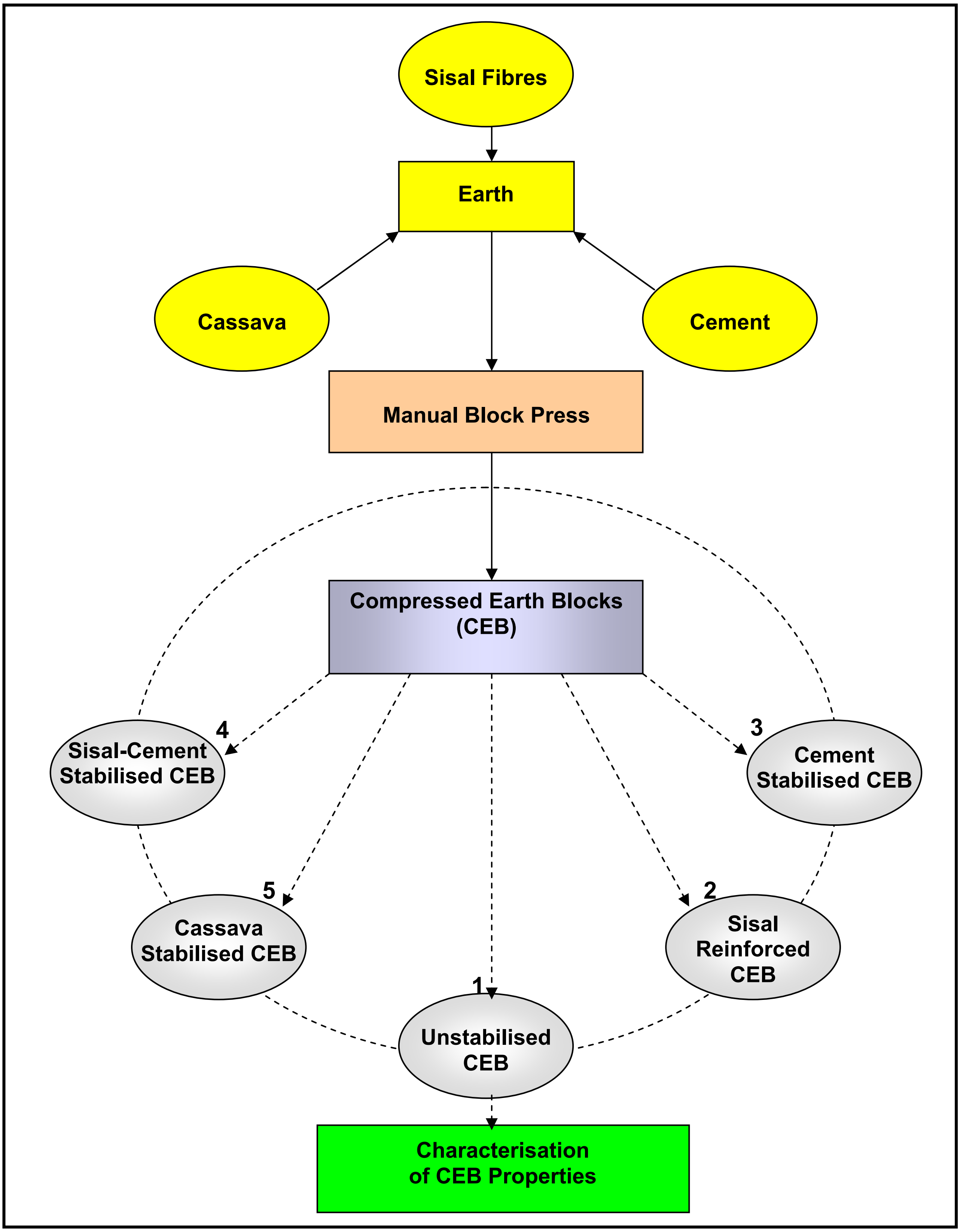


Fig. 5.4: Block making scheme

Mixing sisal in soil requires special care. Chopped sisal fibres tend to ball up if their volume content and length exceed certain critical limits. Based on this knowledge, several sisal amounts were added to the soil and preliminary experiments run with the purpose to establish this critical limit. Amounts exceeding 1.25 wt. % resulted in balling. Similarly fibre length above 20mm also resulted in balling.

Table 5.1 Sample fabrication compositions

S. No.	**Mix Composition, Wt %**				**Specimen Name**	**Number of Specimens**
1	**Earth**	**Sisal**	**Cement**	**Cassava**		
2	100	0	0	0	SC-0	16
3	100	0.25	0	0	SC-0.25	16
		0.5			SC-0.5	16
		0.75			SC-0.75	16
		1.0			SC-1.0	16
		1.25			SC-1.25	16
4	100	0	5	0	CeC-5	16
		0	9		CeC-9	16
		0	12		CeC-12	16
5	100	0.25	5	0	C-SC-5-0.25	16
		0.5			C-SC-5-0.5	16
		0.75			C-SC-5-0.75	16
		1.0			C-SC-5-1.0	16
		1.25			C-SC-5-1.25	16
	100	0.25	9	0	C-SC-9-0.25	16
		0.5			C-SC-9-0.5	16
		0.75			C-SC-9-0.75	16
		1.0			C-SC-9-1.0	16
		1.25			C-SC-9-1.25	16
	100	0.25	12	0	C-SC-12-0.25	16
		0.5			C-SC-12-0.5	16
		0.75			C-SC-12-0.75	16
		1.0			C-SC-12-1.0	16
		1.25			C-SC-12-1.25	16
6	100	0	0	1.5	CaC-1.5	16
				2.5	CaC-2.5	16
				4	CaC-4	16
				5	CaC-5	16
				7	CaC-7	16
				10	CaC-10	16
				15	CaC-15	16
				20	CaC-20	16
7	**Total Number of Specimens**					**512**

6.0 Discussion of Experimental Results

As mentioned earlier, compressive strength is the single most important factor controlling durability. Literature survey points out however, that investigations so far carried out in the area of compressed earth blocks are inconsistent and lack comparability or perhaps reproducibility. This is as a result of non-existent universally acceptable standards. (Walker, 2004) mentions that regional, national and international standards vary considerably in their approaches to testing and specifications for strength performance of pressed earth blocks. Every country apparently has its own norms and specifications, besides soil compositions differ from one region to another. This background has, among others, provided the stimulus for the experimental study reported in this work. Earth blocks are often characterized in terms of their compressive strength. According to (Minke, 2000) compressive strength depends on the quantity and type of clay, grain size distribution of silt, sand and larger aggregates as well as the method of preparation and compaction.

Investigations in to properties of compressed earth blocks have been carried out by many researchers. Such properties are also numerous and it would not serve good purpose to examine all of them. The properties or parameters investigated in the present work were precisely chosen, such that as much well coordinated information as possible would be exposed.

In order to gain knowledge on physical properties of compressed earth blocks, various tests have been carried out. The results are to help understand the suitability of these blocks as building materials. Besides, the results would be the basis upon which a decision is to be made as to whether this dissertation has been able to reach its goal. The goal being, among others, to establish if the material compositions proposed in section 5.2.1 are capable of being used to manufacture building materials referred to here as compressed earth blocks.

Tests taken, as displayed in figure 6.1, included: compressive strength, flexural strength, dry block density, compression ratio and linear shrinkage. Optical and scanning microscopic analyses were also undertaken to help understand the effect of microscopic structure to strength values. Results of the microscopic study were supportive in correlating the physical behaviour of the soil blocks i.e. compressive and flexural strength and the block morphology. Water vapour transmission properties were also studied through water vapour permeability measurements. The results provided information on thermal and moisture transfer capabilities of the pressed earth blocks.

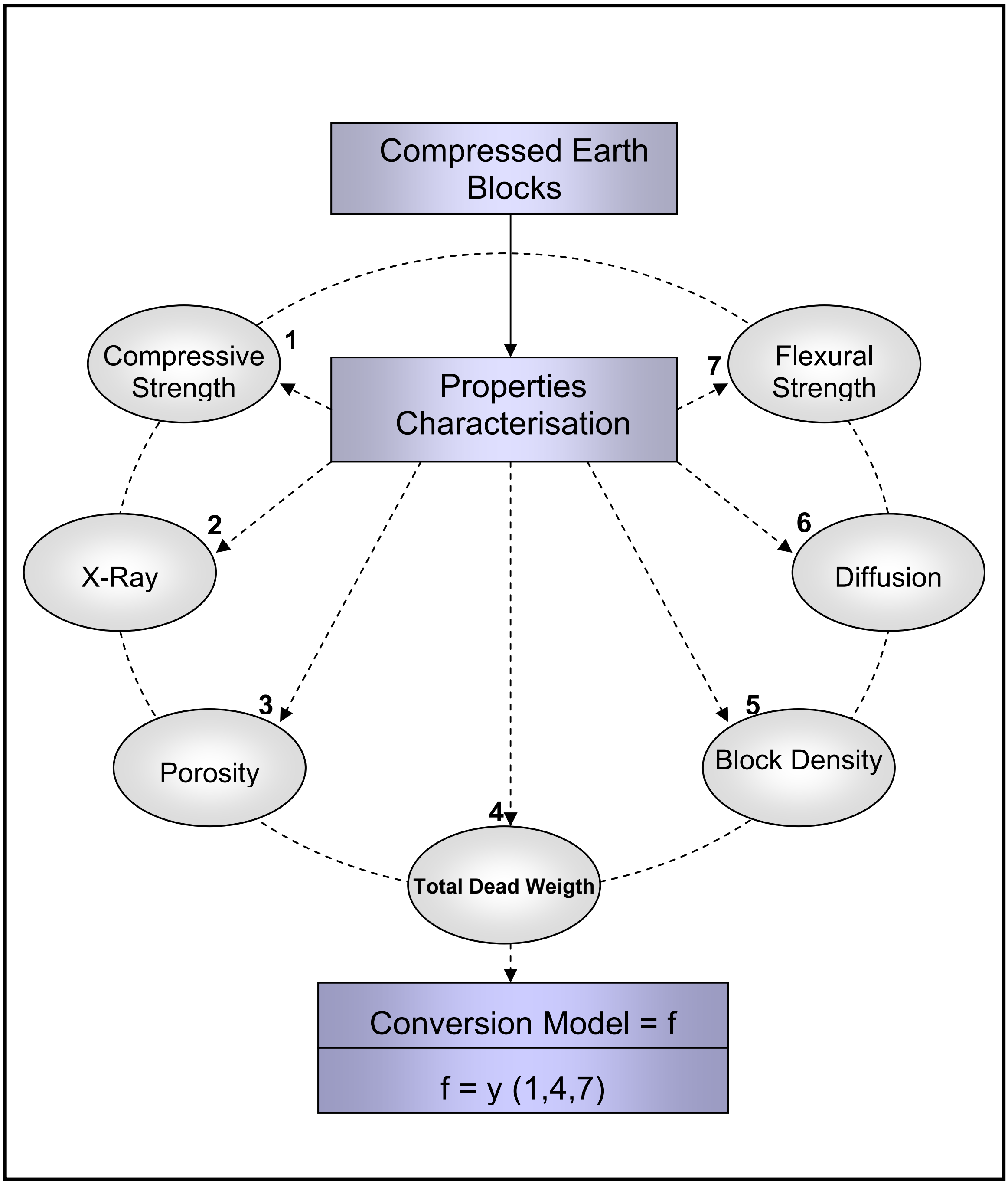


Figure 6.1 Block parameters

6.1 Sisal Reinforced Compressed Earth Blocks (SC)

Table 6.1a depicts the sample composition of mixtures used to manufacture and characterize sisal reinforced compressed earth blocks, abbreviated as SC. Clay is reinforced with 0%, 0.25%, 0.5%, 0.75%, 1.0% and 1.25% amounts of sisal vegetable fibres. For each composition, 4 blocks were prepared to measure compressive and flexural strength and an average value was computed.

Table 6.1a Mix composition of sisal reinforced blocks

Specimen Reference	**SC-0**	**SC-0.25**	**SC-0.50**	**SC-0.75**	**SC-1-0**	**SC-1.25**
Amount of Sisal Used, %	0	0.25	0.50	0.75	1	1.25

6.1.1 Sisal Content and Dry Compressive and Flexural Strength

Research in this area suggests that durability of compressed blocks is, arguably, determined primarily by the compressive strength. It is already established in literature that durability of compressed earth blocks improves with increase in strength (Stulz, 1988). Consequently compressive strength was a prime parameter in the present work. According to the (Kenya Bureau of Standards, Kenya Specification for Stabilised Soil Blocks, UNCHS,1989), the 28-day dry block density should be not less than 3.0 N/mm^2. On the other hand, (DIN 18 954) reports that the permissible compressive strength of earth building elements is between 3 and 5 N/mm^2. (Schneider et al., 1996) provides results of between 2 – 7 N/mm^2.

Compressive and flexural strength were measured on prisms of dimension 160 mm (length) 40 mm (width) and 40 mm (height) according to (DIN EN 196 part 1). For determination of compressive strength, each specimen was loaded in a TONIVERSAL-TONITECHNIK hydraulic press, described in section 4.2.2, continuously at a steady rate of 1.5 N/mm^2/s up to failure. The flexural strength was conducted by uniaxial point loading on TONIVERSAL-TONITECHNIK hydraulic press continuously at a rate of 0.05 kN/s up to failure.

The results of 28-day mean dry compressive and flexural strength, on variation of sisal content, are illustrated in figure 6.2a and tabulated in appendix A, B and C. Although several other workers argue that the wet compressive strength would be a better criterion to evaluate the durability of blocks, this work is rather based on the dry strength values. The reason being that in practical application, the blocks are not immersed in water but rather, are in a fairly dry state. (Walker 2004) reports that under service conditions, earth blocks will necessarily remain dry and therefore determining the dry strength values would be the more logical approach.

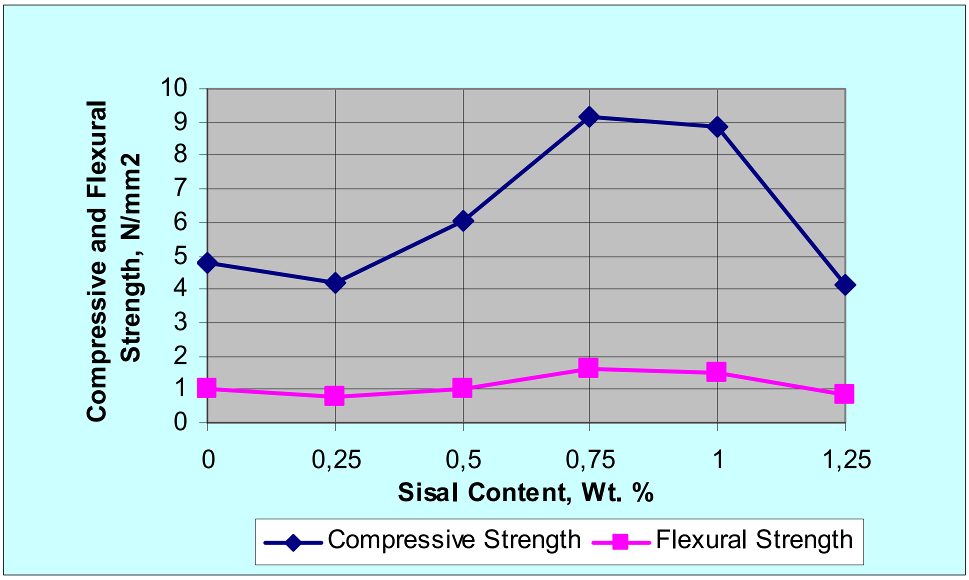


Figure 6.2a Strength as a function of sisal content

Results show a clear increase in both compressive and flexural strength with increasing sisal levels from 0.25% to 1.0%. Flexural strength values ranged between 0.85 N/mm^2 and 1.63 N/mm^2. The optimal value of 1.63 N/mm^2 at 0.75% sisal content suggests a 64.3% increase in flexural strength - compared to the non-reinforced blocks, figure 6.2b. Compressive strength values ranged between 4.16 N/mm^2 and 9.14 N/mm^2. Optimal strength of 9.14 N/mm^2 is also attained at 0.75% sisal content. This is a 90.5% improvement as compared to the non-reinforced (plain) sample. Such high values are not yet catalogued in literature. This insight should provide a platform for new way forward in working with earthen building materials.

Strength increase would have been due to creation of isotropic matrix between the clay structure and the fibre network; such a matrix would oppose movement of particles and create stability mainly because fibres appear to distribute tension throughout the bulk of material. In other words, the presence of omni-directional fibres would improve tensile and compressive strength. Considered at the level of a potential crack, (Houben and Guillaud 1994) explain that the fibre opposes formation of a crack in step with the increase in the stress.

The addition of fibres beyond 1.0% content leads to decrease in strength. Greater amounts of sisal (more than 1.0%) may have led to appearance of micro-fractures at sisal-soil interfaces, such that compressive strength fell to 4.16 N/mm^2 at 1.25% sisal content. It is also possible, according to (Minke, 2000), that addition of fibres to earth may lead to decrease in relative clay content. Over-large quantity reduces density too much while the number of contact points between fibre and soil, which are responsible for transmitting stress, becomes too low so the strength of the block is reduced (Houben and Guillaud, 1994). Table 6.1b and figure 6.2b summarises the deviation of strength values of sisal reinforced blocks from the plain (non-reinforced) earth block. A negative deviation is seen in the case of 0.25% and 1.25% reinforced blocks for reasons explained above.

Table 6.1b Strength values and percentage change

Block Type	**Stabiliser Type and Content**	**Change in Strength**			
		Compressive Strength, N/mm^2	**Change in Strength*, %**	**Flexural Strength, N/mm^2**	**Change in Strength*, %**
SC	**Plain Block**	4.798	**-**	0.992	**-**
	0.25% Sisal	4.181	-12.8	0.751	-24.3
	0.5% Sisal	6.076	**+26.6**	1.035	**+4.3**
	0.75% Sisal	9.14	**+90.5**	1.63	**+64.3**
	1.0% Sisal	8.868	**+84.8**	1.473	**+48.5**
	1.25% Sisal	4.161	-13.3	0.850	-14.3

**+ implies % improvement in strength in comparison to the non-reinforced earth block*

- implies % drop in strength in comparison to the non-reinforced earth block.

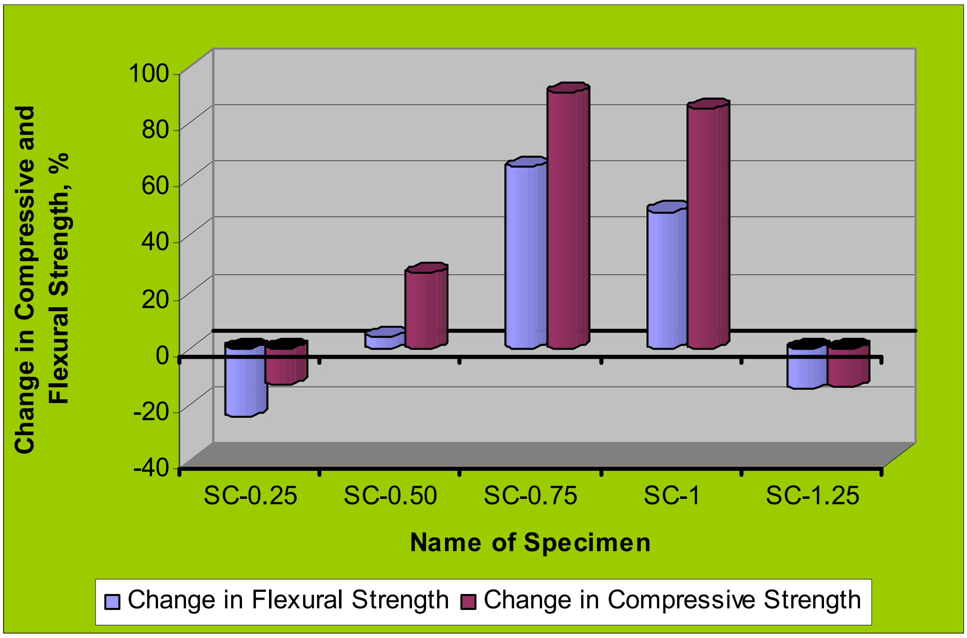


Figure 6.2b Deviation in Compressive and flexural strength from that of plain block

The slight drop in both compressive and flexural strength for non-reinforced blocks as compared to blocks reinforced with 0.25% sisal may have been a testing or experimental error. On the other hand, it may be that the amount of fibres was not significant enough to impart sufficient friction in the matrix.

It is further observed that the flexural strength lies in the range of 16.6% to 20.7% of the compressive strength. Other investigators ((Walker, 1995) point out that the flexural strength is normally 1/5 to 1/10 of the compressive strength. Results obtained in the current work show that for all the specimens tested, compressive strength is 4.84 to 6.02 times flexural strength values, see table in appendix A1 and figure 6.2c below. Based on this, it can be stated that requirements of compressive to flexural strength ratio are satisfied by combining soil and sisal fibres in the manner described earlier in this section.

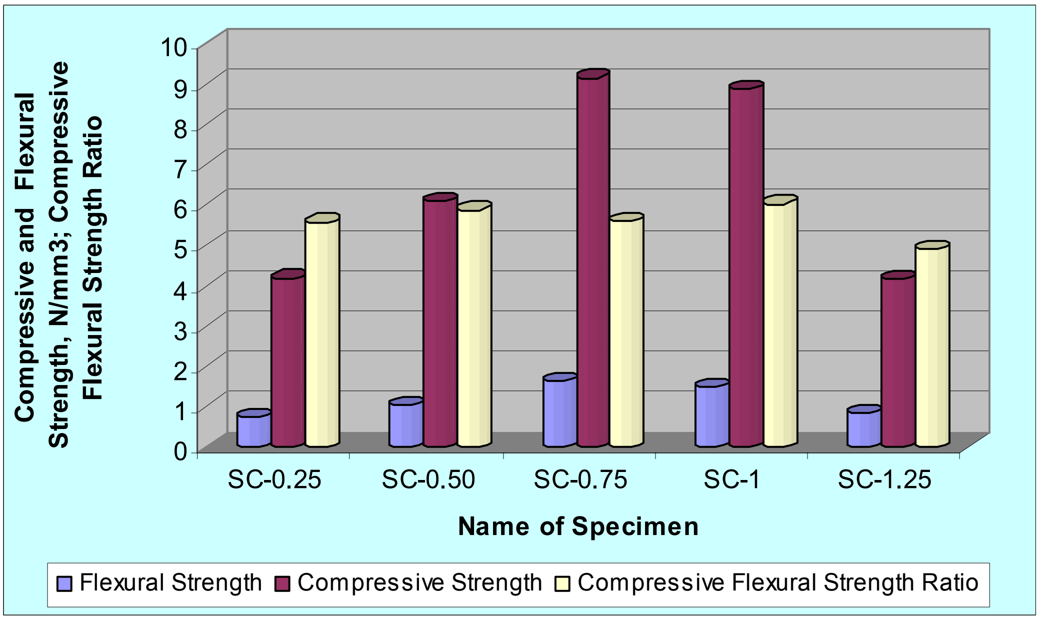


Figure 6.2c Strength and ratio of compressive to flexural strength

All the mix proportions undertaken here except that where soil is reinforced with 1.25% sisal, produce earth blocks with strength values above the minimum recommended by other past researchers, see section 2.3, and are therefore by this requirement suitable to be used for construction of housing walls in low-rise buildings.

Possible sources of error are discussed at the end of section 6.1.2.1

6.1.2 Dry Block Density and Porosity

6.1.2.1 Practical Dry Block Density

Another important durability parameter measured on the manufactured bricks is the practical dry block density (ρ_p). This density is known to be the ratio of measured block mass to volume i.e. $\rho_p = m/v$. The mass was taken after the block is dried in a ventilated oven for 16 hours at a temperature of 105°C in accordance to the Kenyan standards. The drying process was undertaken in order to ascertain that all block samples had uniform moisture content at testing time. Volume remained basically constant since the blocks had been cut precisely, as explained in section 4.2.3, to be of the dimensions 40mm x 40mm x 160mm.

Results of the influence of sisal levels to dry practical block density are outlined in figures 6.3a with the greater details presented in appendix D. the figure shows that the values of practical dry block density lie between 1738 kg/m^3 (for the 1.25% sisal reinforced blocks) and 1895 kg/m^3 (for the 0.75% sisal reinforced blocks).

The density of the sisal reinforced blocks hence increase with increasing sisal levels (between 0.25% and 1.0% sisal content) and thereafter drop at 1.25% sisal content. Density enhancement or reduction can be attributed to the same factors that influenced growth in compressive and flexural strength as discussed in the preceding section.

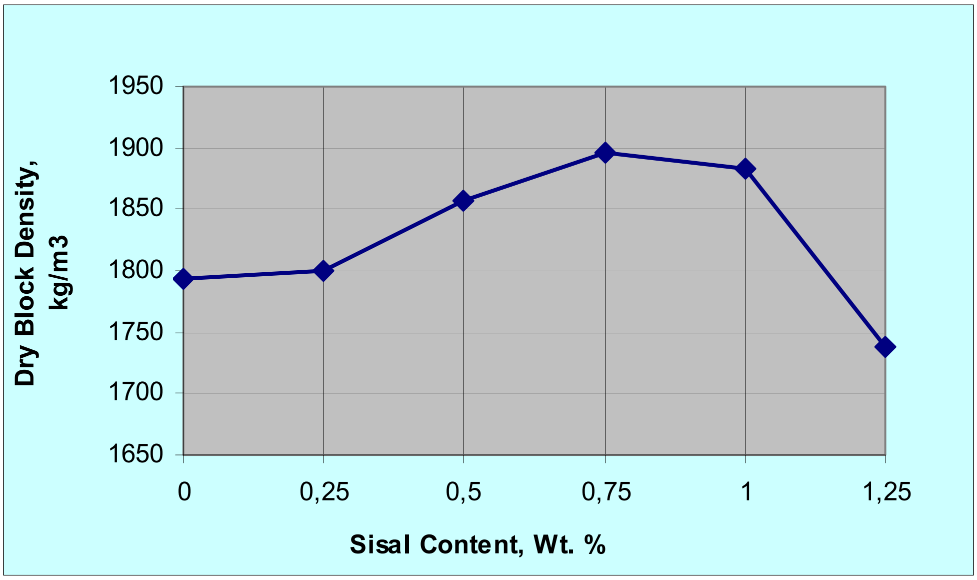


Figure 6.3a Practical dry block density as a function of sisal content

For all the tested samples, the relative deviation in density (with respect to the density of the non-reinforced earth compressed block) against variation of sisal fibre levels is presented in table 6.2 and outlined in figure 6.3b. The negative deviation is witnessed for only the 1.25% sisal reinforced blocks, the reasons being the same as divulged in section 6.1.1.

Table 6.2 Improvement in density in comparison to plain earth block

Block Type	**Stabiliser Type and Content**	**Practical Density, kg/m^3**	**Change in Practical Density*, %**
SC	**Plain Block**	1792.97	-
	0.25% Sisal	1800.78	**+0.44**
	0.5% Sisal	1857.42	**+3.6**
	0.75% Sisal	1895.51	**+5.7**
	1.0% Sisal	1883.79	**+5.1**
	1.25% Sisal	1738.28	-3.1

**+ implies % improvement in density in comparison to the non-reinforced earth block*

- implies % drop in density in comparison to the non-reinforced earth block.

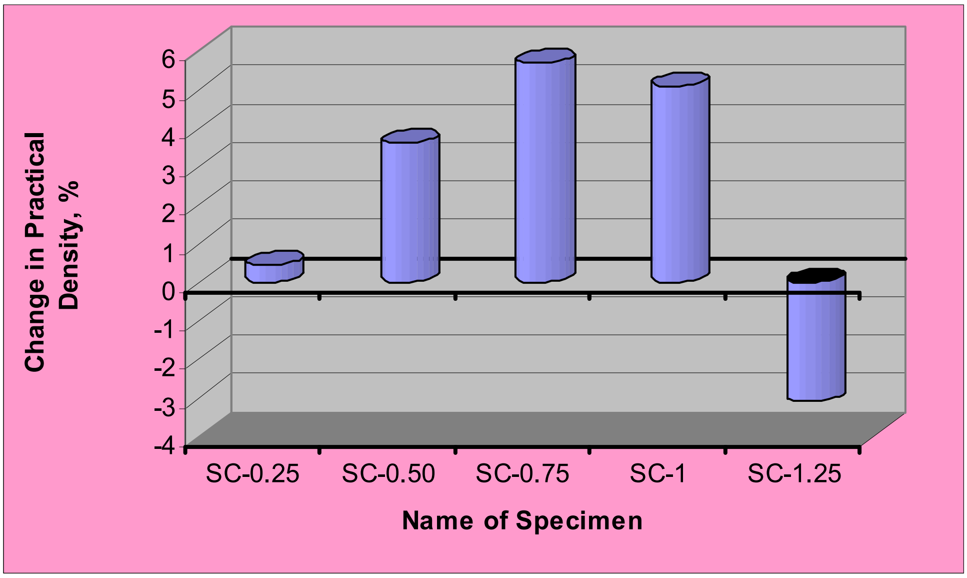


Figure 6.3b Change in practical dry block density

Given that Kenyan standards, among others, state that the 28-day block density should not be less than 1800 kg/m^3, it is logical to conclude that the blocks manufactured by reinforcing soil with 0.25%, 0.75%, and 1.0% sisal fibres are suitable for wall construction. Indeed the obtained density is indicative of sufficient integrity for general wall fixing of up to two-storied houses.

A better understanding of the earth block behaviour is witnessed in observing the correlation between practical dry block density and compressive strength, displayed in figure 6.3c. Density trends exhibit similar tendency as strength characteristics and can be described by the power equation i.e. 6.1. Indeed, compressive strength is a function of dry block density. As expected the lowest values of 1738 kg/m^3 corresponds to the lowest compressive strength of 4.16 N/mm^2 (1.25% sisal content) and the highest value of 1895 kg/m^3 corresponds to the ideal compressive strength of 9.14 N/mm^2 (0.75% sisal

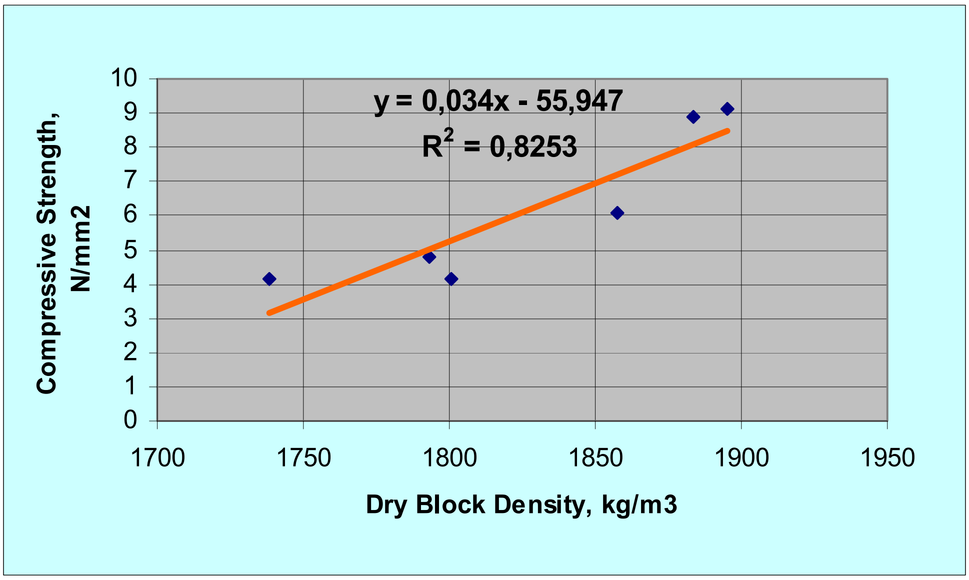


Figure 6.3c Compressive strength as a function of practical dry block density

$$y = 0.034x - 55.95 \qquad (6.1)$$

Where:

y = Compressive Strength

x = Practical block density

Change in density relative to improvement in strength is shown in table 6.3 (only for ideal blocks – 0.75% sisal reinforced bricks). Although the increase in density in comparison to the non-reinforced (plain) blocks represents only 5.6%, the improvement in compressive strength is as high as 90.5%, while flexural strength improves by 64.3%. This strong correlation is supported by the power equation (6.1).

For all sisal reinforced specimens, deviation of density and strength from values obtained for non-reinforced blocks is depicted in figure 6.4. The fact that compressive strength for blocks reinforced with 0.25% sisal dropped by 12.8% yet the practical dry block density improved by 0.44% would, appear to confirm the speculation made in section 6.1.1, that an experimental error is likely to have been made during testing of this block type for compressive and flexural strength.

Table 6.3 Improvement in density verses strength for the ideal case

S.No.	**Sisal Content, %**	**Density, kg/m^3**	**Improvement in Density, %**	**Compressive Strength, N/mm^2**	**Improvement in Compressive Strength, %**
1	**0.0**	1792.97	5.6	4.798	90.5
2	**0.75**	1895.51		9.14	
	Sisal Content, %	**Density, kg/m^3**	**Improvement in Density, %**	**Flexural Strength, N/mm^2**	**Improvement in Flexural Strength, %**
1	**0.0**	1792.97	5.6	0.992	64.3
2	**0.75**	1895.51		1.63	

Possible Sources of Error

It is possible that during strength testing, it may have happened that the hydraulic press would have run at a rate slightly higher than 1.5 N/mm^2/s described earlier in section 4.2.4. This would bring the block to rapture earlier than expected. Another cause of error, which could apply to other specimens (apart from 0.25% reinforced blocks), would be the placement of blocks on the TONIVERSAL-TONITECHNIK hydraulic press such that the blocks were not always in the exact centre (for uniform distribution of load). The handling of blocks after measuring the density could also be a source of error; a block that receives some prior shock due to mishandling (e.g falling down) could develop some micro-fractures. Such micro-fractures would lead to reduction in the load required to determine strength. It is also possible that sisal fibres were not as uniformly distributed within the soil as it was with other mix compositions.

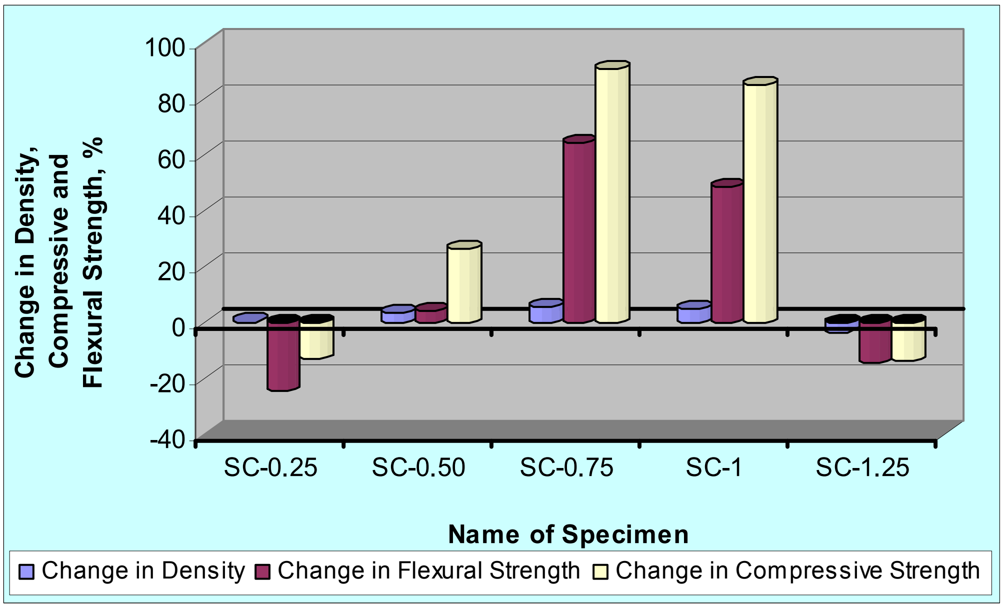


Figure 6.4 Change in strength as a reflection of change in density

Trends seen in figure 6.4 would appear to confirm that compressive and flexural strength are generally a function of block density. Block density is very much dependent on the magnitude of the compaction force; the latter should therefore be kept as high as possible during the manufacture of earth bricks. Moisture content also plays an important role, as already mentioned in section 4.1.1.3**.** The blocks should therefore be tested in the condition where they are believed to be most dry.

6.1.2.2 Theoretical (True) Block Density

Theoretical density of a material is defined as that pure density of system of particles without voids or air pores. An Ultrapycnometer (model No. UPY – 14T) manufactured by Quantachrome Corporation USA was applied in the present work to determine the true density of the samples. It is specifically designed to measure the exact volume and density ρ_t of solid objects by employing Archimedes' principle of fluid displacement and Boyle's law to determine the volume. An inert gas, Helium, of small atomic dimensions ensures penetration of all pores, appendix E shows the detailed theoretical background applied in determination of true block density.

The experimental correlation between theoretical density and sisal levels is outlined in figure 6.5. The best fit shows a strong linear correlation (R^2 =0.9793), represented in equation 6.2. As it would appear to be expected, higher sisal contents are associated with lower true densities. Measurement of true density is, unlike the case of practical density, undertaken on loose sisal mix, i.e. not in compacted (compressed form). Naturally, inclusion of larger amounts of fibres in to soil would result in introduction of more voids or air spaces; this translates in to growth in volume, as a result of which the theoretical density decreases, see equation 10 in appendix E. Additionally, sisal fibres are by themselves voluminous.

$$\rho_t = -26.64 \text{ Sisal Content} + 2661.2 \qquad (6.2)$$

Where:

ρ_t = Theoretical density

x = Sisal content

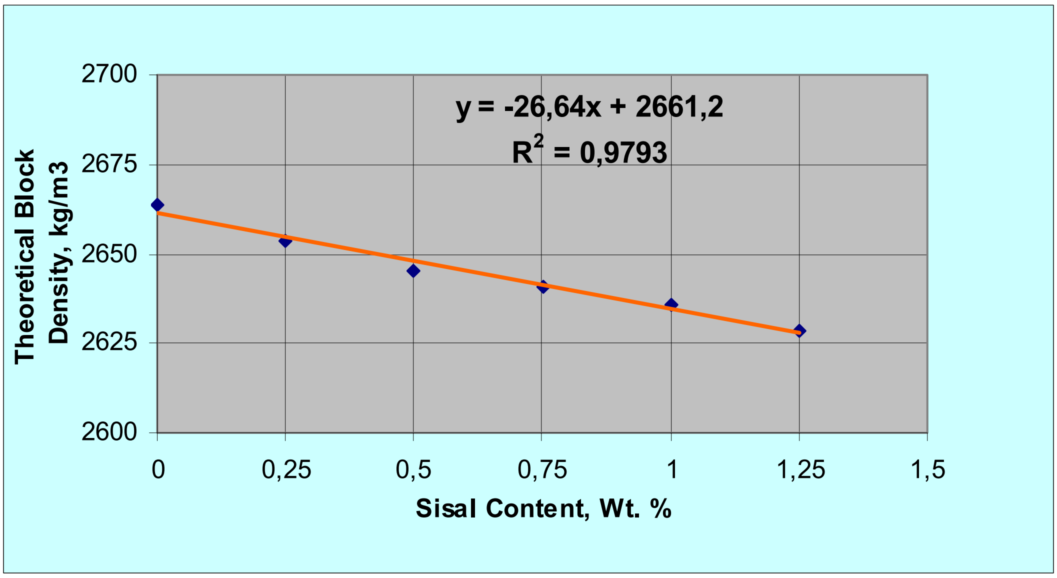


Figure 6.5 Theoretical dry block density as a function of sisal content

With regard to density, compressed earth blocks are, according to catalogued literature, evaluated only with respect to practical density. Evaluation of compressed earth blocks in terms of theoretical density concept is not yet recorded in literature. These investigations have shown therefore that earth blocks can, like other conventional building materials, be evaluated in terms of theoretical density.

Equation 6.2 would also suggest that in the absence equipment needed for determination of compression or flexural strength, it would be possible to use theoretical density values in equation 6.1, with consideration of equation 6.3 and 6.4, to evaluate strength values.

Deviation of Practical from Theoretical Density

Deviation of sample practical densities from theoretical (true) densities is depicted in table 6.4, figure 6.6a and figure 6.6b. The difference in theoretical and practical density, observed in table 6.4 and figures 6.6a and 6.6b lie between 745.29 (0.75% sisal reinforced block) and 890.42 29 (1.25% sisal reinforced block). A mean value is computed to be 816.45 with a standard deviation of 63. In all the cases examined, the theoretical density is higher than the corresponding practical density.

Table 6.4 Difference in theoretical from practical density

S.No.	**Sisal Content, %**	**True Density, ρ_t kg/m^3**	**Practical Density, ρ_p kg/m^3**	***Porosity, %**	**Difference in Density, kg/m^3**	**Difference in Density, %**
1	**0.0**	2663.7	1792.97	32.69	870.73	48.56
2	**0.25**	2653.5	1800.78	32.14	852.72	47.35
3	**0.5**	2645.2	1857.42	29.78	787.78	42.41
4	**0.75**	2640.8	1895.51	28.22	745.29	39.32
5	**1.0**	2635.6	1883.79	28.53	751.81	39.91
6	**1.25**	2628.7	1738.28	33.87	890.42	51.22

* refer to equation 6.3

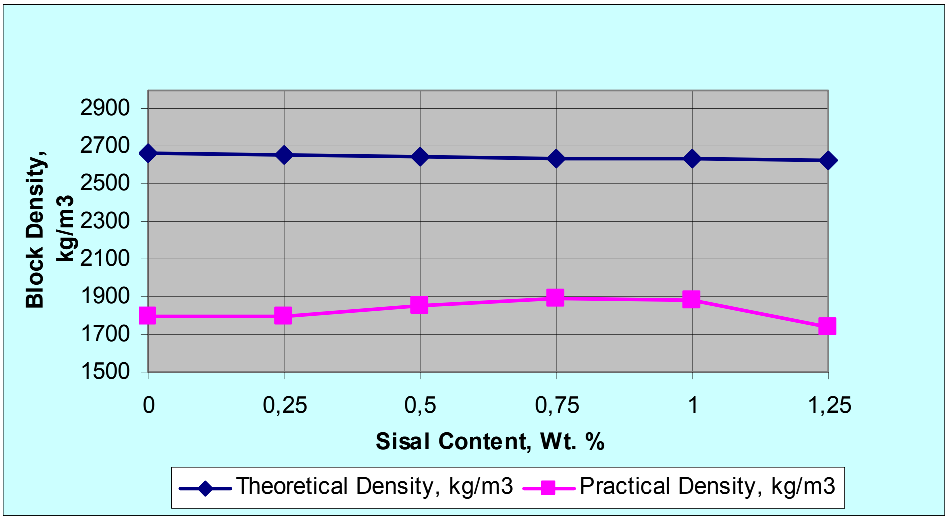


Figure 6.6a Comparison between theoretical and practical density

The practical density of compressed blocks with 1.25% sisal content yield greatest deviation from true density (51.22%) and has consequently the lowest compressive and flexural strength values; the opposite is true for specimen from 0.75% sisal which produce the ideal strength as discussed in section 6.1.1; in this case, the practical density deviates from the true density by 39.32%. These deviations are reflective of the obtained compressive and flexural strength values, discussed earlier in section 6.1.1. It is seen that theoretical density is about 1.5 times greater than the practical density

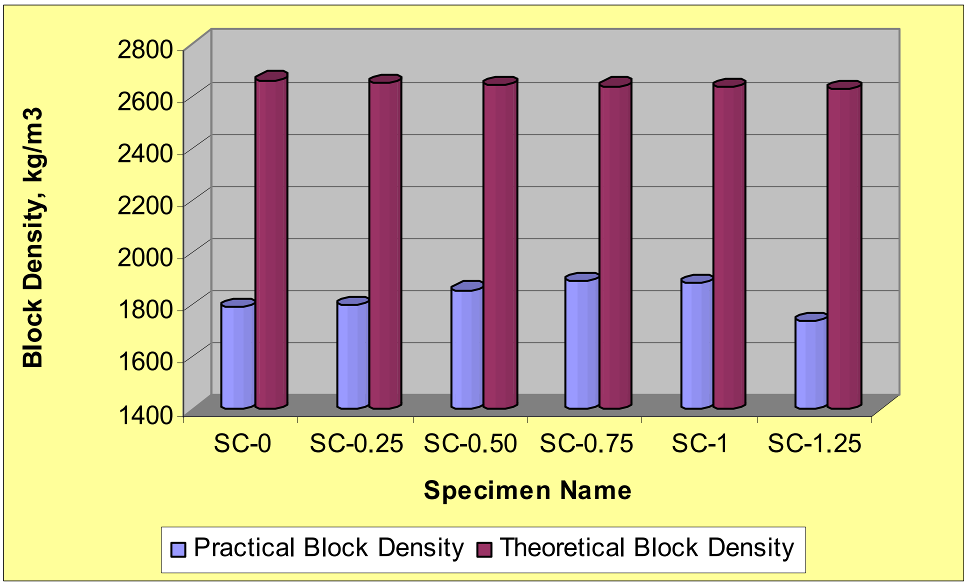


Figure 6.6b Comparison between theoretical and practical density

6.1.2.3 Porosity and Sisal Content

Porosity is defined as the volume of voids in a solid material expressed as a percentage of the total volume. Values of porosity obtained for sisal reinforced blocks are illustrated in table 6.4. Figure 6.7 shows the relationship between sisal levels and the computed porosity values. Porosity was determined by establishing the difference between true (theoretical) density and practical density. After true and practical density of the compressed blocks was determined, porosity of the samples was computed by the use of equation 6.3.

$$P = (1 - (\rho_p / \rho_t)) \times 100 \qquad (6.3)$$

Where:

$P = \text{Porosity}$

$\rho_t = \text{Theoretical density}$

$\rho_p = \text{Practical density}$

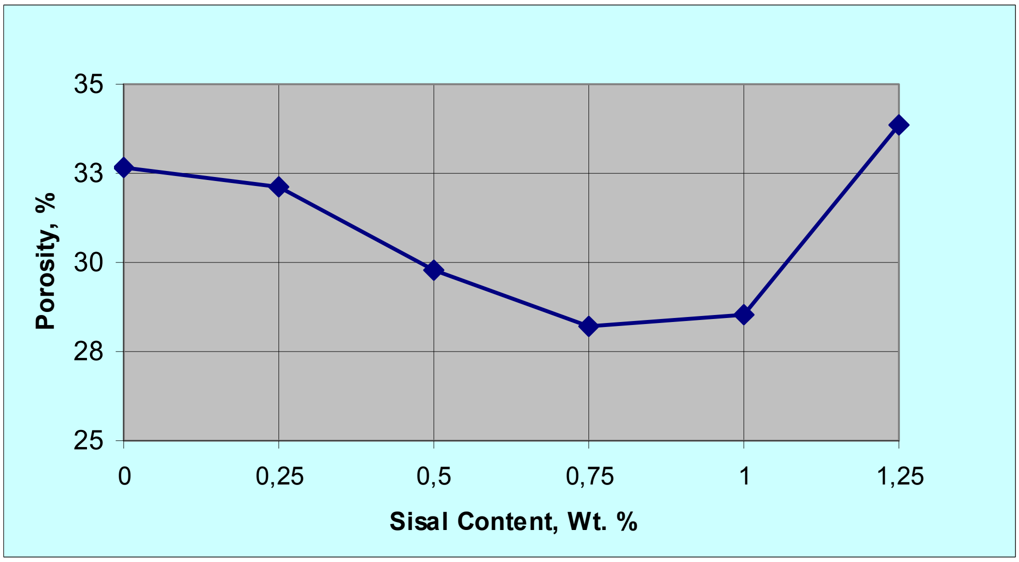


Figure 6.7 Block porosity as a function of sisal content

Porosity values lie between 28.22% (for 0.75% sisal reinforced bricks) and 33.87% (for 1.25% sisal reinforced bricks). It is observed that addition of certain amounts of fibres (up to 1.0%) to earth results in a like hood of reduction of voids; this would provide the possibility of reduction in porosity, reduced porosity would on the hand be the cause of increased compressive and flexural strength. As discussed in section 6.1.1, this may have been due to creation of isotropic matrix between the clay structure and the fibre network, while large amounts sisal fibres may have led to appearance of micro-fractures at sisal-soil interfaces. This opinion is supported by micrographs of the earth block structure presented later in section 6.1.3

6.1.2.4 Porosity and Strength

Compressive and flexural strength display a negative correlation to porosity, as illustrated by figure 6.8a and 6.8b (data extracted from in table 6.5).

The correlation between compressive strength and porosity is described by best fit shown in equation 6.4, thus

$$y = -0.91x + 34.3 \tag{6.4}$$

Where:

y = Compressive Strength

x = Porosity

On the other hand, the correlation between flexural strength and porosity is illustrated by a best fit expressed here in equation 6.5, thus

$$y = -0.13x + 5.14 \tag{6.5}$$

Where:

y = Flexural Strength

x = Porosity

Table 6.5 Density, porosity and strength values

S.No.	Sisal Content, %	Practical Density, ρ_p kg/m^3	Porosity, %	Compressive Strength, N/mm^2	Flexural Strength, N/mm^2
1	**0.0**	1792.97	32.69	4.798	0.992
2	**0.25**	1800.78	32.14	4.181	0.751
3	**0.5**	1857.42	29.78	6.076	1.035
4	**0.75**	1895.51	28.22	9.14	1.63
5	**1.0**	1883.79	28.53	8.868	1.473
6	**1.25**	1738.28	33.87	4.161	0.850

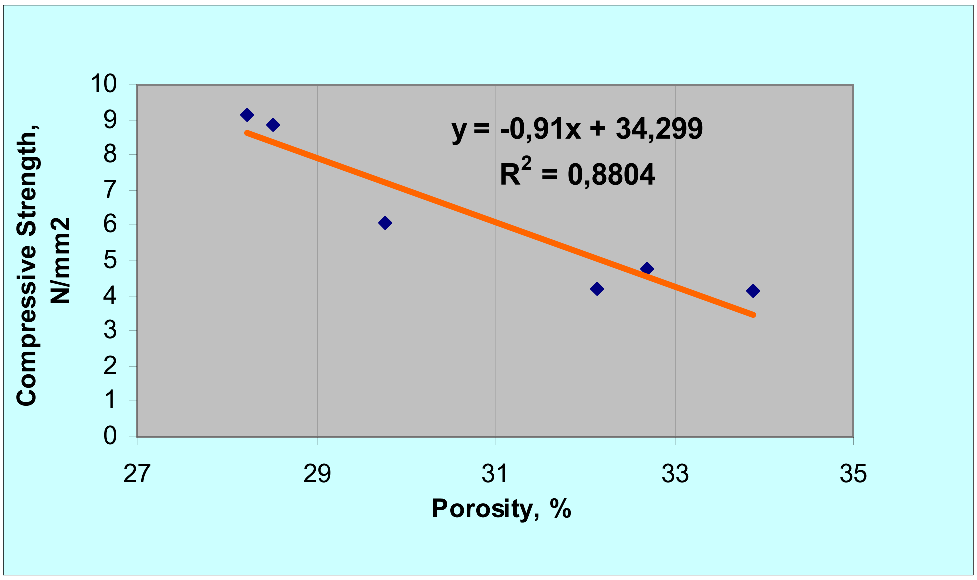


Figure 6.8a Compressive strength as a function of block porosity

It is instructive that both these are power equations. This suggests a strong (negative) correlation between strength and corresponding porosity values. It can be deduced, from this results, that strength is likely to be a function of earth block porosity. This hypothesis is supported strongly by the micrographs of the earth block structure presented later in section 6.1.3; where pores are evident in the structure of blocks reinforced with 1.25% and apparently absent from the 0.25%, 0.75% and 1.0% reinforced compressed blocks.

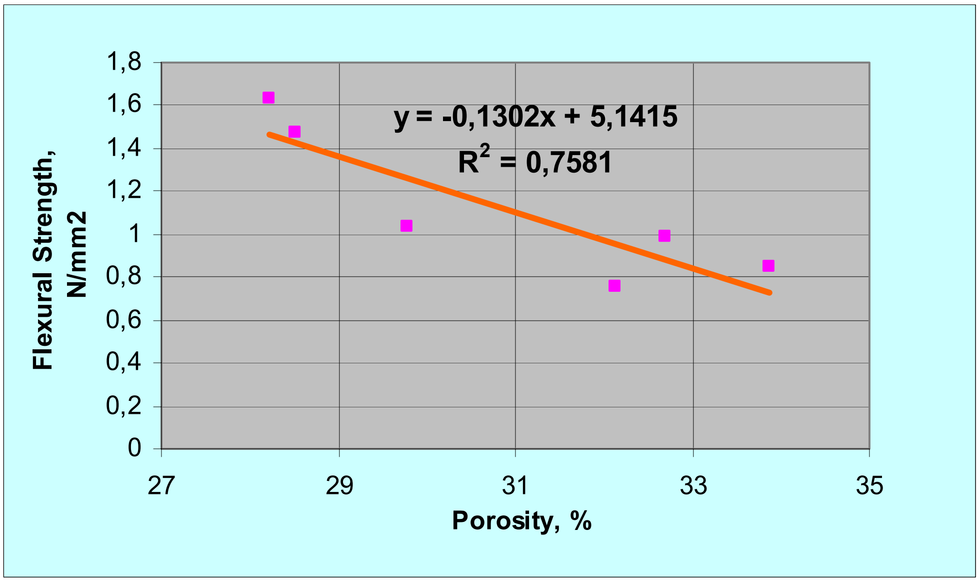


Figure 6.8ba Flexural strength as a function of block porosity

Change in Porosity against relative Change in Compressive Strength

Change in porosity relative to change in compressive strength is illustrated in table 6.6 and presented in figures 6.9a and 6.9b.

Table 6.6 Relative change in porosity against change in compressive strength

S.No.	Sisal Content, %	Porosity, %	Change in *Porosity, %	Compressive Strength, N/mm^2	Change in **Compressive Strength, %
1	0.25	32.14	+7,3	4.14	+46,6
2	0.5	29.78		6.07	
3	0.5	29.78	+5,2	6.07	+50,6
4	0.75	28.22		9.14	
5	0.75	28.22	-1,1	9.14	-3
6	1.0	28.53		8.87	
7	1.0	28.53	-18,7	8.87	-53
8	1.25	33.87		4.16	

* The negative (-) sign symbolises **increase** in porosity; the positive means reduction

** The negative (-) sign symbolises **reduction** in compressive strength; (+) → increase

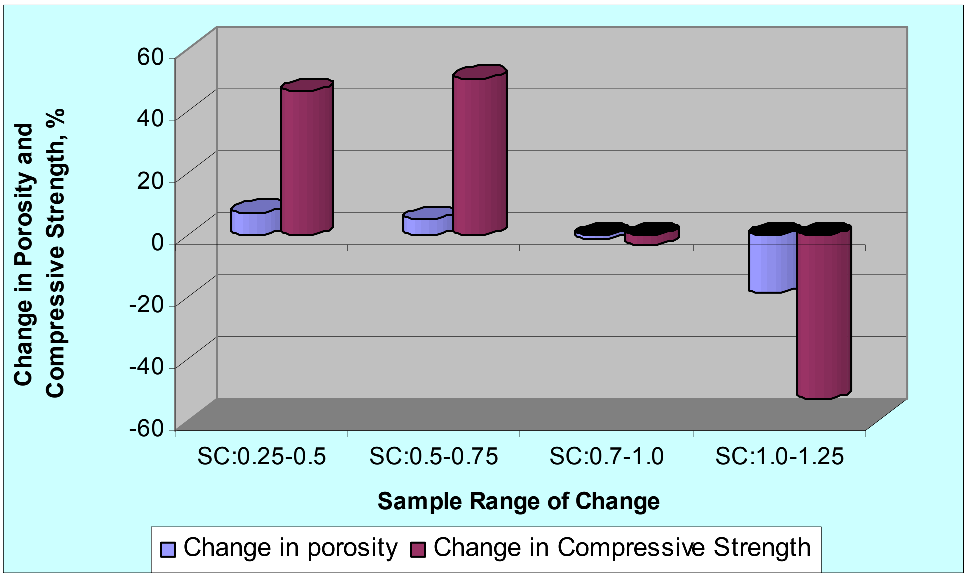


Figure 6.9a Relative change in porosity against change in compressive strength

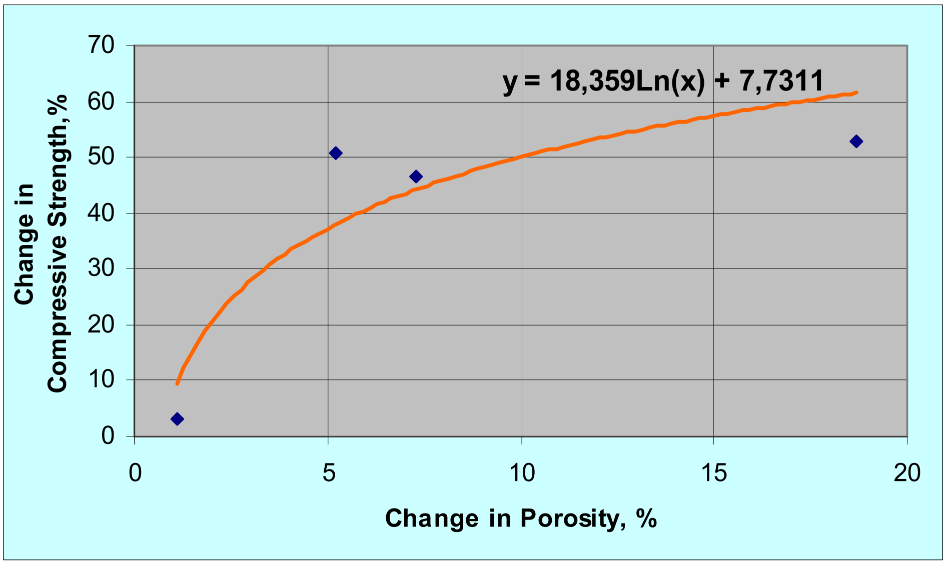


Figure 6.9b Relative change in porosity against change in compressive strength

$$y = 18.359 (Ln)x + 7.7311 \tag{6.6}$$

Where:

y = Change in compressive strength, %

x = Change in porosity, %

Observation of these figures would appear to suggest that a small change in porosity could have a tremendous effect seems to have on compressive strength; this is supported by equation 6.6. A reduction in porosity of only 7.3% (0.25% to 0.5% sisal content) delivers a 46.6% improvement in compressive strength. On the other hand an increase in porosity of 18.7% (1.0% to 1.25% sisal content) delivers a drop in compressive strength of 53%.

The relative change in porosity against relative change in compressive strength is described by a logarithmic equation, equation 6.6. This would appear to propose that the role played by porosity on the structural properties of compressed blocks may be quite significant. Particular care should therefore be taken in material preparation phase, i.e., introducing sisal ingredients in to the soil. Although the sisal fibres are randomly distributed in the soil, this distribution should be as uniform as it can possibly be. During the pressing of the bricks in the mould, sufficient force should be used to effectively compact the blocks; in this case the compression ratio (see description later in section 6.5) should be used as a monitoring tool. Relatively higher compression ratios would mean relatively inadequate compaction pressure; consequently an occurrence of relatively greater number of pores could be possible.

6.1.2.5 Porosity and Practical Block Density

The correlation between porosity and dry block density was examined; results are shown in figure 6.10 and outlined earlier in table 6.5. Porosity is observed to be negatively correlated to the practical dry block density. Increase in porosity is accompanied by a decrease in dry block density; the relationship is described by equation 6.7. This linear relationship with $R^2 = 0.9814$ suggests a strong correlation between porosity and block density.

$$y = -0.0382x + 100.75 \qquad (6.7)$$

Where:

$y =$ Porosity

$x =$ Practical block density

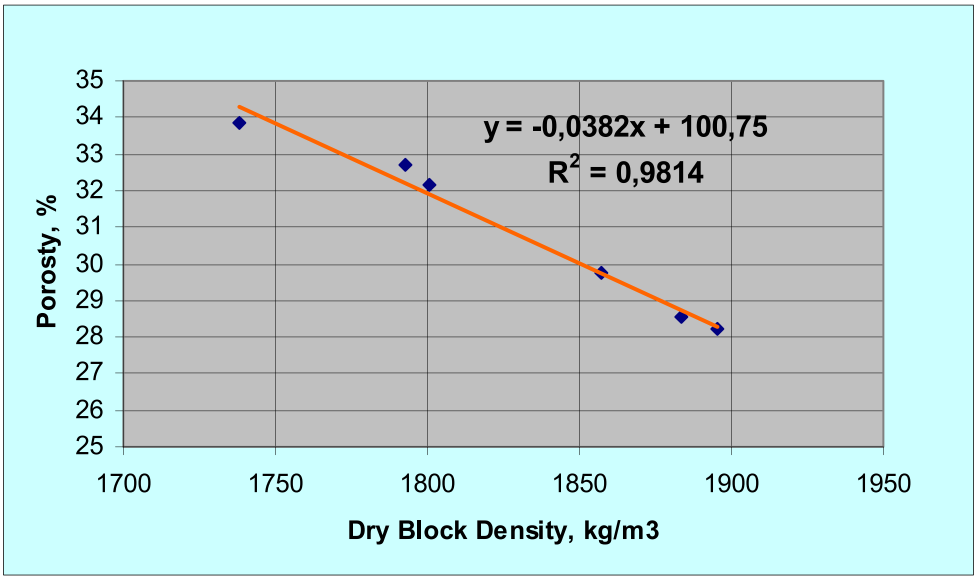


Figure 6.10 Block porosity as a function of practical density

Indeed, higher dry block densities are an illustration of relatively lower pore presence. As expected, large amounts of pores have the tendency to negatively affect on block density and therefore strength as explained in preceding sections. Reasons given in the sections 6.1.2.3 and 6.1.2.4 are therefore also applicable for this observed tendency. Among other past researchers, (Houben and Guillaud, 1994) report that soils with dry block density of between 1600 and 1800kg/m^3 have porosity of less than 40%; this observation would appear to be consistent with the results obtained in the present investigation.

From the foregoing and particularly from observation of equations 6.1 to 6.7 it could be deduced as follows:

There is a strong relationship between strength properties of compressed earth blocks and practical block density on one hand and to porosity on the other. This observation is recorded in equations 6.1, 6.4 and 6.5; that these are all power equations reinforces the strong association. Apparently, the correlation between compressive strength and porosity is slightly higher (R^2 = 0.9158) than that between compressive strength and practical block density (R^2 = 0.851)

Table 6.7 Summary of parameter comparison

S.No.	Property	Variable	R^2	Equation Number	Equation Type
1	compressive strength	Porosity	0.88	6.4	Linear
2	compressive strength	Practical block density	0.83	6.1	Linear
3	Flexural strength	Porosity	0.77	6.5	Linear
4	Practical block density	Porosity	0.9814	6.7	Linear
5	Theoretical block density	Sisal content	0.9793	6.2	Linear

6.1.3 Surface and Internal Structure

Light Optical Microscopy (LOM)

Fractured surface of block samples were investigated by Light optical microscopy (LOM) imaging (Leica microscope) at a magnification factor of 500. Figure 6.11 to 6.15 compare the block fractured surfaces for samples reinforced with between 0.25% to 1.25% sisal levels.

Figure 6.11 Fractured surface of a 0.25% sisal reinforced block

Figure 6.12 Fractured surface of a 0.5% sisal reinforced block

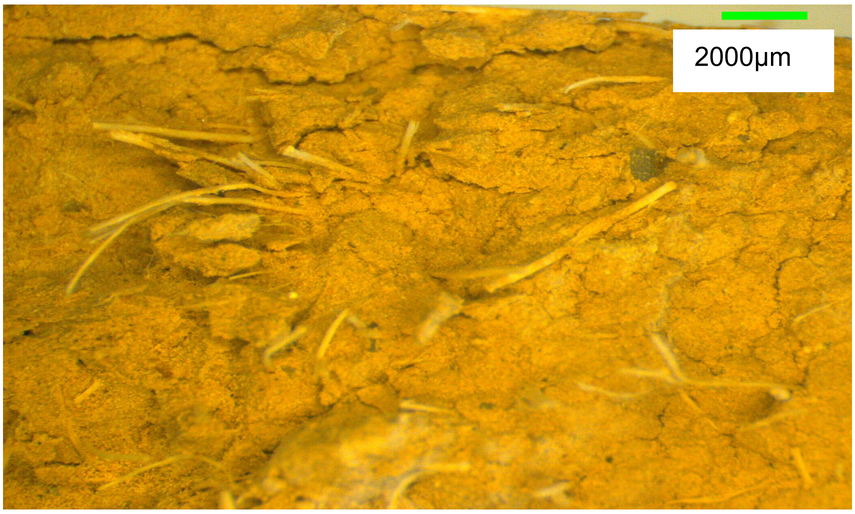


Figure 6.13 Fractured surface of a 0.75% sisal reinforced block

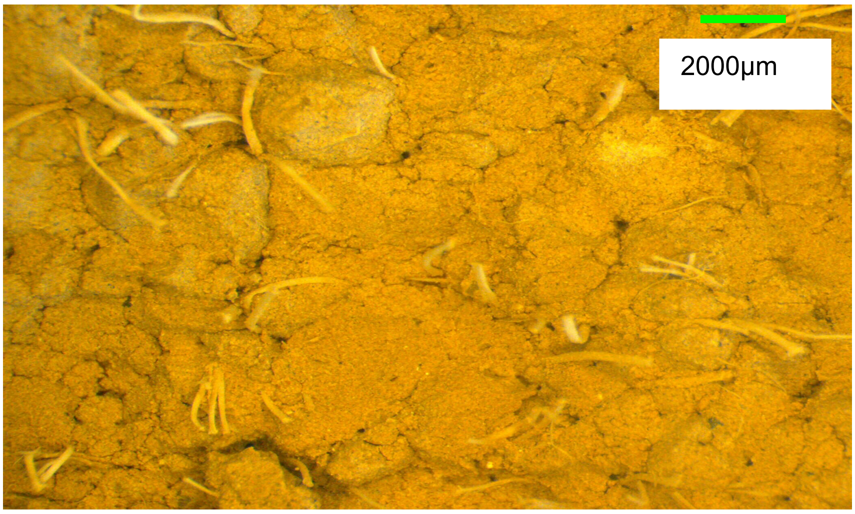


Figure 6.14 Fractured surface of a 1.0% sisal reinforced block

It is visible that the size or magnitude of cracks in the matrix increase with increasing fibre content. The cracks appear to occur more often with increasing sisal fibre levels. It is probable however, that the binding force between fibres and soil particles dominates up to the ideal mix of 0.75% sisal content; more addition of sisal would bring to situation where the cracks have an overwhelming effect, hence reduction of strength and density, and growth of porosity as already observed in previous sections.

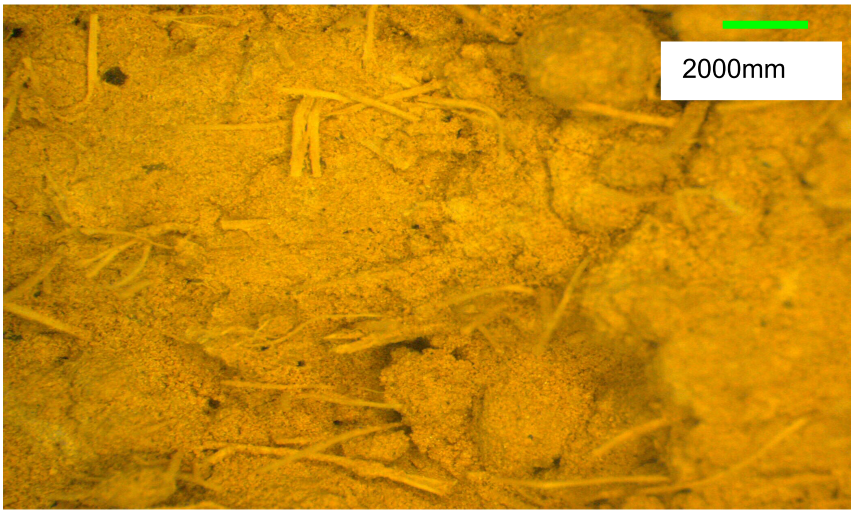


Figure 6.15 Fractured surface of a 1.25% sisal reinforced block

Additionally, the LOM images reveal that the fibres may not be homogeneously mixed up in the soil blocks, but rather randomly distributed. However, it is to be observed from these images that the fibres appear to be in an omni-directional nature. Apparently, the fibres form a matrix which increasingly binds the soil grains with increasing levels of sisal. The phenomena would appear to explain reduction in porosity (increase in density) with subsequent addition of fibres up to the critical volume 0.75%, as reported in section 6.1.2.5.

Scanning Electron Microscopy (SEM)

It was necessary to examine the internal structure of the earth blocks in order to gather some evidence of the effect of the morphology to the properties that have been discussed in the preceding sections.

This for this, scanning electron microscopy (SEM) analysis with a magnification factor of 500 was made for a few selected samples; results are illustrated in figure 6.16 to 6.18. The left side of figure 6.16 represents the non-reinforced sample; the sample seems denser than that reinforced with 0.25% sisal shown on the right side of figure 6.16. It appears that few amounts of sisal present do not provide an ideal network with clay particles; this could be the reason why the blocks reinforced with 0.25% sisal have lower strength than the non-reinforced (plain) blocks, see figure 6.2a.

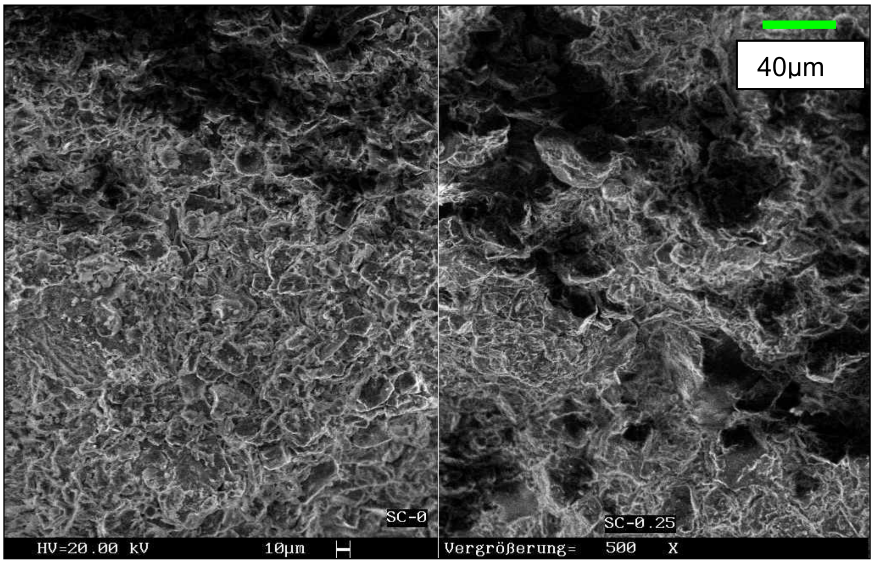


Figure 6.16 Micrograph of non-reinforced and 0.25% sisal reinforced CEB

A different scenario becomes apparent when one relates the non-reinforced sample and that reinforced with 0.75% sisal, as in figure 6.17. The block morphology as revealed by this scanning electron micrograph testifies to the embedment of the fibres in the soil grains; this would explain the improved strength in the block with 0.75% sisal level.

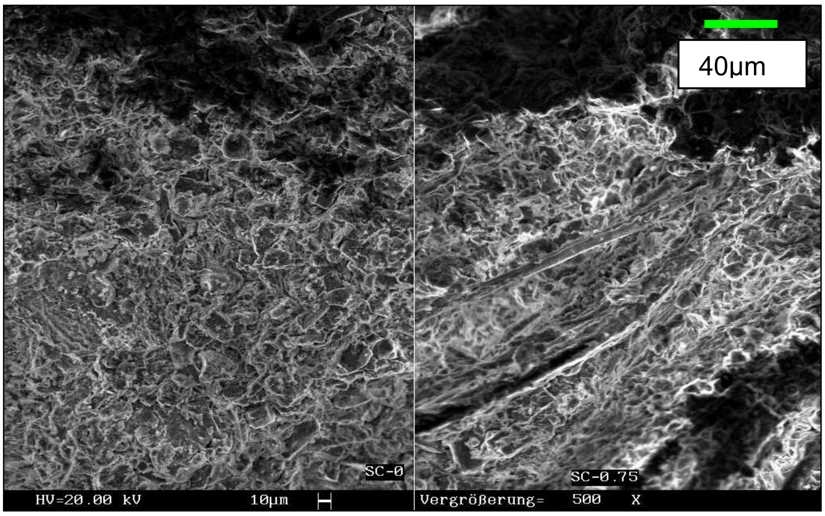


Figure 6.17 Micrograph of non-reinforced and 0.75% sisal reinforced CEB

1.25% sisal content results in a block with porous nature consequently the poor strength characteristics associated with it. Indeed, in figure 6.18, a pore with an approximate diameter of 88.09 µm is to be vividly seen. This amount of sisal, it can be concluded, is above the critical volume. Although fewer pores are witnessed in the non-reinforced sample, it would be clear that the binding force by only clay minerals is inferior to that where fibres are networked within the structure. Consideration of the analysis in section 6.1.1 and in this section supports the fact that the critical sisal fibre volume lie between 0.75% and 1.0 % by weight of dry soil.

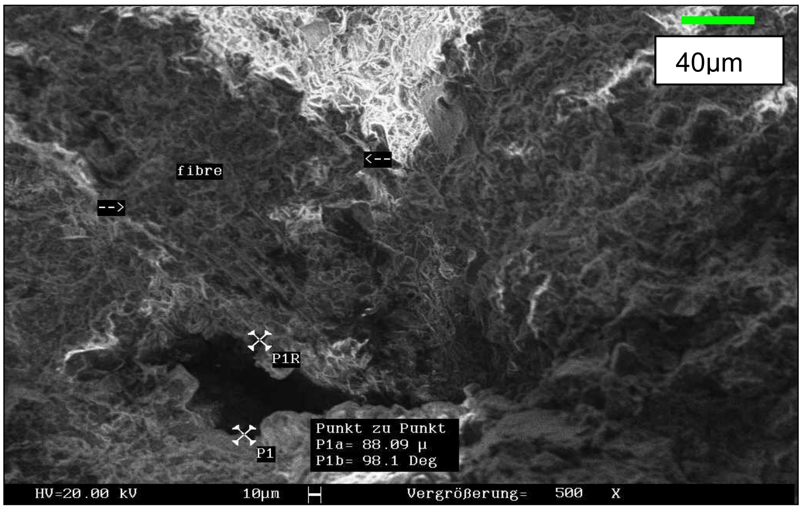


Figure 6.18 Micrograph of 1.25% sisal reinforced CEB

Observation of the fractured surface investigated by LOM imaging and the structure of samples investigated by SEM demonstrate that the amount of sisal added to the soil mix correlates to a high extend with the morphology of the block sample and hence to the obtained strength, density and porosity values.

6.2 Cement Stabilised Compressed Earth Blocks

6.2.1 Compressive, Flexural Strength and Cement Content and

Application of cement as a binder or stabiliser in compressed earth blocks is already well documented by past workers, as illustrated in section 2.3. It is therefore used in the present work more else as control experiment, to observe the influence of cement content to the strength characteristics for the selected soil sample and compare results with those of sisal reinforced blocks. Literature points out that cement when well mixed with soil and the blocks adequately cured after compaction, tends to increase the strength of the resultant soil blocks. Previous workers have shown that cement contents below 3% will not provide desired results (Rigassi, 1995)

Table 6.8 depicts the sample composition of mixtures used to manufacture and characterise cement stabilized compressed earth blocks, abbreviated as CeC. Clay is reinforced with 5%, 9% and 12%, cement respectively. Addition of cement to soil, just as was the case of sisal fibres (section 6.1), was done in ratios by weight of dry soil.

Table 6.8 Mix composition of cement stabilized blocks

Specimen Reference	**CeC-0**	**CeC -5**	**CeC -9**	**CeC -12**
Amount of Cement Used, %	0	5	9	12

A range of obtained experimental data is summarised in appendix A, F and G. A look a figure 6.19a below reveal, as would be expected and discussed in section 2.3, a linear increase in both 28-day dry compressive and flexural strength with increase in cement levels from 5% to 12%. The strong linear correlation is shown in equation 6.8 (R^2 = 0.9995) and equation 6.9 (R^2 = 0.9705).

It is not yet very clear why there occurred a slight drop in strength from the non-stabilized blocks to those stabilized with 5% cement, figure 6.19b. Possibly, the use of such a low cement by-volume ratio may have required a lot of mixing time to get the cement distributed thoroughly within the soil; poor mixing may therefore have been the cause.

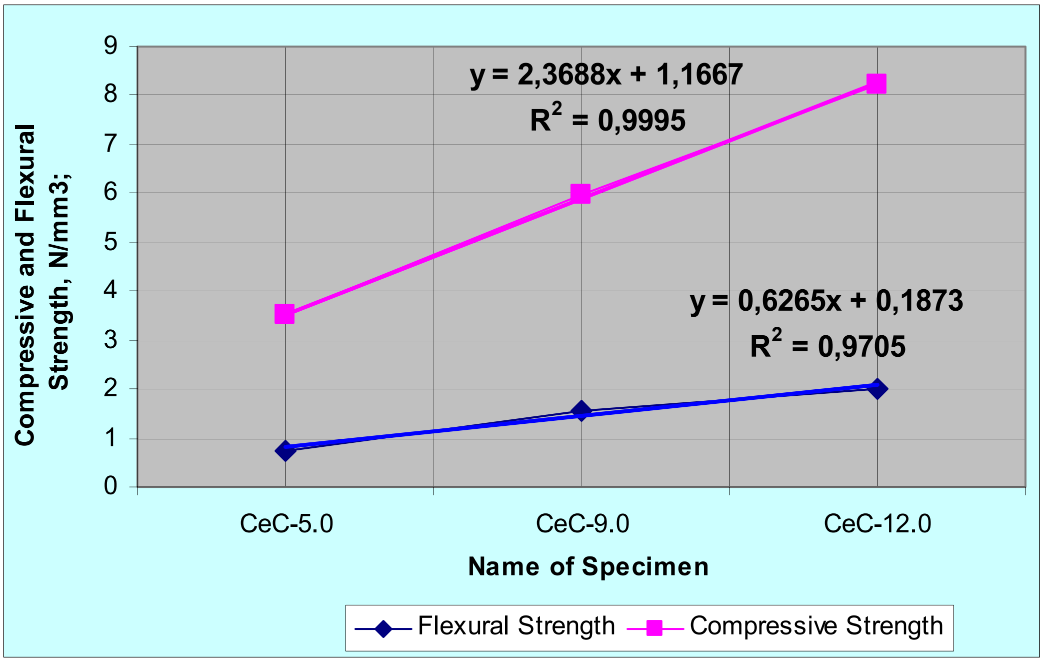


Figure 6.19a Compressive and flexural strength against cement levels

$$y_c = 2.3688x + 1.1667 \tag{6.8}$$

Where:

y = Compressive strength

x = Cement content

$$y_f = 0.6265x + 0.1873 \tag{6.9}$$

Where:

y = Flexural strength

x = Cement content

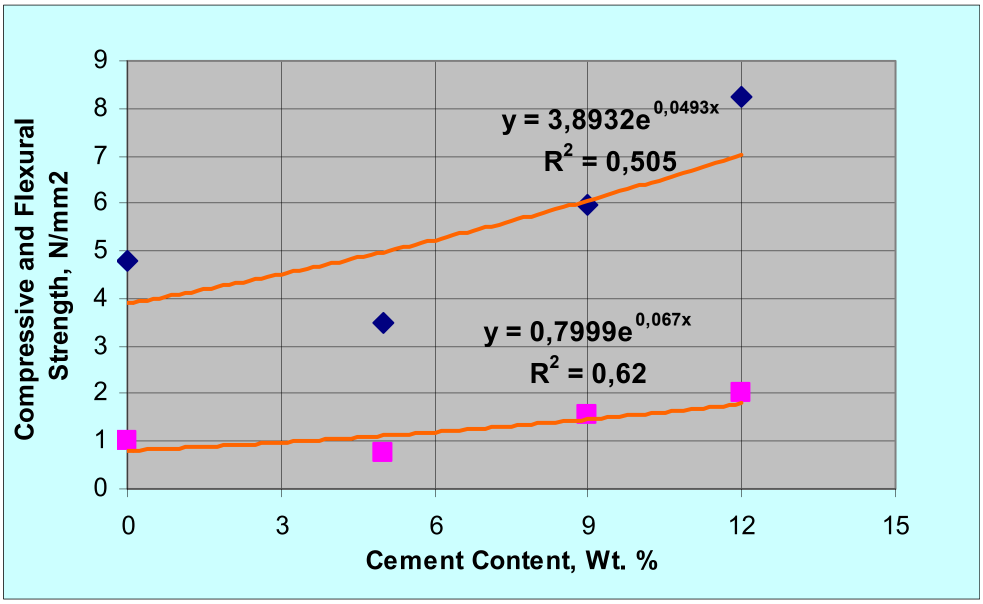


Figure 6.19b Compressive and flexural strength against cement content

$$y = 0.2938x + 3.7182 \tag{6.10}$$

Where:

y = Compressive strength

x = Cement content

$$y = 0.0909x + 0.7374 \tag{6.11}$$

Where:

y = Flexural strength

x = Cement content

Proposed Reasons for the Observed Strength Behaviour

Strength increase would be as a result of increased bonding between cement paste and clay minerals. According to (Mukerji K., 1994) hydrated cement reacts in two different ways in a soil: Firstly, by conventional hardening of the cement through hydration and bonding with the sandy "skeleton" of the soil. Secondly, by undergoing a 3-phase reaction with clay, thus:

- Hydration triggers the formation of cement gels on the surface of the clay aggregates. The lime, which is released during the hydration of the cement, tends to react with the clay. The lime is quickly used up and the clay starts to change its character,
- Hydration proceeds and encourages the clay aggregates to break down. The latter are deeply penetrated by cement gels,
- The cement gels and the clay aggregates become intimately interlinked. Hydration continues, but more slowly.

In effect, three combined structures are obtained, thus, an inert sandy matrix bound with clay, a matrix of stabilized clay and a matrix of non-stabilized soil.

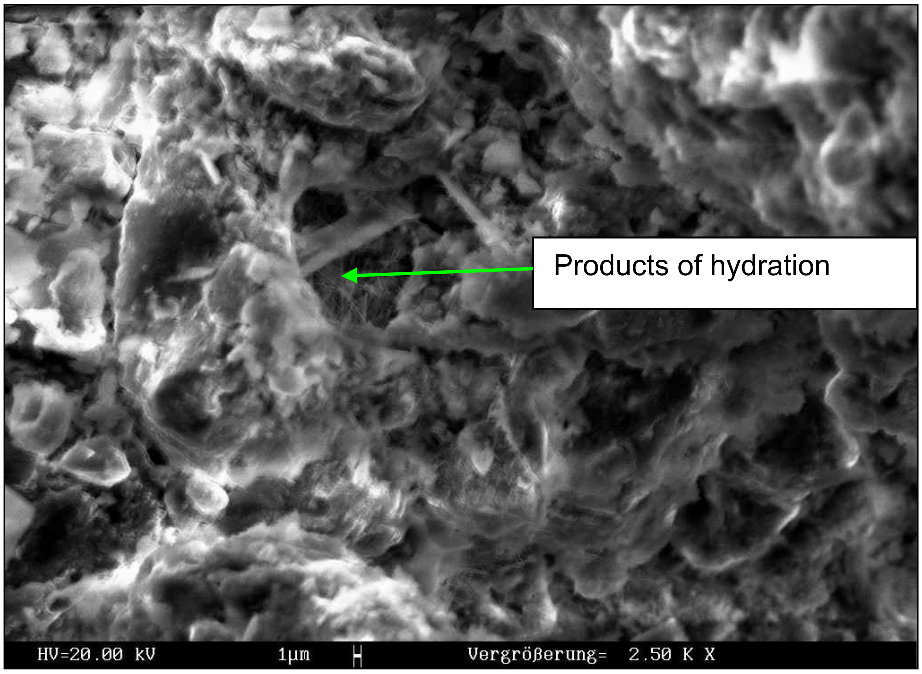


Figure 6.20 Micrograph of products of hydration

Table 6.9 attempts to show proportional increase in strength accompanying the change in cement content. Variation of cement from 5% to 9% (this represents an 80% increase in cement content), delivers an increase of 70% in compressive strength while an increase in cement content from 9% to 12% (this represents a 33% increase in cement content) delivers a 38% improvement in compressive strength.

Table 6.9 Relative change in strength against change in cement levels

S.No.	**Cement Content, %**	**Increament in Cement Content, %**	**Compressive Strength, N/mm^2**	**Improvement in Compressive Strength, %**
1	**5**	80	**3.50**	70
	9		**5.96**	
2	**9**	33	**5.96**	38
	12		**8.24**	
	Cement Content, %	**Change in Cement Content, %**	**Flexural Strength, N/mm^2**	**Improvement in Flexural Strength, %**
3	**5**	80	**0.75**	108
	9		**1.56**	
4	**9**	33	**1.56**	28.2
	12		**2.00**	

There appear to be therefore, a more else direct proportionality between growth in strength and increase in cement content. This view is supported by the strong correlation shown in equations 6.8 and 6.9. It is worth noting that a strength value of 5.96 N/mm^2 (at 9% cement content) is already sufficient as per recommendations of Kenya standard specifications for compressed soil blocks, see section 6.1.2. It may be concluded therefore that blocks stabilized with 9% and 12% cement content meet the strength requirements needed for use in housing-wall construction in Kenya.

A look at table 6.10 and figure 6.21, confirms as follows: compared to plain blocks, compressive strength increase by application of 9% cement, amounts to 24.3% (57.8%

growth of flexural strength) while inclusion of 12% cement brings about a 71.7% increase in compression strength (101% growth of flexural strength). 5% cement inclusion results in a drop of about 25% for both compressive and flexural strength.

Table 6.10 Strength values and percentage change

Block Type	Stabiliser Type and Content	Change in Strength			
		Compressive Strength, N/mm^2	Change in Strength*, %	Flexural Strength, N/mm^2	Change in Strength*, %
CeC	**Plain Block**	4.798	-	0.992	-
	5% Cement	3.505	-26.9	0.750	-24.4
	9% Cement	5.965	**+24.3**	1.566	**+57.8**
	12% Cement	8.24	**+71.7**	2.00	**+101**

*+ implies % improvement in strength comparison to the non-reinforced earth block

- implies % drop in strength in comparison to the non-reinforced earth block.

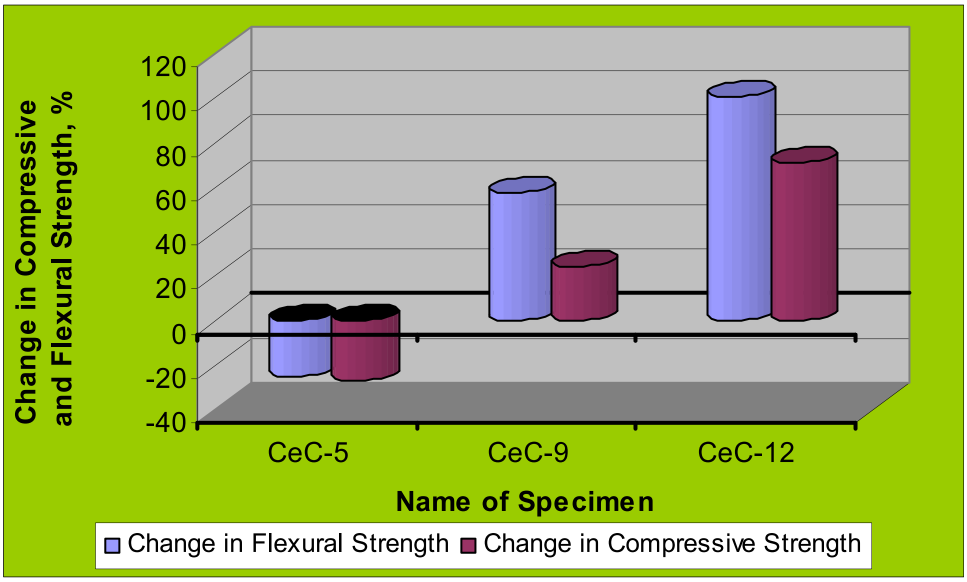


Figure 6.21 Relative change in strength against change in cement levels

Ratio of Compressive to Flexural Strength

Data extracted from table 6.11 and illustrated in figure 6.22 would appear to suggest that compressive strength is about 4 to 5 times its flexural counterpart and is within the limits recommended by other past workers, see section 2.5.1. Indeed the range obtained for cement stabilized blocks is consistent with the results obtained for the sisal-reinforced earth blocks, see section 6.1.1. It would be possible to suggest, in this background, that the ratio can be applied as a quality control tool. Based on this tool, experiments carried out in this work can be authenticated by evaluation of this ratio.

Table 6.11 Strength and ratio of compressive to flexural strength

S.No.	Sample Name	Flexural Strength, N/mm^2	Compressive Strength, N/mm^2	Ratio of Flexural to Compressive Strength	
				Gross	**Mean**
Cement Stabilised Compressed Earth Blocks					
1	**CeC-0**	0.992	4.79875	4.83745	4.196685
2	**CeC-5**	0.75075	3.505	4.668665	
3	**CeC-9**	1.5665	5.965	3.807852	
4	**CeC-12**	2.00375	8.2425	4.113537	

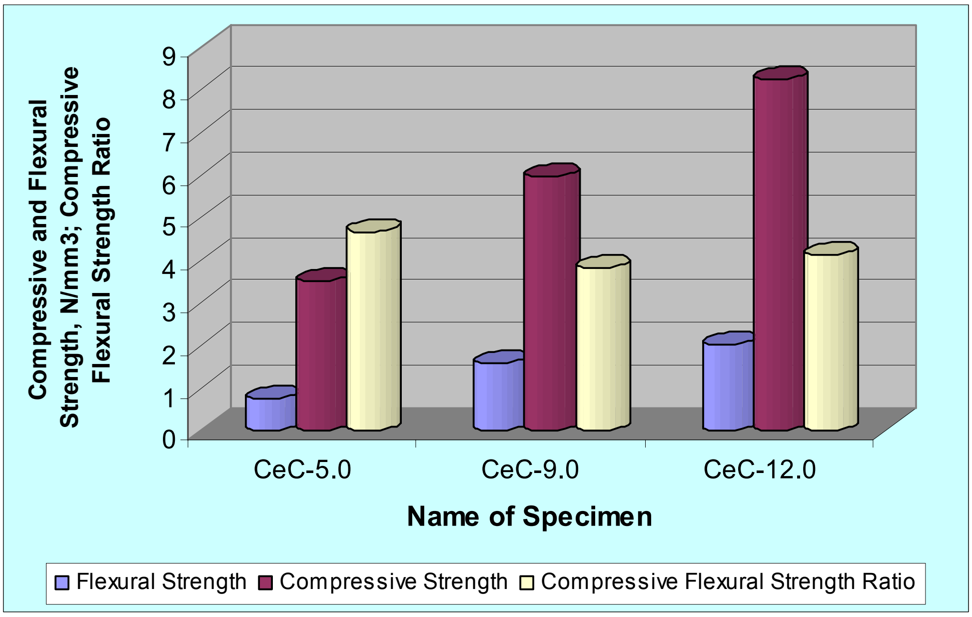


Figure 6.22 Strength and ratio of compressive to flexural strength

Comparison of Sisal and Cement stabilised Earth Blocks

It is of significance that the results of cement stabilised compressed blocks be looked at, in the background of those obtained for sisal reinforced compressed blocks, section 6.1.1. Tables 6.12a and 6.12b provide this summary, outlined further in figure 6.23.

Table 6.12a Strength comparison of sisal reinforced and cement stabilised blocks

S.No.	**Stabilizer Type and CEB Characteristic**	**Stabilizer Amount and Value of Characteristic**			
1.0	**Cement Content, %**	**0**	**5**	**9**	**12**
1.1	**Compressive Strength, N/mm^2**	4.798	3.50	5.96	8.24
1.2	**Flexural Strength, N/mm^2**	0.992	0.75	1.56	2.0
2.0	**Sisal Content, %**	**0**	**0.25**	**0.5**	**0.75**
2.1	**Compressive Strength, N/mm^2**	4.798	4.18	6.08	9.14
2.2	**Flexural Strength, N/mm^2**	0.992	0.75	1.035	1.63

Table 6.12b Summary of the ideal strength values

Block Type	**Stabiliser Type and optimum Content**	**Improvement in Strength for Ideal mix proportions**			
		Compressive Strength, N/mm^2	**Percentage Improvement in Strength**	**Flexural Strength, N/mm^2**	**Percentage Improvement in Strength**
SC	**0.75% Sisal**	9.14	**+90.5**	1.63	**+64.3**
CeC	**12% Cement**	8.24	**+71.7**	2.00	**+101**

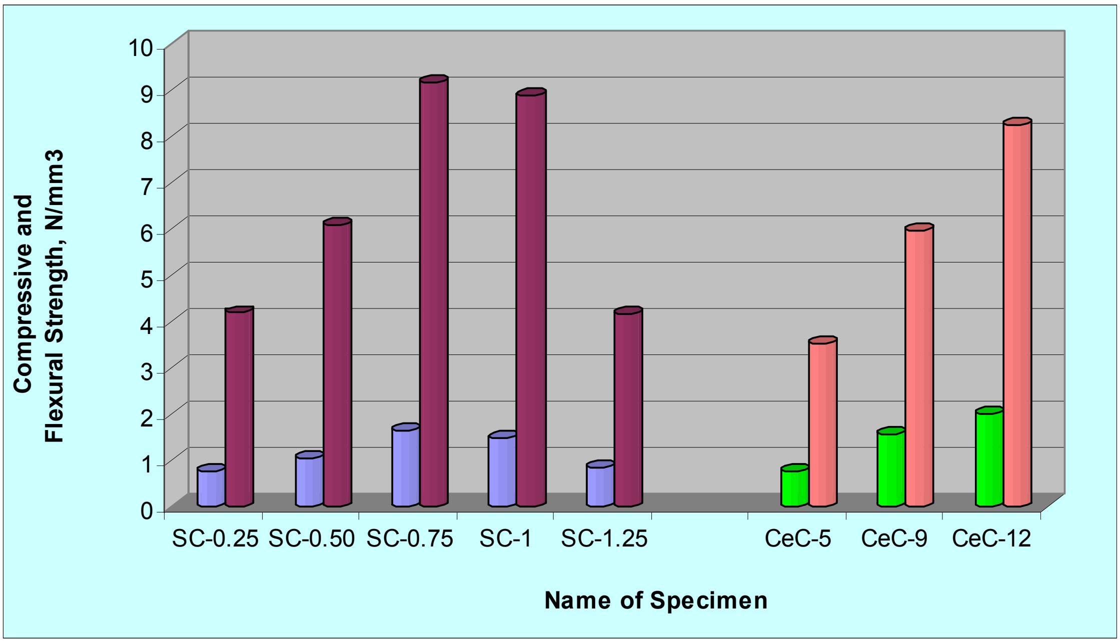


Figure 6.23 Comparison of sisal reinforced and cement stabilised blocks

Important to note from table 6.12 and figure 6.23, would be that 9% cement content yields blocks with a compressive strength of 5.96 N/mm^2 (flexural strength 1.56 N/mm^2) and are fairly comparable to those with 0.5% sisal content which provide a compressive strength of 6.08 N/mm^2 (flexural strength of 1.035 N/mm^2).

Blocks with 12% cement levels have compressive strength of 8.24 N/mm^2 (flexural strength of 2 N/mm^2) and are comparable to blocks with 0.75% sisal content which results into a compressive strength of 9.14 N/mm^2 (flexural strength of 1.63 N/mm^2).

At this point in time, it is not clear why the flexural strength of cement stabilised bricks appear to be slightly higher than that of the sisal reinforced counterparts although the opposite is true for compressive strength parameter.

From afore mentioned and based on strength values, it may be deduced that sisal vegetable fibres can replace the relatively expensive cement binder as stabilising agent for earth bricks. It may be stated further that sisal being a renewable natural resource available widely in Kenya, its use as reinforcing agent would cut costs of building considerably and therefore bring decent housing near to the rural population of Kenya.

On this basis one of the goals of this study as indicated in sections 1 and 2 can be said to have been achieved.

6.2.2 Dry Block Density and Porosity

Practical Dry Block Density

The practical dry block density, determined in the same way as described in section 6.1.2, dropped on addition of 5% cement; from about 1800 kg/m^3 to about 1690 kg/m^3. The density then remained constant even on addition of further amounts of cement (9%, 12%) as displayed in figure 6.24 and the table in appendix A and H.

The reason as to why the density drops in comparison to the non-reinforced blocks, and why it remains constant in spite of cement addition (from 5% to 12%) was not able to be established in the current study.

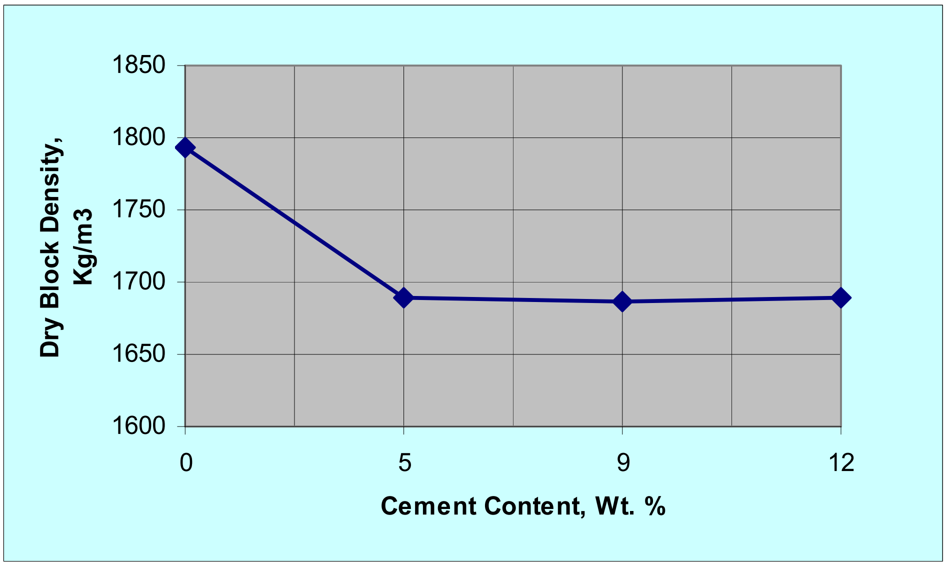


Figure 6.24 Dry block density as a function of cement content

Table 6.13 and figure 6.25 shows that the decrease in density (in comparison to the plain earth block) is about 6% for all the 3 mix proportions. It is also somehow amazing and against past research findings that the lower densities (figure 6.26) provided better compressive and flexural strength; no past worker, to the best of knowledge available, has recorded such findings.

More advanced research in the type of bonding or reaction between montmorillonite minerals and products of cement hydration is recommended to be carried out; this should help to better understand the internal block structure and perhaps provide explanation to this phenomena.

Table 6.13 Reduction in density in comparison to plain earth block

Block Type	**Stabiliser Type and Content**	**Practical Density, kg/m^3**	**Change in Practical Density*, %**
CeC	**Plain Block**	1792.97	-
	CeC-5	1689.45	-5.8
	CeC-9	1686.52	-6.0
	CeC-12	1689.45	-5.8

- implies % drop in strength in comparison to the non-reinforced earth block.

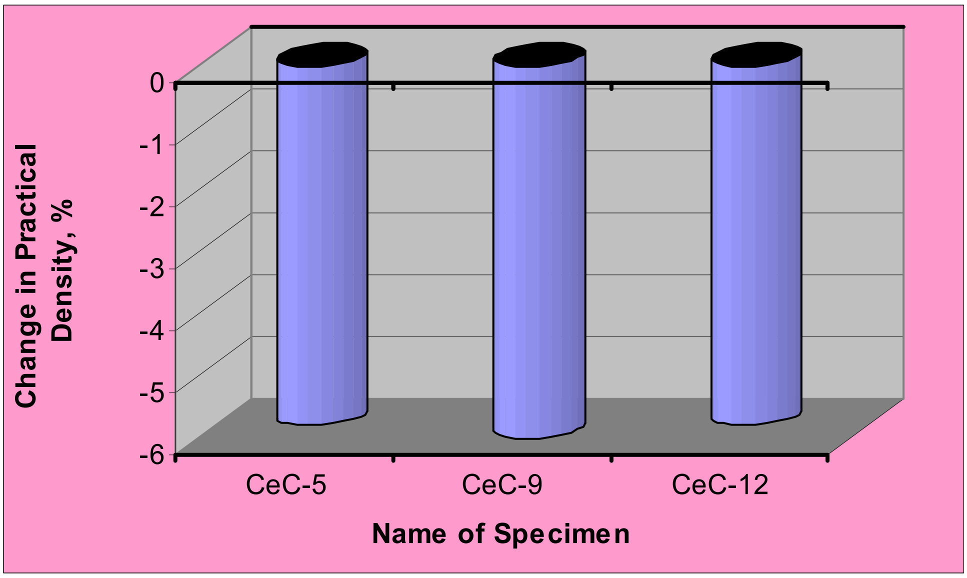


Figure 6.25 Change in practical dry block density

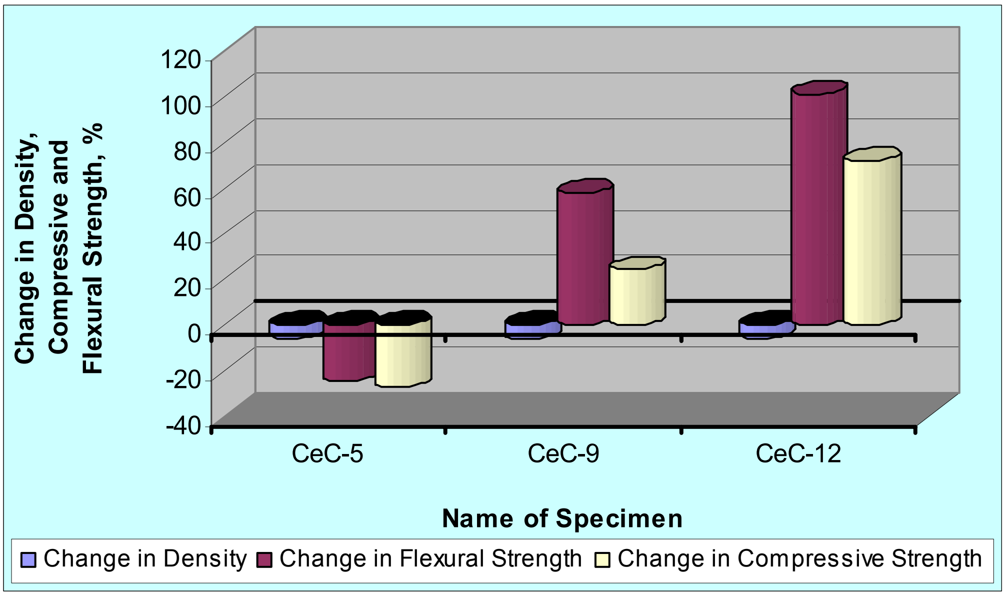


Figure 6.26 Change in strength as a reflection of change in density

Theoretical Density

The theoretical density is determined in the same manner as described in section 6.1.3.2. The values, depicted in table 6.14 and figure 6.27, are identical for the 3 cement proportions, i.e., 2663.7, 2661.2, 2662.1 and 2658.6 kg/m^3 (for 0, 5, 9 and 12% cement amounts respectively).

Table 6.14 Difference in theoretical from practical density

S.No.	**Cement Content, %**	**True Density, kg/m^3**	**Practical Density, kg/m^3**	**Increase in Density, kg/m^3**	**Change in Density, %**	**Porosity, %**
1	**0.0**	2663.7	1792.97	870.73	48.56	32.69
2	**5.0**	2661.2	1689.45	971.75	57.52	36.52
3	**9.0**	2662.1	1686.52	975.58	57.85	36.65
4	**12.0**	2658.6	1689.45	969.15	57.36	36.45

The percentage increase in true dry density compared to practical block density as illustrated in table 6.14 is an average of 57.5% for all the 3 cement contents; this appears to confirm the insignificance of cement with respect to density as a parameter. Such results are unrecorded in past investigations. Cement content, it could be concluded, has therefore no effect on both practical and theoretical density.

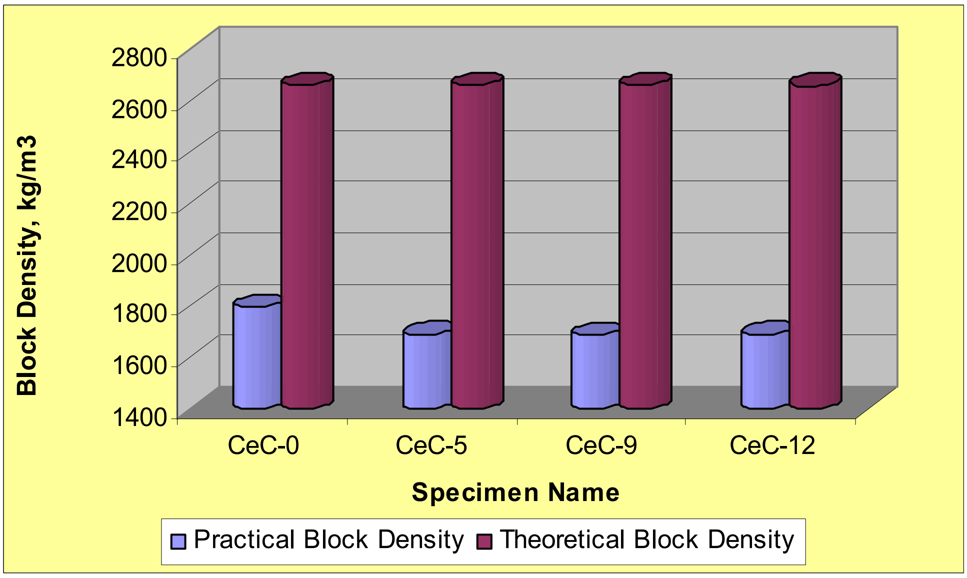


Figure 6.27 Comparison between theoretical and practical density

The experimental correlation between theoretical density and cement levels is outlined in figure 6.28. The best fit shows a linear correlation (R^2 =0.7238), represented in equation 6.12.

$$\rho_t = -0.3494 \text{ Cement Content} + 2663.7 \qquad (6.12)$$

Just like the case was for sisal reinforced earth blocks the best fit is a near linear function. This would appear to suggest that the general relationship between theoretical density and stabilizer content for compressed earth blocks is linear in nature. Besides, the theoretical density is, as was the case of sisal reinforced blocks, about 1.5 times greater than the practical density. The general practical applicability of equation 6.12 would be similar to deductions made in section 6.1.2.2, with respect to equation 6.2.

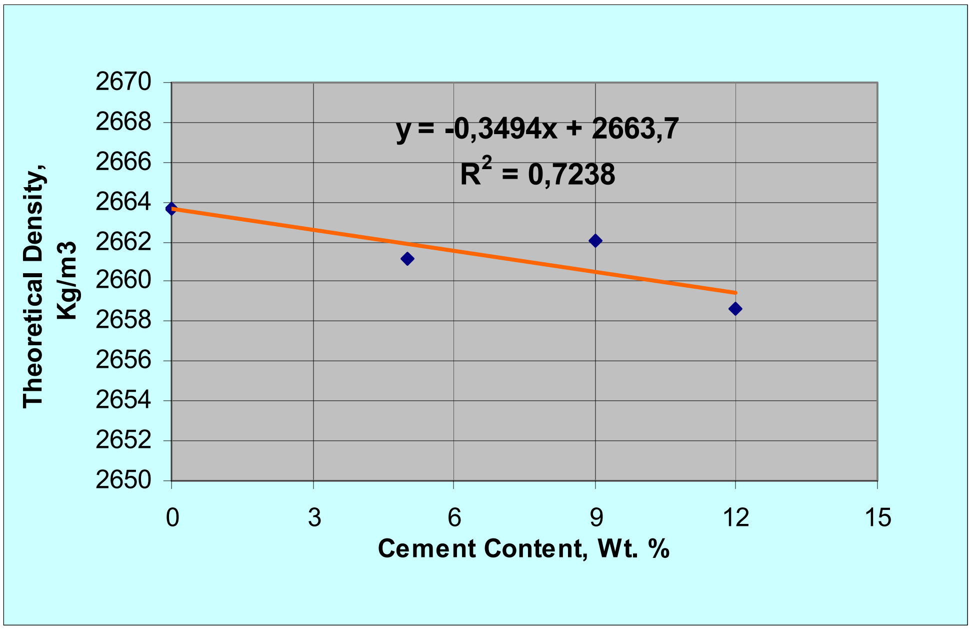


Figure 6.28 Theoretical dry block density as a function of cement content

Porosity

The porosity values established in the same way as described in section 6.1.3.3, i.e. by use of equation 6.3, were as follows: 32.69, 36.52, 36.65 and 36.45% for 0, 5, 9 and 12% cement amounts respectively.

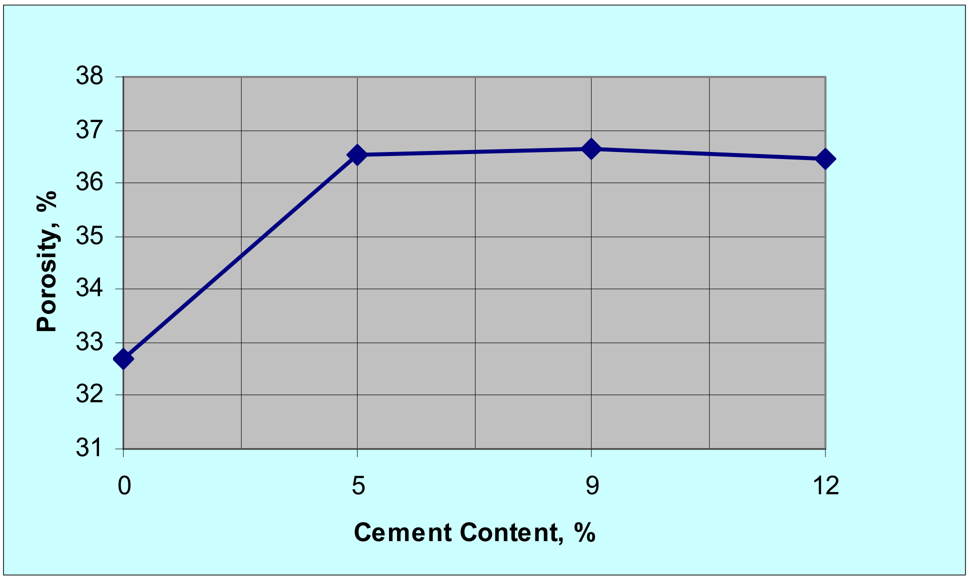


Figure 6.29 Porosity as a function of cement content

As expected and discussed in section 6.1.3.3, the porosity of the earth blocks is inversely proportional to the practical dry block density. Comparison of figure 6.24 and 6.29 would appear to confirm this view. On the other hand it is noted that the porosity of blocks stabilised by 5, 9 and 12% cement is basically the same (similar scenario with the practical dry block density in the preceding section).

In the background of this information, it is not yet clear why the compressive strength of cement stabilised earth blocks increases on addition of cement from 5% to 12% although the porosity remains constant. The literature available does not document such results. It can, at this time however, be said that the amount of cement used in these investigations has no effect on the porosity nor on density. Remarks made above over behaviour of practical density with respect to further research would thus, appear to be applicable in this case too.

6.3 Cement-Sisal Stabilized Compressed Earth Blocks

The combination of cement and sisal fibres for reinforcement or stabilization of soil is unrecorded in literature. The nearest similarity is the investigations where sisal has been used to reinforce concrete elements. Another similar investigation is carried out by (Eko et. al., 1994). The study considers the structural engineering properties of soil-cement reinforced with sugarcane bagasse vegetable fibres. In the work, the influence of bagasse vegetable fibres and cement level on the compressive strength, flexural strength is studied; it is found that bagasse had a negative impact on the strength values of the reinforced blocks. (Osunade, et. al., 1992) reinforces concrete with elephant grass (also a vegetable fibre) and finds too, no strength improvement.

6.3.1 Cement-Sisal Content and Compressive Strength

Because two variables (sisal and cement) are considered in this particular case, it was necessary to plot two independent diagrams; one showing the effect of increasing sisal content and the other depicting the influence of increasing cement content on the compressive strength.

Change in the 28-day dry compressive strength as a function of both cement and sisal stabilization is summarized in the table in appendix A and I and below in figure 6.30 and 6.31. Observation of these diagrams gives in some clear tendencies worth illustration.

In general, for each level of sisal content, i.e. 0.25%, 0.5%, 0.75%, 1.0% and 1.25%, the 28-day dry compressive strength increased with an increasing level of cement in a linear relationship, figure 6.30. This would be due to the increasing amount of C_2S and C_3S brought about by increasing level of cement. The increasing amount of $C_3S_2H_3$ which is derived from the hydration of C_2S and C_3S better tied fibres and soil particles together in the mixture, leading to an increase of strength. It may have been expected that a combination of both cement and fibres would provide greater strength than cement or fibres on their own.

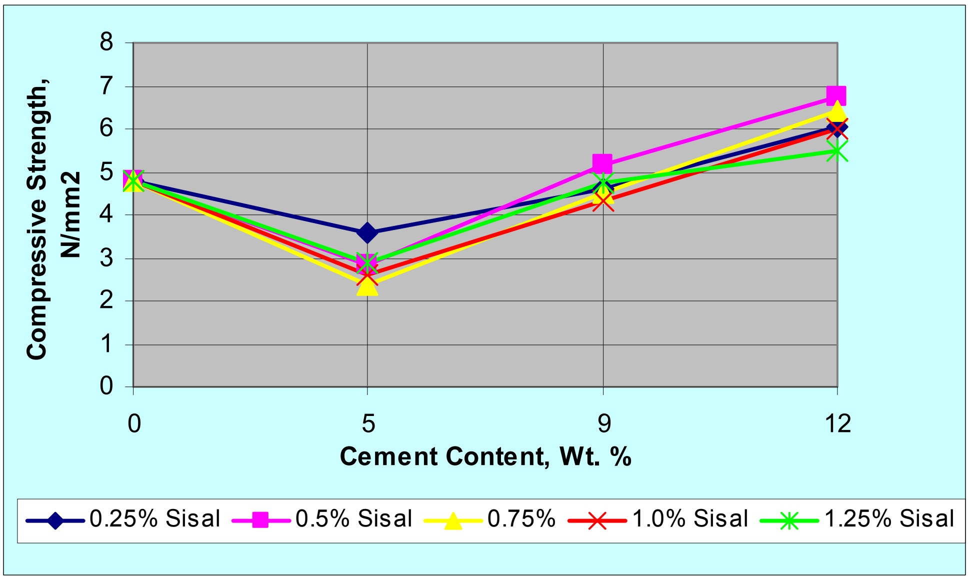


Figure 6.30 Compressive strength as a function of cement content

Results of the present investigations show however, that this is not the case. Compared with blocks reinforced with only sisal (section 6.1) or stabilised with only cement (section 6.2), it is noted that the compressive strength rises within a rather limited range of 2.37 N/mm^2 to 6.75 N/mm^2. As expected, the rate of increase is lower for 1.0% and 1.25% sisal levels, meaning therefore that higher amounts of sisal in combination with cement are relatively detrimental to compressive strength.

It is catalogued by (Houben and Guillaud, 1994) that the fibre armature has its effect at the macroscopic level; fibres thus reinforce at the level of grain aggregations rather than at the level of individual grains. Cement stabilisation on the other hand, results in filling of voids with an insoluble binder which coats the grains and holds them in an inert matrix.

The influence of sisal levels to strength characteristics in cement-sisal stabilised soil blocks is better illustrated by figure 6.31. Clearly, sisal content, in the presence of cement does not seem to have any effect on the strength characteristics of compressed earth blocks. Similar results are not yet recorded in the past findings;

indeed it is not yet clear why sisal, in the presence of cement, would not have any effect on the strength parameters of compressed earth blocks.

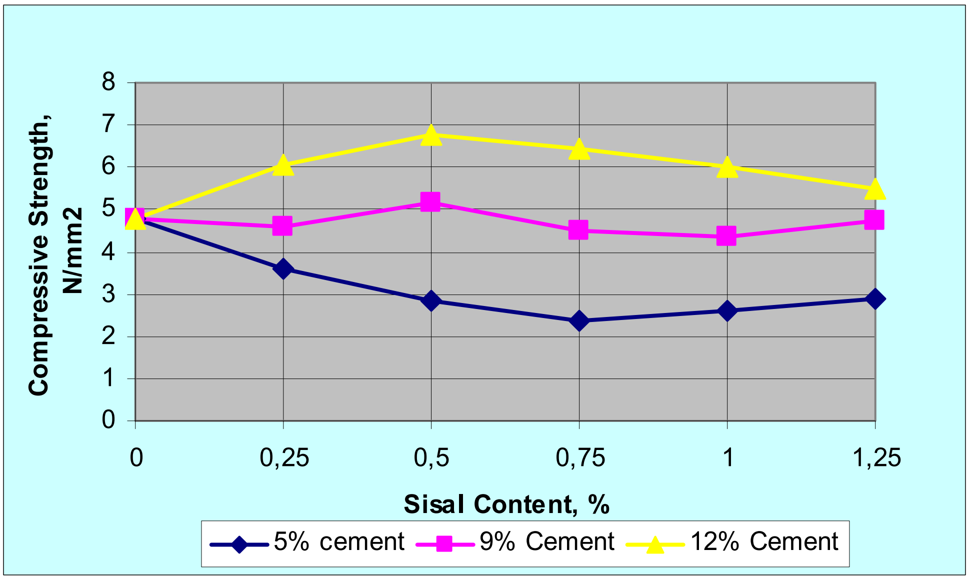


Figure 6.31 Compressive strength as a function of sisal content

It would appear therefore that, improvement of compressive strength in cement-sisal stabilised blocks is due to cement and not sisal presence. Likely, in situations of high sisal content, the amount of soil-cement which surrounded each fibre may no longer have been enough to provide sufficient friction. In this light, findings of other workers described briefly in section 6.1.1 may be seen to be right.

6.3.2 Sisal Content and Block Flexural Strength

The results of the influence of both sisal and cement levels flexural strength are presented in appendix A and J and depicted in figure 6.32 and figure 6.33 below. Block density values are shown in appendix A and K.

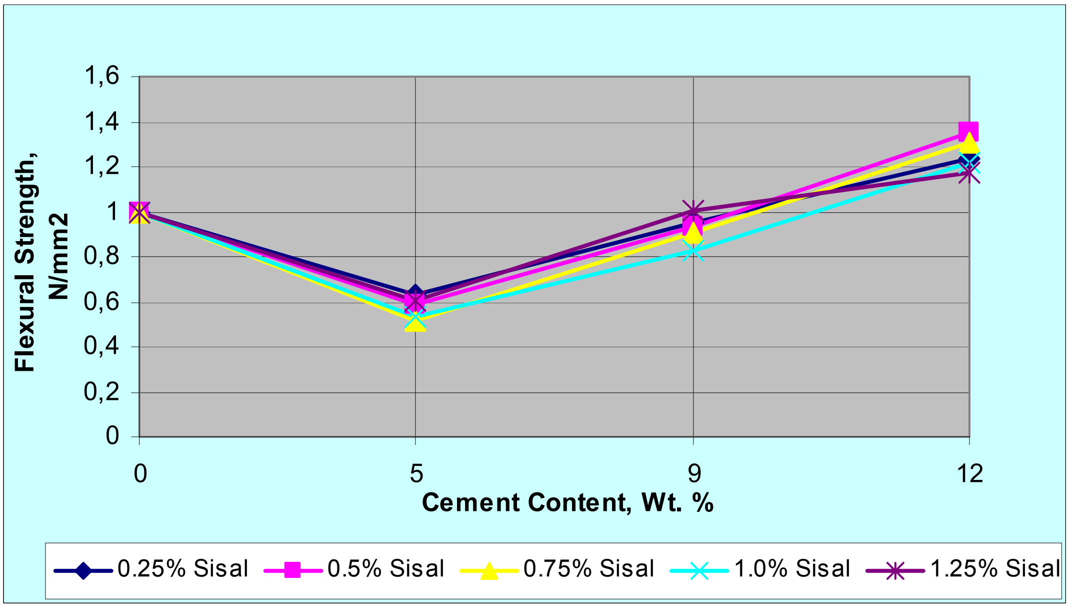


Figure 6.32 Flexural strength as a function of cement content

The trends are similar to compressive strength tendencies. Indeed, the flexural strength lies in the range of 17.5% to 22% of the compressive strength.

The flexural strength of fibre reinforced specimens was lower than that of non-reinforced specimens at 5% and 9% cement level, the vegetable fibres were therefore detrimental to matrix quality for this test. At 12% cement level, the flexural strength is for all the 6 sisal fibre levels greater than the non-reinforced case, figure 6.32.

At each level of sisal, there was an increase in flexural strength with an increasing level of cement; this would be due to $C_3S_2H_3$ compounds brought about by the hydration of cement. In general, 0.5% sisal content provides the best flexural strength; likely, according to (Eko R., et al, 1994) because this fibre content and the amount of soil-cement which surrounded each fibre might be the optimum combination of the two for the composite to provide both friction and shear strength.

Observation of figure 6.33 would confirm what earlier stated in section 6.3.1, that improvement of strength in cement-sisal stabilised blocks is due to cement and not sisal presence. It is clear that the flexural strength for both 5% and 9% cement contents is lower than in the non-reinforced soil block. Stabilisation with 12% cement brings about strength (up to 1.36 N/mm^2) that is only slightly higher than in the non-reinforced case (0.992 N/mm^2).

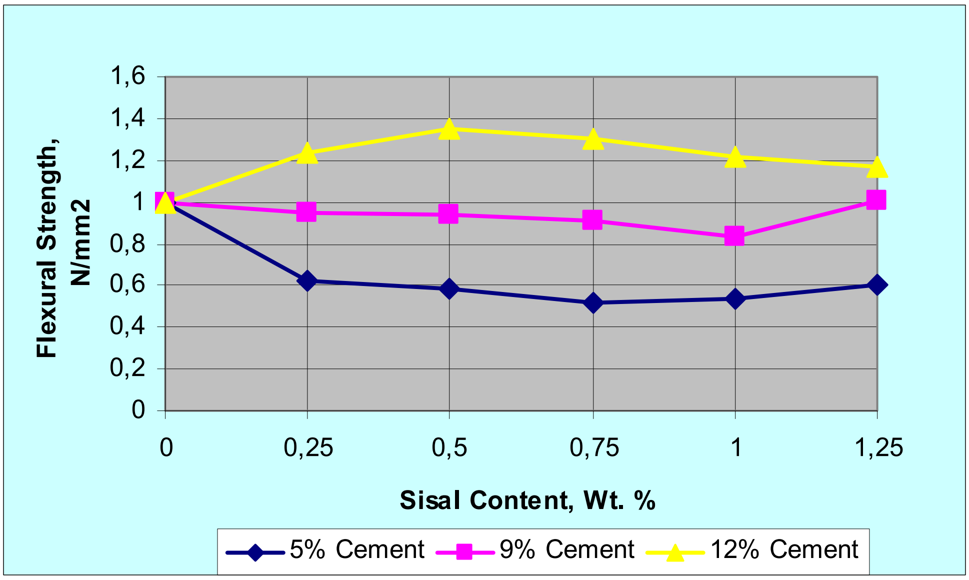


Figure 6.33 Flexural strength as a function of sisal content

It is not very clear at this juncture why the sisal fibres on their own have a positive impact on the strength characteristics as discussed in section 6.1 and yet appear not to play the same role when in combination with cement. More research particularly on the microstructure of the cement-sisal-soil matrix is still required in order to establish an acceptable explanation.

Ideal Case

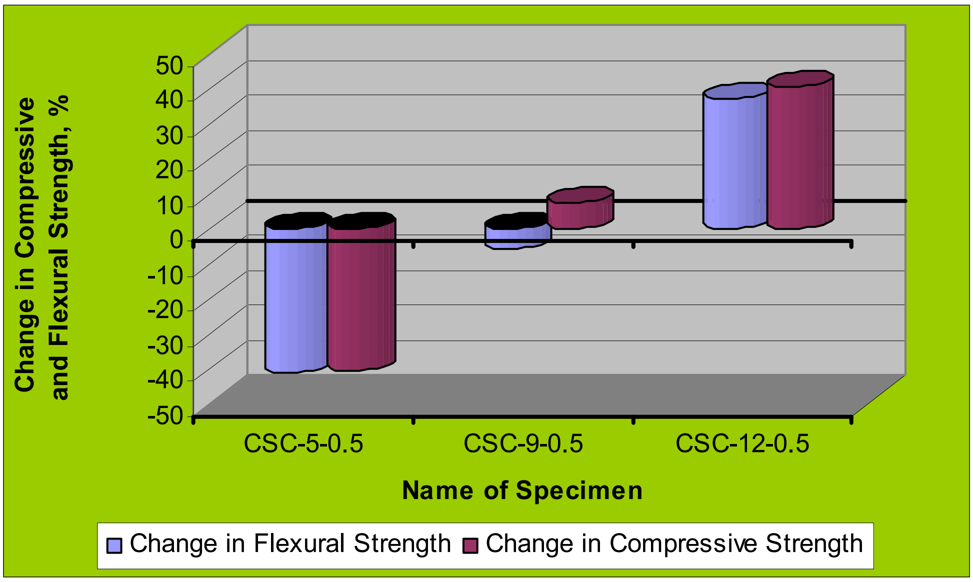
From the above observations, it is seen that the ideal combination among the sisal-cement mixtures is that of 0.5% sisal alongside with 12% cement content (abbreviated as CSC-0.5-12). The strength values and improvement in this combination, among others, is presented in table 6.15 and outlined in figure 6.34. An improvement of 40.7% in compressive strength and 37.1% for flexural strength (in comparison to the plain block) is witnessed when soil is reinforced by 0.5% sisal and 12% cement. The proposed cause for this positive change, as well as for the reduction in strength for other mix combinations has been described early in this section. Table in Appendix K2 and figures in appendix K1 to K3 show the density relationships.

Table 6.15 Strength values and percentage change

Block Type	**Stabiliser Type and Content**	**Change in Strength**			
		Compressive Strength, N/mm^2	**Change in Strength*, %**	**Flexural Strength, N/mm^2**	**Change in Strength*, %**
CSC	**Plain Block**	4.798	**-**	0.992	**-**
	0.5% Sisal and 5% Cement	2.843	-40.7	0.583	-41.2
	0.5% Sisal and 9% Cement	5.16	**+7.5**	0.934	-5.8
	0.5% Sisal and 12% Cement	6.75	**+40.7**	1.36	**+37.1**

**+ implies % improvement in strength in comparison to the non-reinforced earth block*

- implies % drop in strength in comparison to the non-reinforced earth block.

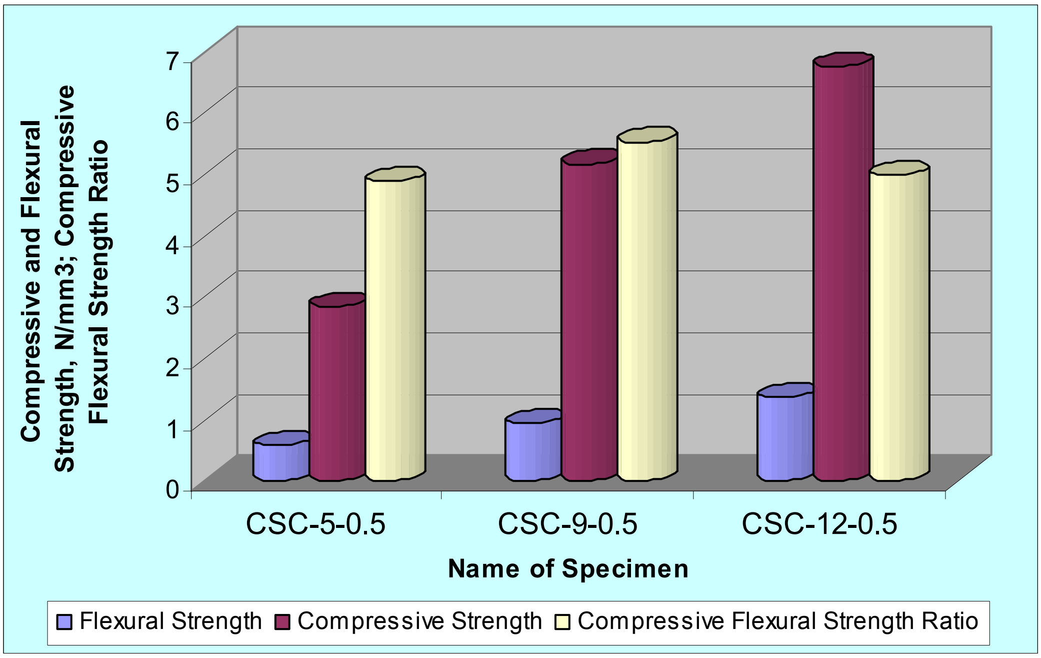


6.34 Deviation in Compressive and flexural strength from that of plain block

It is further observed from table 6.16, figure 6.35 and appendix A1 that the compressive strength is 4.8 to 5.5 times higher than flexural strength for all the specimens tested. This is reflective of the results obtained in section 6.1.1 and 6.2.1. The proposal in section 6.2.1 that this ratio can be applied as a quality control tool can therefore be said to have been further reinforced. It can also be deduced that requirements of compressive to flexural strength ratio, for this cement-sisal blocks as a building material, have been satisfied.

Table 6.16 Strength and ratio of compressive to flexural strength

S.No.	**Sample Name**	**Flexural Strength, N/mm^2**	**Compressive Strength, N/mm^2**	**Ratio of Flexural to Compressive Strength**	
				Gross	**Mean**
Cement-Sisal reinforced compressed earth blocks					
1	**CSC-0**	0.992	4.79875	4.83745	5.125949
2	**CSC-5-0.5**	0.58325	2.843125	4.874625	
3	**CSC-9-0.5**	0.9345	5.16	5.521669	
4	**CSC-12-0.5**	1.35525	6.75125	4.981553	



6.35 Strength and ratio of compressive to flexural strength

Strength comparison in sisal, cement and cement-sisal reinforced blocks

The data in table 6.17, table 6.18, figure 6.36a and figure 6.36b show comparison in strength for sisal reinforced (refer to section 6.1), cement stabilized (see section 6.2) and cement-sisal (see section 6.3) reinforced compressed earth blocks).

Table 6.17 Strength comparison of SC, CeC and CSC

S.No.	Stabilizer Type and CEB Characteristic	Stabilizer Amount and Value of Characteristic			
1.0	**Sisal Content, %**	**0**	**0.25**	**0.5**	**0.75**
1.1	**Compressive Strength, N/mm^2**	4.798	4.18	6.08	9.14
1.2	**Flexural Strength, N/mm^2**	0.992	0.75	1.035	1.63
2.0	**Cement Content, %**	**0**	**5**	**9**	**12**
2.1	**Compressive Strength, N/mm^2**	4.798	3.50	5.96	8.24
2.2	**Flexural Strength, N/mm^2**	0.992	0.75	1.56	2.0
3.0	**Cement-Sisal, %**	**0**	**5-0.5**	**9-0.5**	**12-0.5**
3.1	**Compressive Strength, N/mm^2**	4.798	2.843	5.16	6.75
3.2	**Flexural Strength, N/mm^2**	0.992	0.583	0.934	1.36

Table 6.18 Summary of the ideal strength values

Block Type	**Stabiliser Type and optimum Content**	**Improvement in Strength for Ideal mix proportions**			
		Compressive Strength, N/mm^2	**Percentage Improvement in Strength**	**Flexural Strength, N/mm^2**	**Percentage Improvement in Strength**
SC	**0.75% Sisal**	9.14	**+90.5**	1.63	**+64.3**
CeC	**12% Cement**	8.24	**+71.7**	2.00	**+101**
CSC	**0.5% Sisal and 12% Cement**	6.75	**+40.7**	1.36	**+37.1**

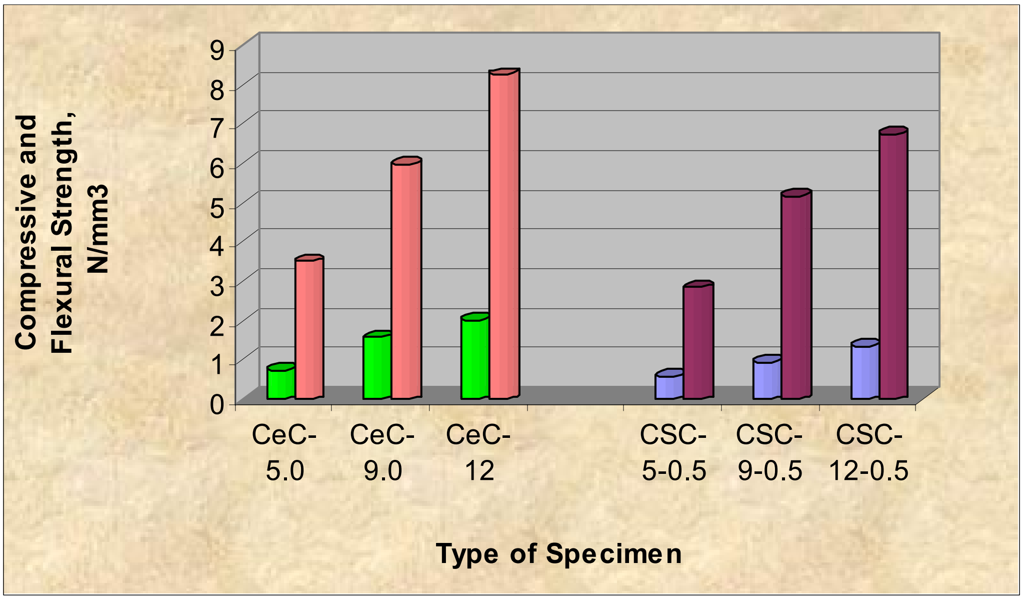


Figure 6.36a Strength comparison for CeC and CSC

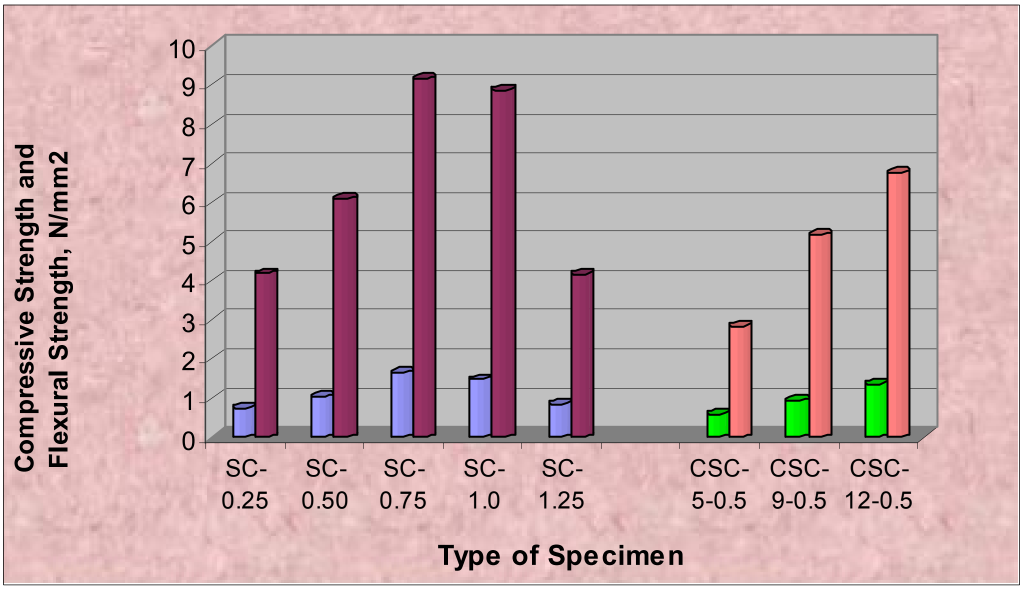


Figure 6.36b Strength comparison for SC and CSC

Comparison between the sisal reinforced blocks and cement stabilised ones has been carried out in section 6.2.1. It has already been established that the ideal sisal reinforced blocks (0.75% sisal content – with 90.5% improvement), from the point of view of strength, appear to be superior to the cement stabilised ones (12% cement content – with 71.7% improvement). The deal cement-sisal reinforced blocks would seem in this consideration inferior to the previous two types (40.7% improvement).

On the other hand, the 6.75 N/mm^2 value of compressive strength is comparable with the strength of 0.5% sisal reinforced blocks (6.08 N/mm^2) and that of 9% cement stabilized blocks (5.96N/mm^2). Based on strength consideration, it would be appear that out of the three types of blocks, the sisal reinforced would be preferred for housing wall construction.

6.4 Cassava Stabilised Compressed Earth Blocks (CaC)

The use of Cassava powder as a building material has no precedent; no past researcher has documented findings to this effect. Cassava plant (a root tuber) described in section 3.4, is grown and is readily available in developing countries.

Table 6.19 depicts the sample composition of mixtures used to manufacture and characterize cassava stabilized compressed earth blocks, abbreviated as CaC. Clay or earth is reinforced with 0%, 1.5%, 2.5%, 4.0%, 5.0%, and 7.0% cassava powder. A wide range of mixture proportions has been selected due to the unavailability of prior knowledge. Like in all previous cases, addition of cassava powder to soil was done in ratios by weight of dry soil. For each mix composition described in section 5.2.1, 4 blocks were prepared to measure compressive and flexural strength; a mean value from the 4 blocks was calculated and used for evaluation of the strength characteristics.

Table 6.19 Composition of cassava stabilized blocks

Specimen Reference	**CaC-0**	**CaC-1.5**	**CaC-2.5**	**CaC-4.0**	**CaC-5.0**	**CaC-7.0**
Amount of Cassava Used, %	0	1.5	2.5	4.0	5.0	7.0

6.4.1 Cassava Content and Dry Compressive and Flexural Strength

Compressive strength, as mentioned earlier, is the single most important determinant of durability for compressed blocks. It was necessary to establish this parameter for cassava-soil compositions, given that this matrix has not been investigated before. Details of the results for the established strength are contained in appendix A, L and M

The correlation between compressive and flexural strength and cassava powder content is depicted in figure 6.37. Compressive strength lies between 7.3625 N/mm^2 (for 1.5% cassava content) and 4.298 N/mm^2 (for 7% cassava content). The plain (i.e. non-stabilised) earth block has a compressive strength of 4.798 N/mm^2.

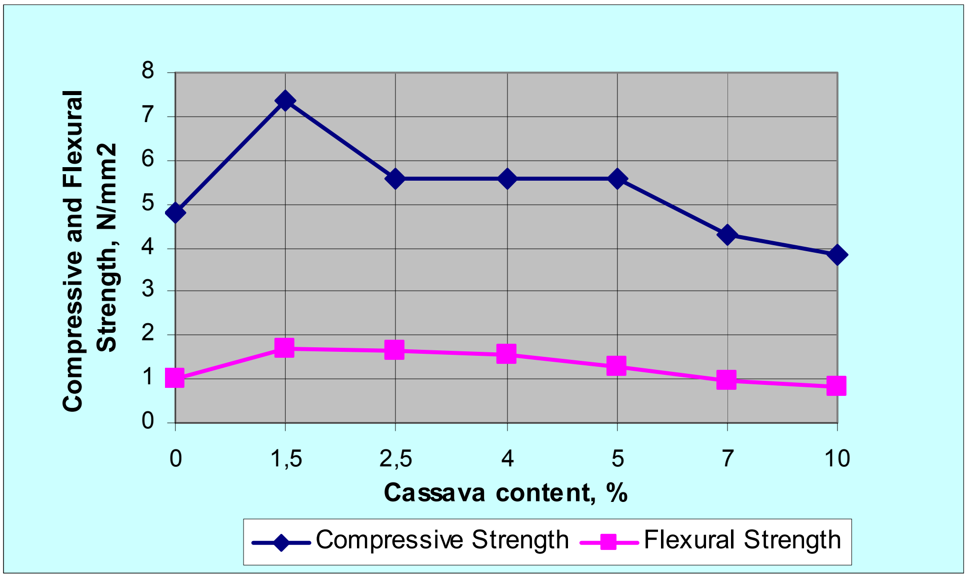


Figure 6.37 Compressive and flexural strength as a function of cassava content

The optimum compressive strength, witnessed by addition of 1.5% cassava, provides therefore a 53.5% improvement – compared with the plain earth block, table 6.20. Addition of larger amounts of cassava results in a significant drop in compressive strength. The lowest strength of 4.298 N/mm^2 attained at 7% cassava content, is nevertheless only a slight drop (i.e. 10% decrease) with respect to the plain blocks; this value, on the other hand, is still above the minimum 28-day compressive strength of 3 N/mm^2 recommended by the Kenya Specification for Stabilised Soil Blocks.

It is worth noting that in general, although the strength exhibited at 2.5%, 5% and 7% does not show significant difference from each other, it is still higher than that of the non-stabilised earth blocks, figure 6.37.

Deviation in Strength of stabilized blocks from non-stabilized ones

Table 6.20 and figure 6.38 summarises the deviation of strength values of cassava stabilized blocks from those of plain (non-reinforced) earth blocks. A negative deviation is seen only in the case of 7% cassava content; proposed causes for these deviations are found later in this section.

Table 6.20 Strength values and percentage change

Block Type	**Stabiliser Type and Content**	**Change in Strength**			
		Compressive Strength, N/mm^2	**Change in Strength, %**	**Flexural Strength, N/mm^2**	**Change in Strength, %**
CaC	**Plain Block**	4.798	**-**	0.992	**-**
	1.5% Cassava	7.362	**+53.5**	1.711	**+72.5**
	2.5% Cassava	5.593	**+16.5**	1.637	**+65.0**
	4% Cassava	5.576	**+16.2**	1.557	**+57.0**
	5% Cassava	5.565	**+16.0**	1.283	**+29.3**
	7% Cassava	4.298	-10.4	0.945	-4.7

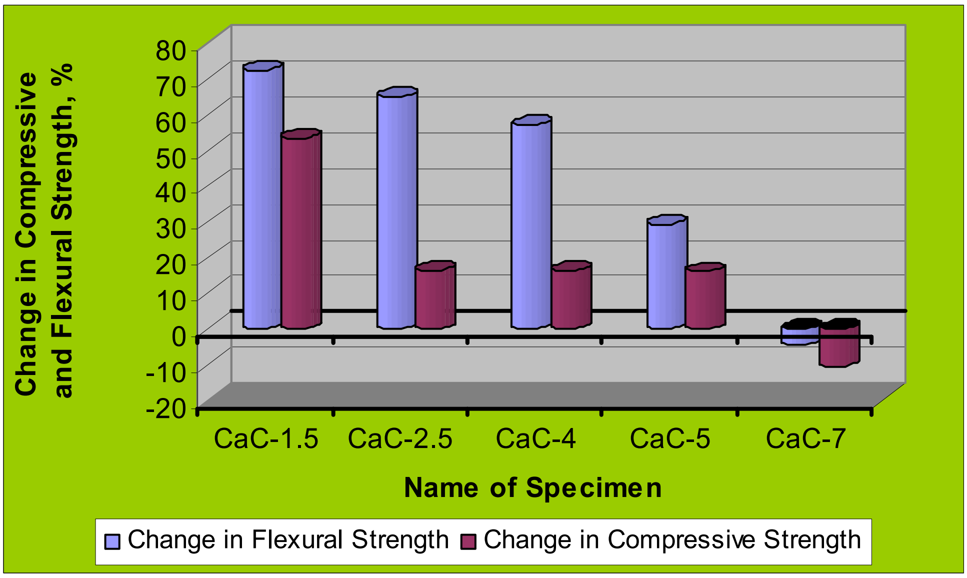


Figure 6.38 Deviation in Compressive and flexural strength from that of plain block

The trend of flexural strength values is as expected similar to that of the compressive strength. The values range between 0.945 N/mm^2 and 1.71155 N/mm^2. The optimal value of 1.71155 N/mm^2 at 1.5% cassava content suggests a 72.5% increase in flexural strength - compared to the non-reinforced blocks.

The lowest value of flexural strength of 0.945 N/mm^2 corresponding to 7% cassava content is only slightly lower than that of non-stabilised block, i.e. 0.99 N/mm^2 (4.5% drop). Possible causes in strength are contained here further below.

Ratio of Compressive to Flexural Strength

The compressive strength values are in the range of 3.4 to 4.8 times higher than flexural strength ones (see table 6. 21 and figure 6.39); this is in agreement with data established by several past researchers engaged in the study of compressed earth blocks as illustrated in previous sections. These values are also consistent with those found earlier in this work for sisal reinforced, cement stabilized and cement-sisal reinforced earth blocks, what in essence would suggest authentication of the investigations carried out here.

Table 6.21 Strength and ratio of compressive to flexural strength

S.No.	**Sample Name**	**Flexural Strength, N/mm^2**	**Compressive Strength, N/mm^2**	**Ratio of Flexural to Compressive Strength**	
				Gross	**Mean**
		Cassava Stabilised Compressed Earth Blocks			
1	**CaC-0**	0.992	4.79875	4.83745	4.196685
2	**CaC-1.5**	1.7115	7.3625	4.301782	
3	**CaC-2.5**	1.6375	5.59375	3.416031	
4	**CaC-4**	1.557333	5.576667	3.580908	
5	**CaC-5**	1.283	5.565	4.33749	
5	**CaC-7**	0.945333	4.298333	4.546897	

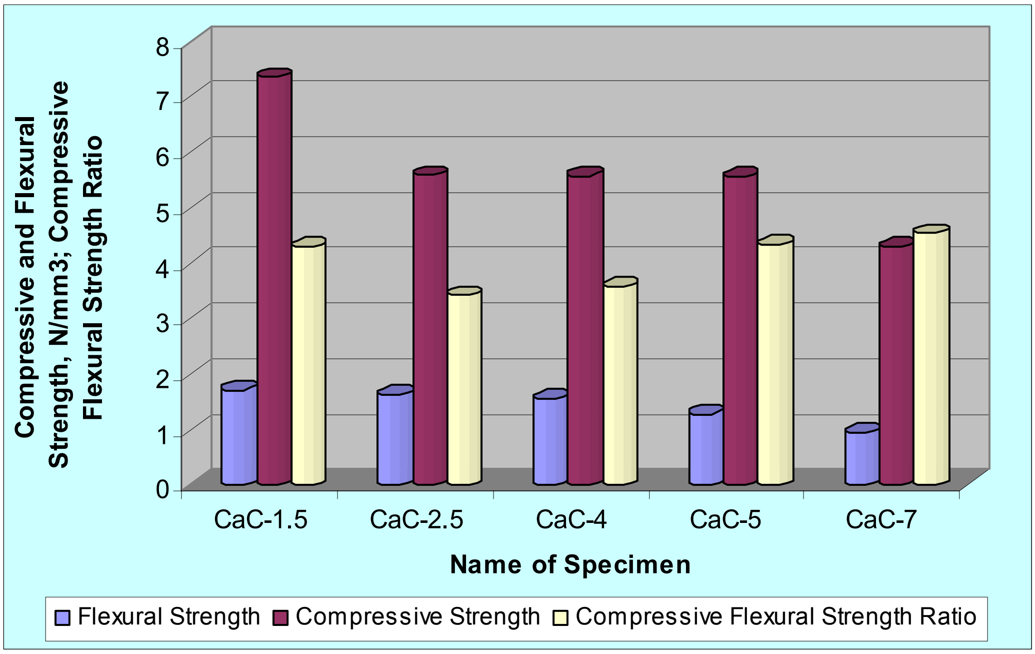


Figure 6.39 Strength and ratio of compressive to flexural strength

Possible Causes of Strength Behaviour

Although it is at this moment not very clear why addition of certain amount of cassava has a positive effect to the strength characteristics of compressed earth blocks, it is quite possible that cassava powder which is basically starch as established in section 4.1.3, could likely have developed polysaccharides molecules on contact with mixing water. The bonding of these molecules with soil in the moist state could have been responsible for improvement in compressive and flexural strength. In a fairly similar work, (Eko et. al., 2001), reinforces soils with sugarcane bagasse vegetable fibres. The sugar in the bagasse is found to have evolved to the form of polysaccharides; these molecules are established by the author to bind clay particles and increase the strength of earth blocks. The author records a maximum compressive strength of 5 N/mm2 which is still lower that optimal strength of 7.3625 N/mm^2 obtained in the present work.

Diagram 6.40 depicts the micrograph of plain earth block and that stabilised by 1.5% cassava. The cassava powder is randomly but fairly well distributed within the structure of the earth block, hence the positive bonding effect. Addition of large amounts of cassava (above 7% by dry weight) clearly inhibits growth in strength; these phenomena could be as a result of reduced contact between clay particles; it would also mean that bonding between polysaccharide molecules is weaker than that between polysaccharides and clay particles.

It can therefore be stated that based on both compressive and flexural strength parameters obtained in the current work, the use of defined amounts of cassava powder as a stabilizer for compressed earth blocks has been established to be viable.

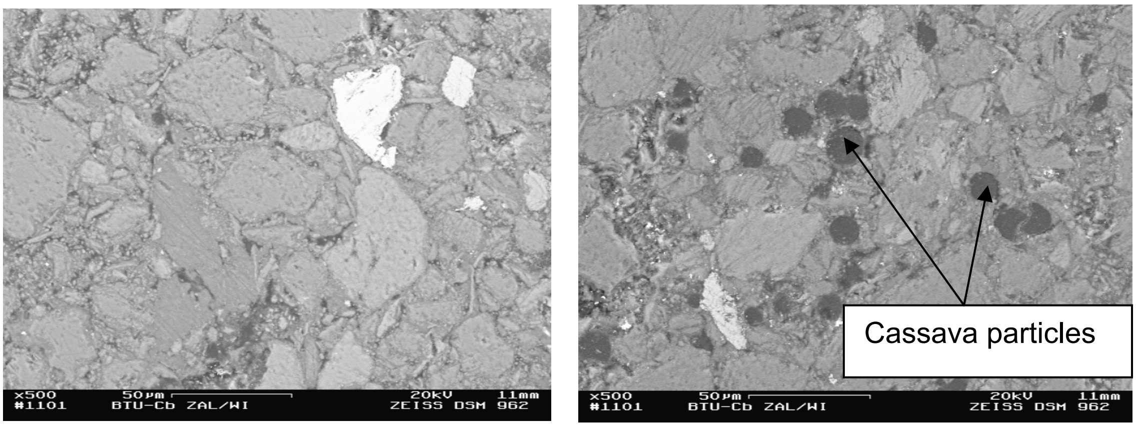


Figure 6.40 Micrograph of a non-stabilised and 1.5% cassava stabilized block

6.4.2 Theoretical and Practical Block Density

Block density is another relevant parameter for earth brick makers and researchers. The density has direct effect on strength and therefore durability of earth bricks; indeed high densities are associated with lower porosities and consequently better strength as observed from evaluations carried out in section 6.1.

Determination of practical dry block density as well as theoretical density was executed in the same manner as described earlier in section 6.1.2. Results of this investigation have been plotted in figure 6.41; details of the obtained data are also illustrated in the table in appendix A and N.

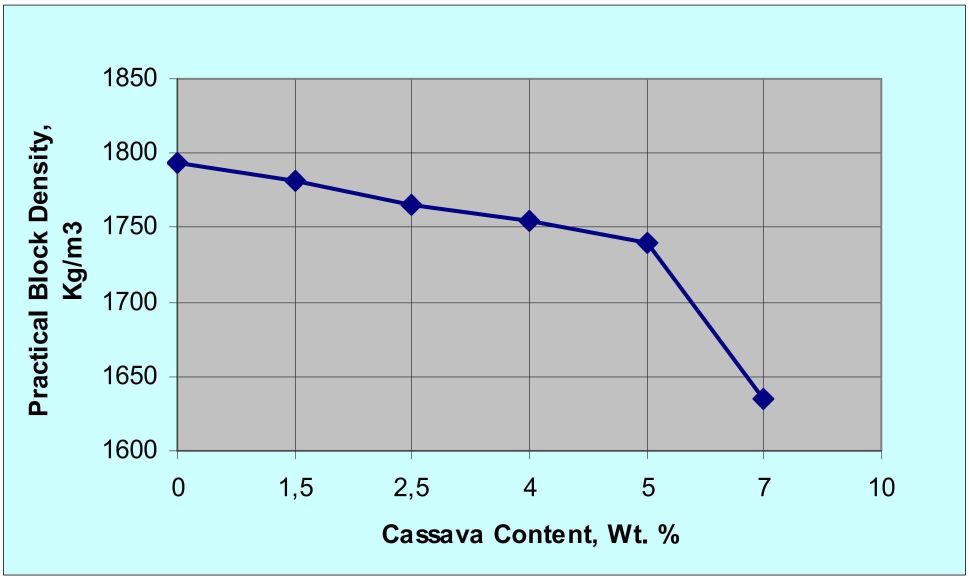


Figure 6.41 Dry block density as a function of cassava content

Values of practical dry block density lie between 1781.25 kg/m^3 for 1.5% cassava stabilised CEB and 1635.31 kg/m^3 for 7% stabilised ones. This represents an 8% drop in density which delivers on the other hand a drop of 42% in compressive strength; an indication of the great influence density has on strength.

Practical block density trends exhibit thus similar tendency as compressive and flexural strength characteristics; indeed, compressive strength is seen here to be a function of dry block density just as was the case with sisal reinforced earth blocks discussed in section 6.1.2.

Variation of Density against Strength

For all the tested samples, the relative deviation in practical density (with respect to the density of the non-reinforced earth compressed block) against variation of cassava powder levels is presented in table 6.22 and outlined in figure 6.42a. This change relative to both compressive and flexural strength is depicted in figure 6.42b. The negative deviation is witnessed for all the 5 block types. The idea that blocks stabilized by cassava powder (1.5%, 2.5%, 4% and 5%) have higher strength than those of non-stabilized block although they are in possession of lower density is unconventional. It would imply that they exist other parameters whose influence upon block strength would be more paramount. Likely, in the case of cassava stabilized blocks, unlike the sisal reinforced and cement stabilized ones, binding forces play greater role.

Table 6.22 Change in density in comparison to plain earth block

Block Type	Stabiliser Type and Content	Theoretical Density, kg/m^3	Practical Density, kg/m^3	Change in Practical Density*, %
CaC	**Plain Block**	2663.7	1792.97	-
	1.5% Cassava	2644	1781.25	-0.65
	2.5% Cassava	2619.5	1765.62	-1.5
	4% Cassava	2595.2	1753.90	-2.2
	5% Cassava	2583.4	1740.23	-3.0
	7.0% Cassava	2544.1	1635.31	-8.8

Negative (-) implies % drop in density in comparison to the non-reinforced earth block.

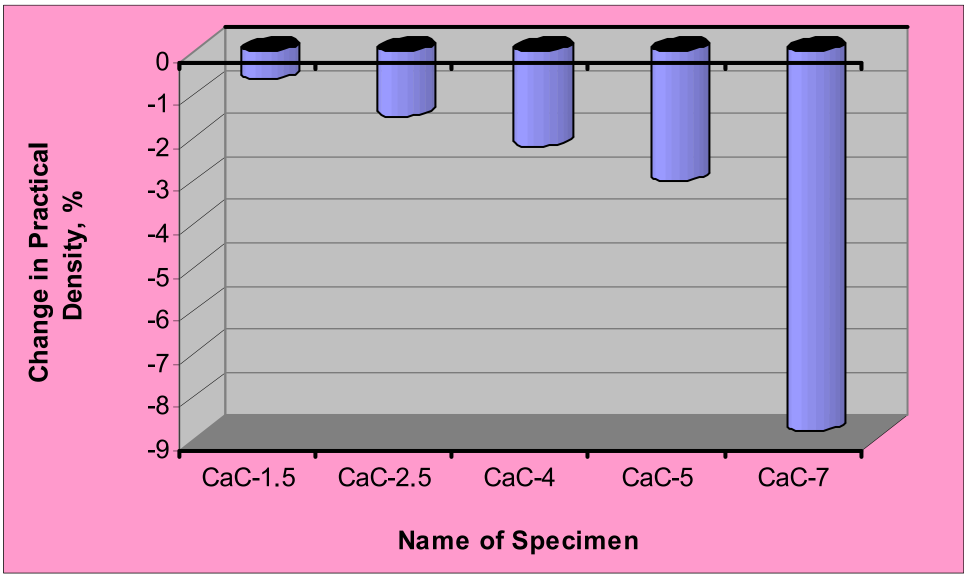


Figure 6.42a Change in practical dry block density

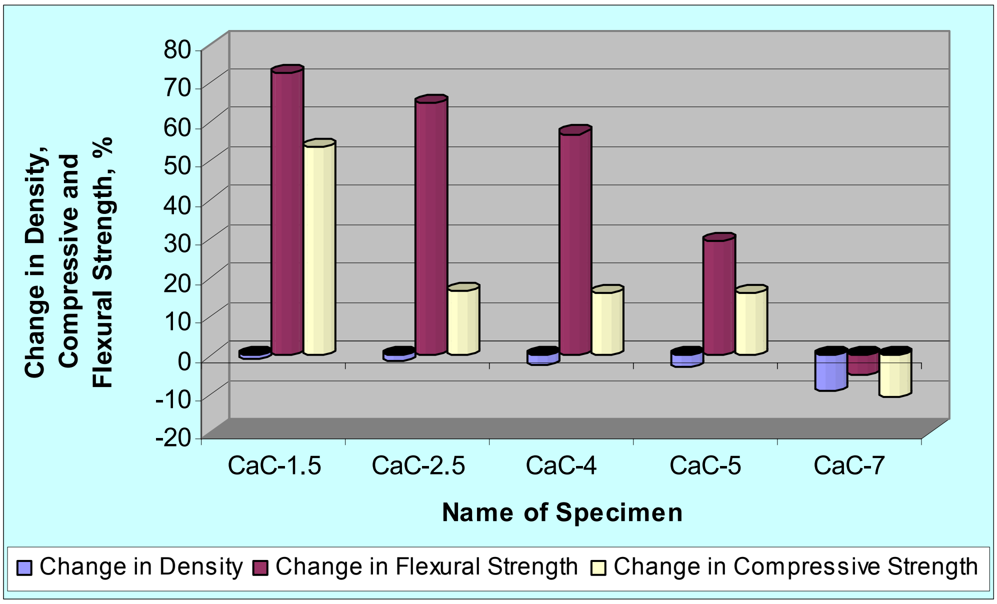


Figure 6.42b Change in strength as a reflection of change in density

Addition of more cassava powder has the effect of reducing the density. This would be expected, in that cassava powder which replaces soil in the mix has a lower density as soil. Reduction in density should also explain the fall in strength with increase in cassava levels.

Theoretical Density

The theoretical density ρ_t of cassava stabilised soil blocks, determined on the premises that the sample block is devoid of pores, provides a true reflection of the density phenomena. Figure 6.43a depicts the theoretical density of these blocks with change in cassava content. A near linear relationship, shown by equation 6.13, between density and cassava content has been established, the equation has $R^2 = 0.9845$ which implies a strong linear correlation between the two variables.

$$\rho_t = -17.123 \text{ Cassava Content} + 2665.4 \tag{6.13}$$

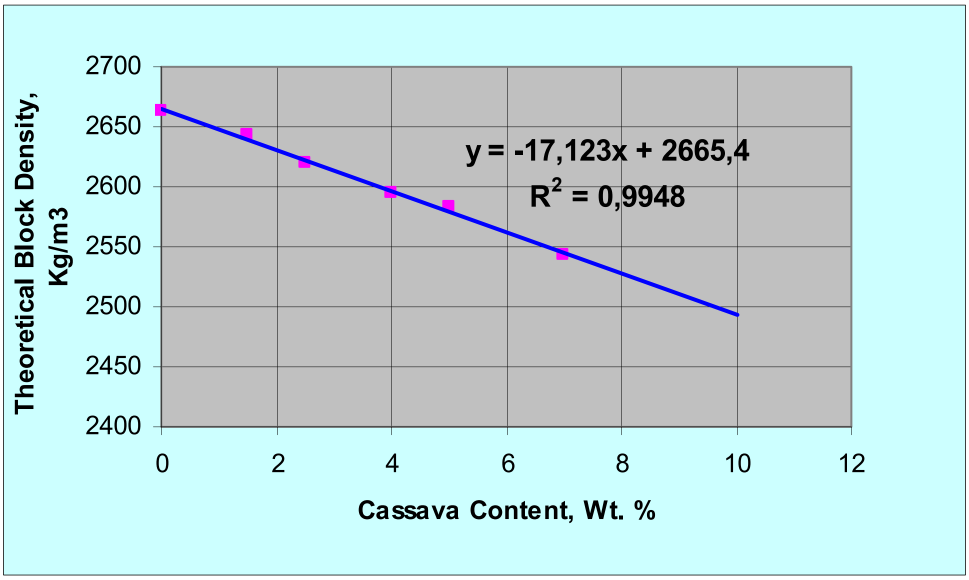


Figure 6.43a True or theoretical block density as a function of cassava content

Deviation of Theoretical Density from Practical Density

The densities, practical and theoretical, deviate from one another and as is to be expected the theoretical densities are higher than the corresponding practical ones, table 6.23 and figure 6.43b.

Table 6.23 Difference in true and practical block density

S.No.	Cassava Content, %	True Density, kg/m^3	Practical Density, kg/m^3	Change in Density, kg/m^3	Change in Density, %
1	0.0	2663.7	1792.97	870.73	48.56
2	1.5	2644	1781.25	862.75	48.44
3	2.5	2619.5	1765.62	853.88	48.36
4	4.0	2595.2	1753.90	841.30	47.97
5	5.0	2583.4	1740.23	843.17	48.45
6	7.0	2544.1	1635.31	908.79	55.57
7	10.0	2508.5	1649.90	858.60	52.04

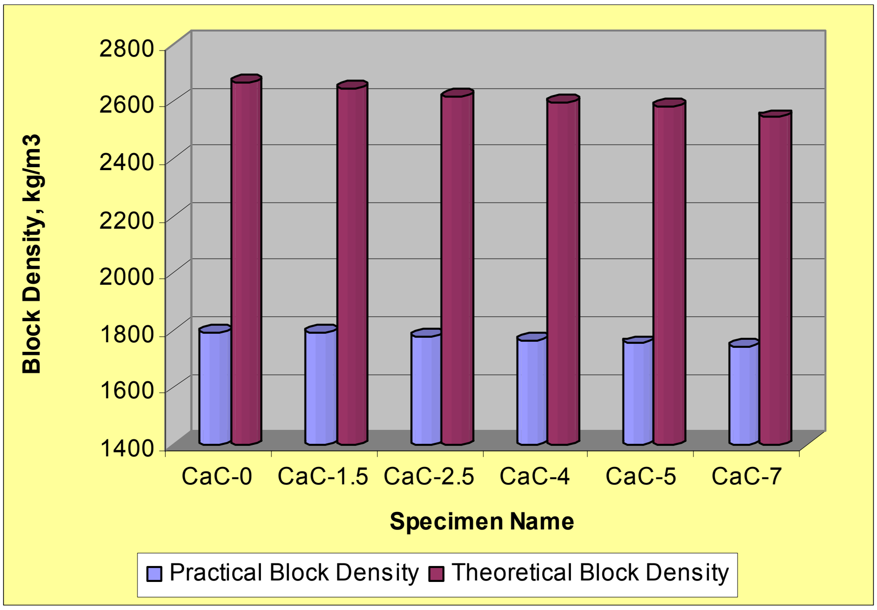


Figure 6.43b Comparison between theoretical and practical density

In all the cases, the deviation of 841.30 kg/m^3 to 908.79 kg/m^3 is recorded; a mean of 862.745---and standard deviation of 22.81--- have been computed. The deviations recalculated in to percentage would mean that the theoretical density is higher than the respective practical density by 47.97% to 55.57%, with a standard deviation of 2.85

Literature does not document any related past results for cassava stabilised earth bricks, it is hence not possible to make comparison in that context. It is instructive however, that the theoretical density value was found in the previous cases (sisal reinforced blocks – section 6.1.2.2 and cement stabilised blocks – section 6.2.2) to be 1.5 times greater than the corresponding value. It is therefore logical to conclude as follows:

- That theoretical density is in general about one and a half (1.5) times greater than the corresponding practical density, equation 6.14.

$$\text{Practical Density} \times 1.5 = \text{Theoretical Density} \qquad (6.14)$$

- The correlation between theoretical density and stabilising agent is linear in nature.

The trends exhibited by porosity of the cassava stabilized blocks with respect to compressive strength, block density and cassava content, illustrated in appendix O, P and Q, confirm the tendencies discussed in the above section. Higher porosities translate in to lower densities and hence inhibit growth of compressive and flexural strength. This observation is similar to the one made in the discussion over sisal reinforced blocks in section 6.1.2.

Comparison of Sisal to Cement stabilised Earth Blocks

The data in table 6.24, table 6.25, figure 6.44a, figure 6.44b and figure 6.44c show comparison in strength for sisal reinforced (refer to section 6.1), cement stabilized (see section 6.2), cement-sisal (see section 6.3) and cassava stabilized reinforced compressed earth blocks.

Table 6.24 Strength comparison for all block types

Stabilizer Type and CEB Characteristic	**Stabilizer Amount and Value of Characteristic**					
Sisal reinforced compressed Earth Blocks						
Sisal Content, %	**0**	**0.25**	**0.5**	**0.75**		
Compressive Strength, N/mm^2	4.798	4.18	6.08	9.14		
Flexural Strength, N/mm^2	0.992	0.75	1.035	1.63		
Cement Stabilized Compressed Earth Blocks						
Cement Content, %	**0**	**5**	**9**	**12**		
Compressive Strength, N/mm^2	4.798	3.50	5.96	8.24		
Flexural Strength, N/mm^2	0.992	0.75	1.56	2.0		
Cement-Sisal Compressed Earth Blocks						
Cement-Sisal Content, %	**0**	**5-0.5**	**9-0.5**	**12-0.5**		
Compressive Strength, N/mm^2	4.798	2.843	5.16	6.75		
Flexural Strength, N/mm^2	0.992	0.583	0.934	1.36		
Cassava Stabilized Compressed Earth Blocks						
Cassava Content, %	**0**	**1.5**	**2.5**	**4**	**5**	**7**
Compressive Strength, N/mm^2	4.798	7.362	5.593	5.576	5.565	4.298
Flexural Strength, N/mm^2	0.992	1.711	1.637	1.557	1.283	0.945

Table 6.25 Summary of the ideal strength values

Block Type	**Stabiliser Type and optimum Content**	**Improvement in Strength for Ideal mix proportions**			
		Compressive Strength, N/mm^2	**Percentage Improvement in Strength**	**Flexural Strength, N/mm^2**	**Percentage Improvement in Strength**
SC	**0.75% Sisal**	9.14	**+90.5**	1.63	**+64.3**
CeC	**12% Cement**	8.24	**+71.7**	2.00	**+101**
CSC	**0.5% Sisal and 12% Cement**	6.75	**+40.7**	1.36	**+37.1**
CaC	**1.5% Cassava**	7.3625	**+53.5**	1.71155	**+72.5**

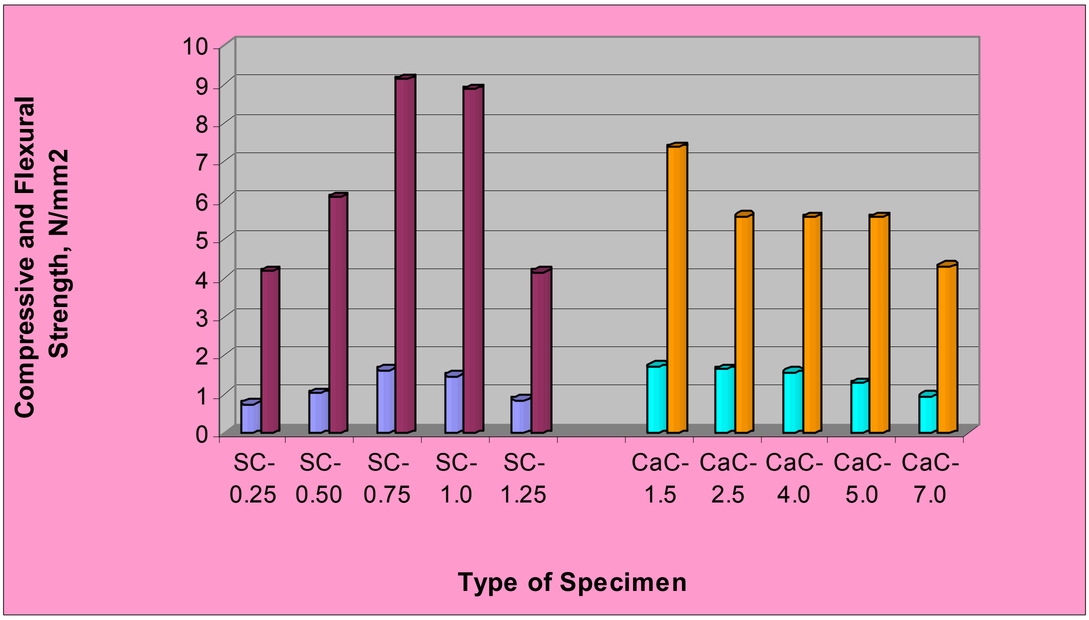


Figure 6.44a Strength comparison for sisal reinforced and cassava stabilised CEB

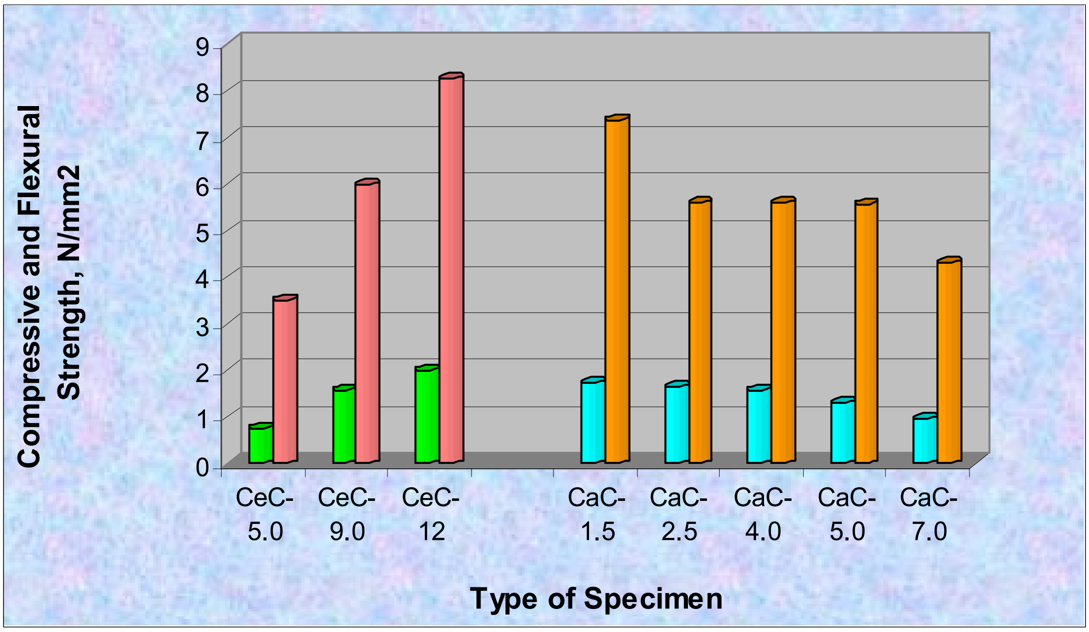


Figure 6.44b Strength comparison for cement and cassava stabilised CEB

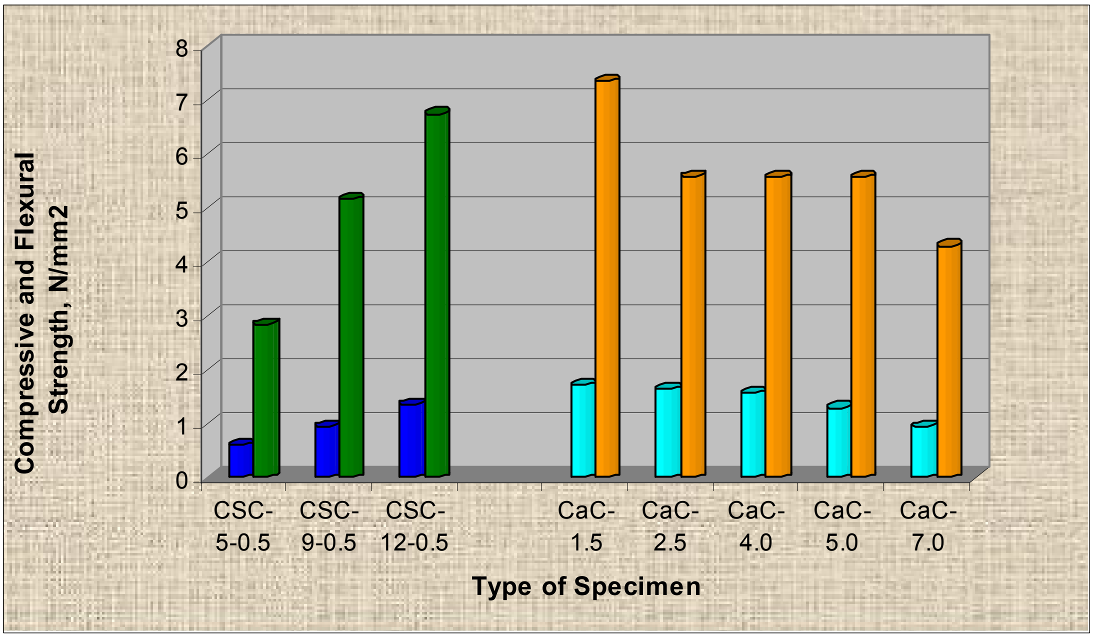


Figure 6.44c Strength comparison in cement-sisal and cassava stabilised CEB

Comparison between the sisal reinforced blocks, cement stabilised ones and cement-sisal reinforced blocks has been carried out in section 6.3.2. It has already been established that the ideal sisal reinforced blocks (0.75% sisal content – with 90.5% improvement), from the point of view of strength, appear to be superior to the cement stabilised ones (12% cement content – with a 71.7% improvement) as well as to ideal cement-sisal reinforced blocks (0.5% sisal and 12%cement - with a 40.7% improvement).

It can also be said, from the results of this section, that the ideal cassava stabilised blocks (1.5% cassava – with a 53.5% improvement in strength) are inferior to both sisal reinforced and cement stabilised. They are however, superior to the cement-sisal reinforced ones.

On the other hand, it would be important to note that the compressive strength value of 7.3625 N/mm^2 (ideal cassava stabilised blocks) is comparable with the strength of 0.75% sisal reinforced blocks (9.14 N/mm^2) and that of 12% cement stabilized blocks (8.24 N/mm^2).

Strength exhibited at 2.5% (5.593 N/mm^2), 5% (5.576 N/mm^2) and 4% (5.565 N/mm^2) cassava stabilization is slightly higher than the 9% cement stabilized blocks and comparable to the strength of 0.5% sisal reinforced blocks. Besides, these three block types have strength higher than the recommended minimum as discussed in earlier sections. Based on these results it may be concluded that the 1.5%, 2.5%, 4% and 5% cassava stabilized earth blocks can be recommended to be used for housing wall construction.

6.5 Linear Shrinkage and Compression Ratio

Linear Shrinkage

Shrinking of earth blocks when drying out is disadvantages, if they are to be used as building materials. According to (Minke, 2000), shrinkage depends on the type and quantity of clay; where by, montmorillonite clay has a much more effect on shrinkage than kaolinite and illite. This phenomena is related to the structure of these minerals, refer to section 3.1.3. In general, soils with relatively high amounts of sand fraction, experience less shrinkage or have shrinkage levels which are within recommended values. The linear shrinkage measurement on the blocks investigated in this work are presented in table 6.26 and outlined in figure 6.45a.

Table 6.26 Linear Shrinkage

S.No	Type of CEB	Original Length, mm	Final Length, mm	Linear Shrinkage, %
1	**Plain**	230	225	2.17%
2	**SC**	230	227	1.3%
3	**CeC**	230	229	0.434%
4	**CSC**	230	229	0.434%
5	**CaC**	230	226	1.74%

It is observed that addition of sisal, cement-sisal or cassava powder to soils has the effect of reducing shrinkage. Shrinkage values for cement and cement-sisal stabilised soils are the lowest (0.434%), while the blocks reinforced with sisal and those stabilised by cassava powder experience almost the same amount of shrinkage (1.3% and 1.74% respectively).

It is likely that the fibres ability to hold or bind soil particles more closely would deter the possibility of block contraction hence the lower levels of shrinkage observed. Cement, on the hand and as discussed in section 6.2 and 6.3, binds, through the products of hydration the clay particles together, consequently reducing the effects of shrinkage. The speculation earlier in this section that moist cassava powder is likely to have developed polysaccharides molecules that hold on clay particles, appears to supported when one observes that the cassava stabilized blocks have lower shrinkage values than plain (non-reinforced) blocks.

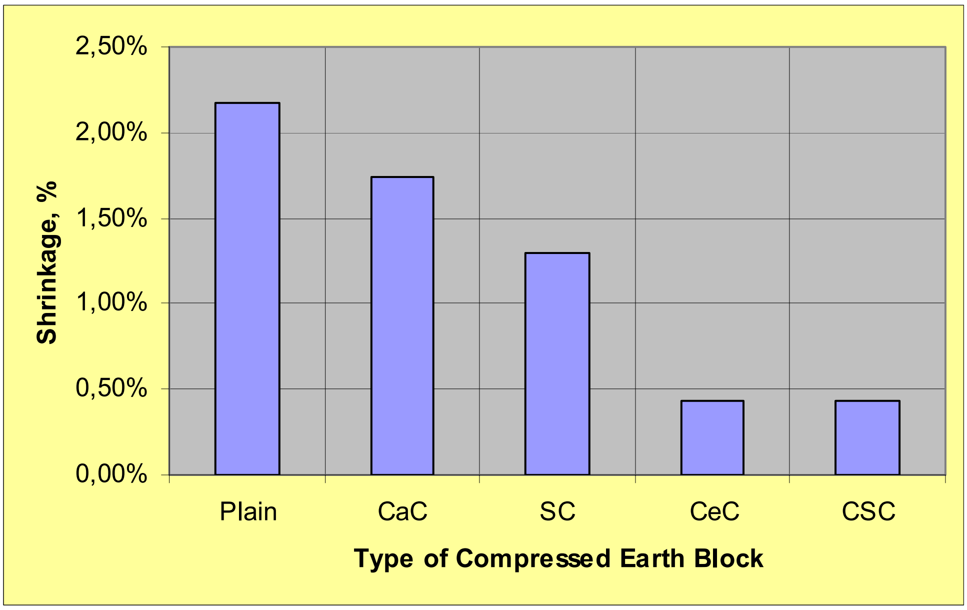


Figure 6.45a Shrinkage comparison amongst the earth blocks

According to (Houben, H., et al., 1994), montmorillonite soils experience shrinkage, with values in the range of 12 to 23% (soils used here were found to be of montmorillonite in nature, see section 4.1.1.1). On the other hand, (Walker, 2004) reports a maximum value of 3% for soils without cement and 1% for those stabilised with cement. (Kenya Bureau of Standards, Kenya Specification for Stabilised Soil Blocks, UNCHS, 1989) states that shrinkage cracks should not be more than 3 mm wide; observations of the blocks in this study revealed no visible cracks. It can be deduced from the aforesaid that the blocks investigated here are, with respect to shrinkage, suitable to be used as building materials.

Comparison of Compression Ratio

This is the ratio between the depth of the press mould before compression (90mm) and the depth at the end of compression (corresponds to height of the compressed earth block). Compression ratios for the blocks investigated are presented in table 6.27 and figure 6.45b.

Table 6.27 Compression Ratio

S.No	Type of CEB	Original Height	Final Height	Compression Ratio
1	**Non-reinforced**	90	45	2
2	**SC**	90	40	2.25
3	**CeC**	90	43	2.09
4	**CSC**	90	42	2.14
5	**CaC**	90	43	2.09

The height of the compressed block would differ from one composition to another. It will also depend among others, on the compression energy applied. It was useful to determine this parameter, for this ratio would inform us about the consistency of the compression force or input elements. For sisal reinforced compressed earth blocks, the compression ratio was established to be 2.09. The compression ratio of cement-sisal reinforced earth blocks was found to be very close to that of cement stabilised compressed earth blocks. The value of 2.14 was established in the present work.

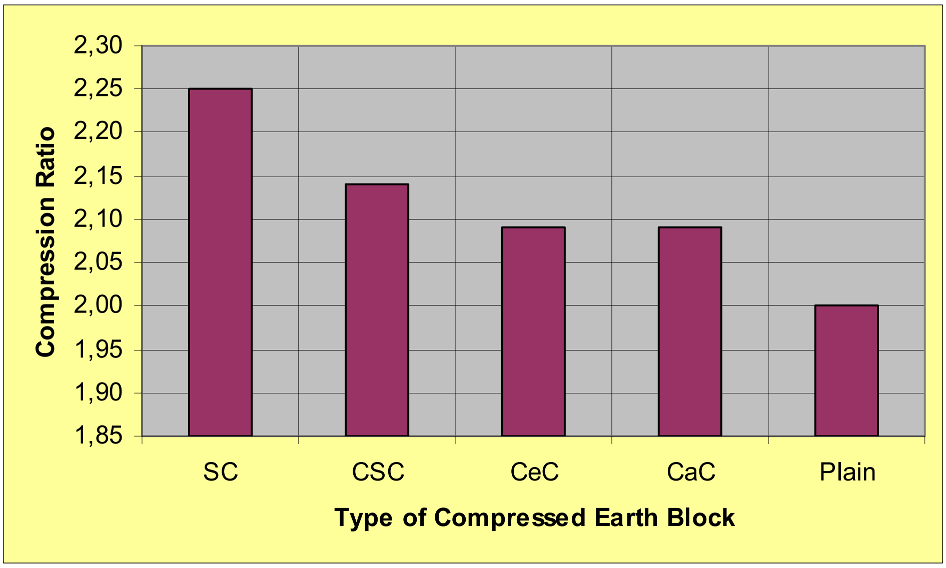


Figure 6.45b Compression ratio comparison amongst the earth blocks

6.6 Determination of Water Vapour Transmission Properties

Damage caused by uncontrolled moisture accumulation in building enclosures greatly concerns the construction sector. Moisture transfer in buildings affects energy efficiency, it also influences building's durability and indoor air quality hence health and safety of the occupants. Moisture diffusivity in building materials is determined through water vapour permeability measurements; results of these measurements help to understand the concept of moisture transfer and therefore appropriate design of houses. The aim of this section is to investigate the water vapour permeability of compressed earth blocks that were manufactured as per section 5.2.

Moisture flow through the wall of a building material, also referred to as water vapour permeability, is evaluated through the value of the so called "water vapour equivalent air layer thickness" (also known as the s_d-value). A classification of the clay or earth blocks as "diffusion-open", "diffusion-inhibitive" or "diffusion-impermeable" is only possible when this s_d-value is known. The water vapour equivalent air layer thickness for the various earth blocks mentioned earlier in this work was therefore determined. According to DIN 4108-3 (07-2001), the s_d-value describes or is defined as the thickness of a stile air layer, which has the same resistance to water vapour diffusion as the building component/material layer in consideration. It determines, in other words, the resistance against water vapour diffusion and is computed with the help of equation 6.5.1.

$$s_d = \mu * d \qquad (6.6.1)$$

Where:
μ = water vapour diffusion flow resistance coefficient
d = Thickness of the earth block sample, in m

The water vapour diffusion flow resistance coefficient (μ) is the factor by which the water vapour diffusion resistance of the examined material is higher than that of a stile air layer having the same thickness and at the same temperature.

According to DIN 4108-3 (07-2001), the limits of building materials can be, with respect to the s_d-value, classified as follows:

diffusion open layer:	$s_d \leq 0.5$ m
diffusion inhibitive:	$0.5 \text{ m} < s_d < 1500$ m
diffusion impermeable:	$s_d \geq 1500$ m

Experimental

Specimens tested for water vapour permeability measurements are shown in table 6.13; the specimen reference names have been explained in section 5.2. Circular samples of 71 mm radius were drilled out from the full earth blocks and reduced to thickness of 6 mm by cutting through using a diamond coated rotary power saw described in section 4.2.3. The specimens are shown in figure 6.46. Overall, 3 specimens of each mixture were made in this manner, as a result a total of 57 samples were examined.

Table 6.28 Mix compositions of tested specimens

Specimen Reference					
SC	SC-0	SC-0.25	SC-0.50	SC-0.75	SC-1-0
CaC	CaC-0	CaC-1.5	CaC-2.5	CaC-5.0	CaC-7.0
CeC	CeC-0	CeC-5	CeC-9	CeC-12	-
C-SC	C-SC-0	C-SC-0.5-5	C-SC-0.5-9	C-SC-0.5-12	-

Figure 6.46 Original full blocks and drilled out earth sample

After the samples of earth block test materials were prepared as mentioned above, shown in the right side picture in figure 6.46, they were sealed into the mouths of impermeable "cups" containing a vapour pressure regulator; the vapour pressure regulator used in the present investigations was Calcium Chloride ($CaCl_2$). The impermeable cups made of pure aluminium with a free testing zone of area A = 0.005 m^2 are shown in figure 6.47. Use of Calcium Chloride as vapour pressure regulator is recommended by (McLean et al., 1990)

Figure 6.47 Empty cup and one containing vapour pressure regulator

The sealing of the samples in the mouth of the cup was done by use of wax. By pouring wax at the edge of the cup, after the sample had been mounted on the cup, it was made sure that the samples were sealed water vapour tight. An absorption space was as a result created beneath the cylindrical sample in the cup; figure 6.48 illustrates this.

Figure 6.48 Prepared samples (left) and cups with sealed test specimen

The sealed cups were weighed on analytical balance and then positioned in an environmental chamber at a constant temperature of 23 ± 1 °C, relative humidity of about 75%, and an air flow of approximately 0.02 m/s to 0.3 m/s.

Beneath the sealed specimen in the cup, temperature was held at 23°C while relative humidity was 0 + 1%. With this arrangement (difference in relative humidity), a constant vapour pressure difference was maintained across the material; consequently a constant vapour flux g (equation 6.6.2) was generated leading to steady change in the weight of the cup.

Figure 6.49a Sample weighing and specimens in the environmental chamber

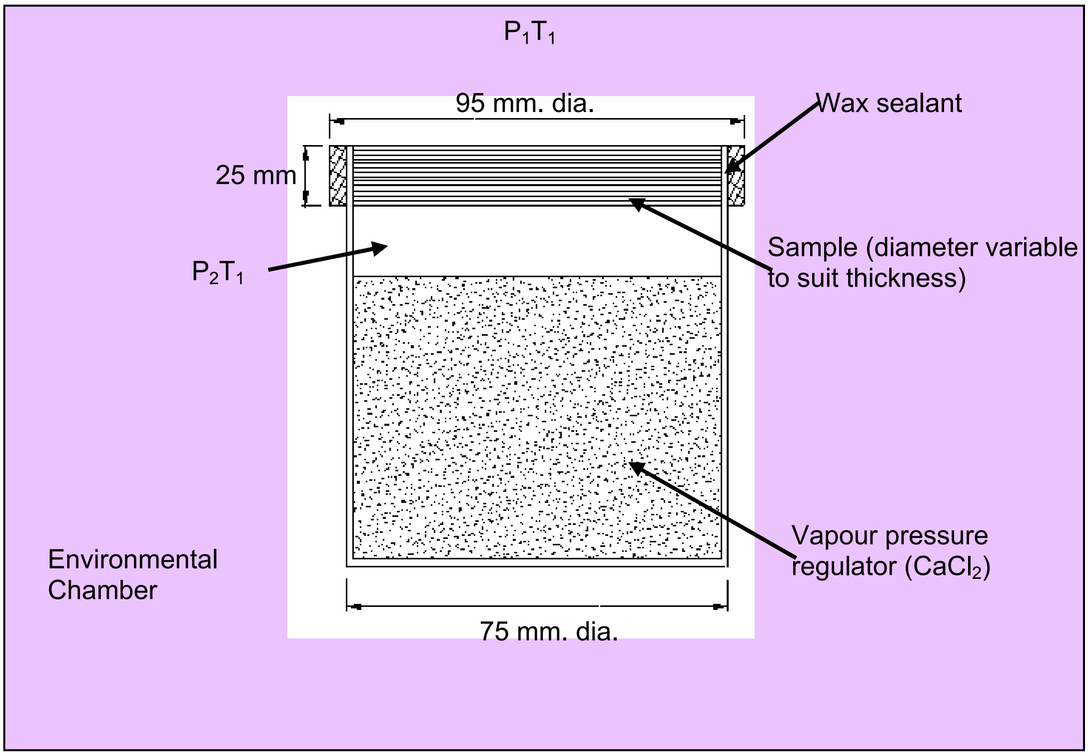


Figure 6.49b Overall concept of the cup in an environmental chamber

Subsequently, the cups were weighed, figure 6.49a, at regular intervals of about 48 hours in order to determine the weight gain sustained by the cups. The results of change in weight with time for 3 samples of 0.75% sisal reinforced compressed earth blocks are illustrated in table 6.29 and plotted on graphs in figures 6.50 - sample I, 6.51 - sample II and 6.52 - sample III.

The graphs show a fairly steady change in weight; the change with time delivers an almost linear relationship with an R^2 of 0.97-0.98. Similar results are obtained for all samples of other mix compositions presented earlier in table 6.28; these results are tabulated in appendix R, S, T and U. Computation of the s_d-values, with the help of equations 6.6.2, 6.6.3, 6.6.4 and 6.6.5, has then been made based on this results. The values of the obtained s_d-values for all the tested specimens are shown in table 6.30.

Table 6.29 Weights of the diffusion cup for blocks reinforced with 0.75% sisal

		Specimen Reference and Weight. g			**Mean Weight. g**
S.No.	**Date**	**SC-0.75-1**	**SC-0.75-2**	**SC-0.75-3**	
1	05.01.06	344.067	346.803	343.836	344.902
2	07.01.06	347.566	350.892	347.543	348.667
3	09.01.06	350.701	354.492	350.872	352.0217
4	11.01.06	353.140	357.646	353.460	354.7487
5	13.01.06	355.768	360.568	356.259	357.5317
6	15.01.06	358.239	363.369	358.807	360.1383
7	17.01.06	360.456	365.712	361.228	362.4653
8	19.01.06	362.675	368.260	363.596	364.8437
9	21.01.06	364.711	370.880	365.801	367.1307
10	23.01.06	366.990	373.741	368.207	369.646
11	25.01.06	369.006	375.913	370.245	371.7213
12	27.01.06	370.951	377.766	372.168	373.6283
13	29.01.06	372.606	379.255	373.801	375.2207
14	31.01.06	374.359	380.967	375.525	376.9503
15	02.02.06	375.788	382.191	376.901	378.2933
16	04.02.06	377.057	383.402	378.129	379.5293
17	06.02.06	378.381	384.824	379.494	380.8997

By consideration of only the initial and the final weight measurements from table 6.29, the following values illustrated in table 6.30 are extracted from table 6.29 and are required for computation of vapour flux g, in equation 2.

Table 6.30 Values from weight measurements of the 3 samples for SC-0.75

Sample	**Weight, g**			**Time interval between measurements**	
	m_1, g (05.01.06)	**m_2, g (06.02.06)**	**Δm_{21}, g**	**h**	**s**
I	344.067	378.381	34.314	768	2764800
II	346.803	384.824	38.021	768	2764800
III	343.836	379.494	35.658	768	2764800

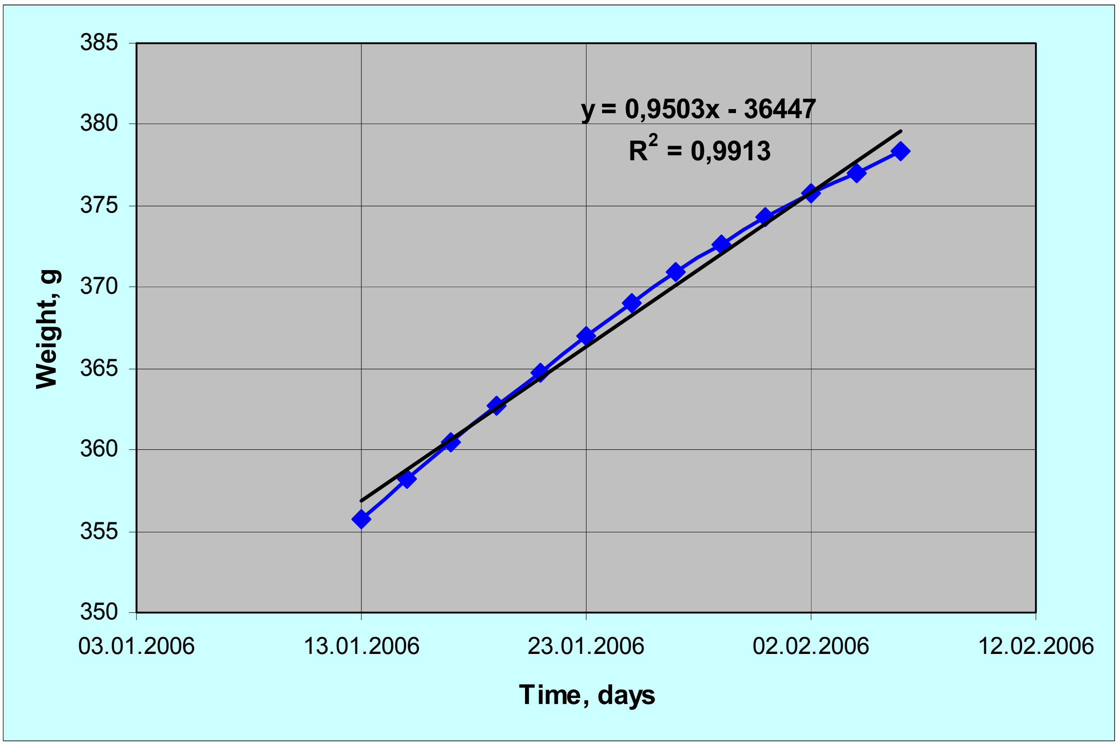


Figure 6.50 Change in weight with time for sample I

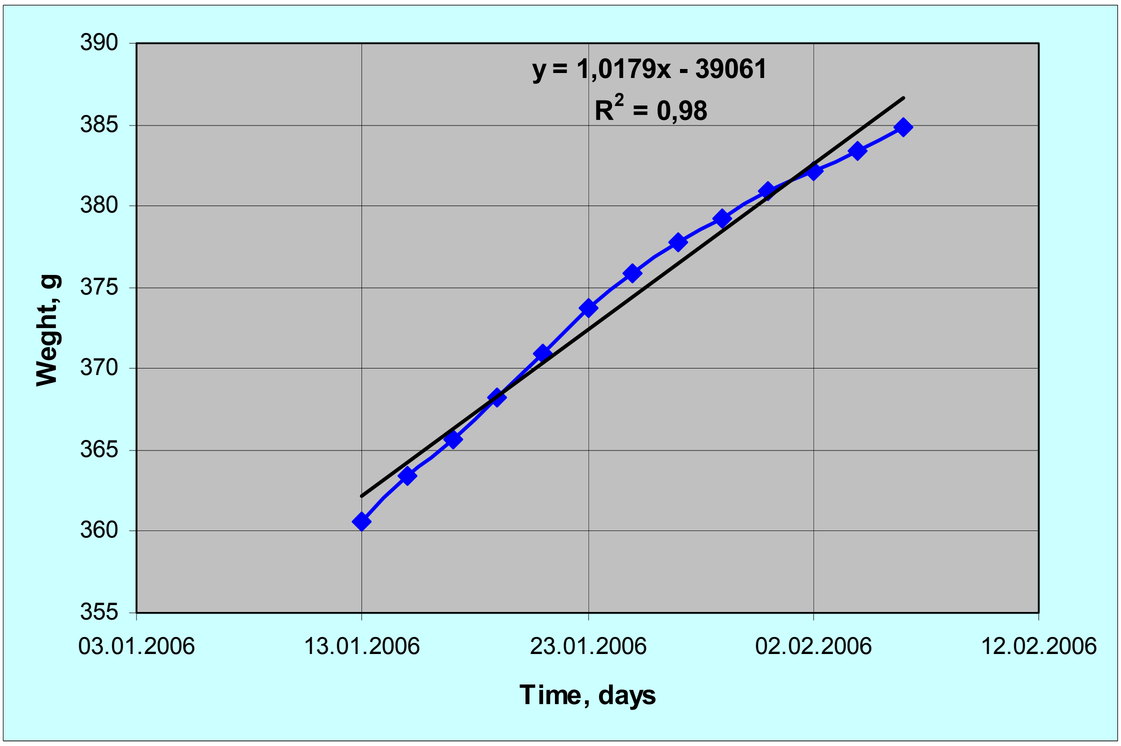


Figure 6.51 Change in weight with time for sample II

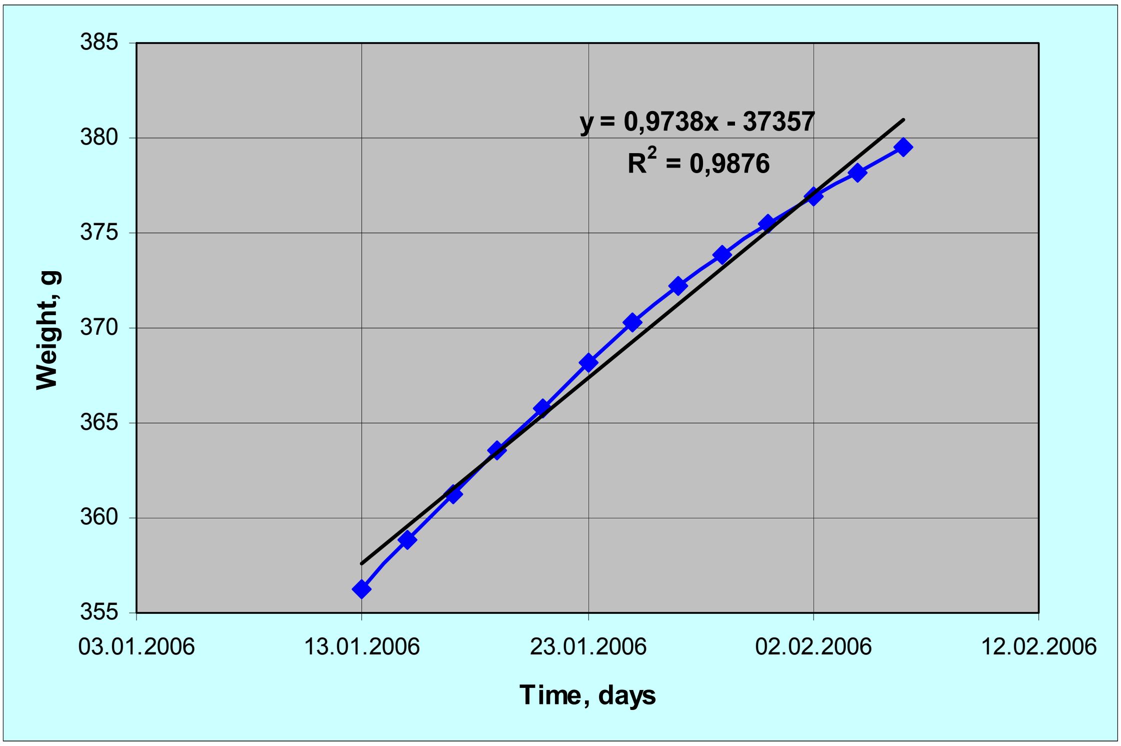


Figure 6.52 Change in weight with time for sample III

Applied Equations

As already stated earlier, computation of the s_d-value is done by use of equation 1. However, in order to determine the value of μ in equation 6.6.1; equations 6.6.2, 6.6.3, 6.6.4 and 6.6.5 are applied.

Due to the difference in partial pressure in the chamber and the absorption area of the cup as mentioned earlier, a flow of moist air will penetrate through the earth block sample. The vapour flux g of this moist stream is determined by formula 6.6.2 as recommended by (DIN EN 1931)

$$g = \frac{\Delta m_{21}}{A \cdot \Delta t} \text{ in } \frac{\text{kg}}{\text{m}^2\text{h}} \qquad (6.6.2)$$

Where by

Δm_{21} = Change in weight (initial and final weight) – tabulated in table 6.30

A = Surface area of the cylindrical earth block sample, m^2

Δt = Time interval between measurements, s

$$\Delta m_{21} = (m_2 - m_1) \tag{6.6.3}$$

m_2, m_1 = weight of the sample, kg

The value of vapour flux g is required for determination of the water vapour diffusion flow resistance coefficient µ as per equation 6.6.4

$$\mu = \frac{1}{d} \cdot (\lambda_{\text{ma}} \cdot \frac{(p_1 - p_2)}{g} - s_{\text{a}}) \tag{6.6.4}$$

Where by:

d = Sample thickness, m

g = Vapour flux, kg/(m^{2}s)

λ_{ma} = Moist stream conductivity (dependant on the air pressure and temperature) as per equation 6.6.5, kg/(msPa)

p_1, p_2 = Water vapour partial pressure on the upper side of the earth block sample, Pa

s_{a} = Thickness of air layer underneath the earth block sample in the diffusion shell, m

The moist stream conductivity is, on other hand, calculated by use of equation 6.6.5

$$\lambda_{\text{ma}} = \frac{\frac{0{,}083}{3600}}{R_{\text{D}} \cdot T} \cdot \frac{p_0}{p} \cdot (\frac{T}{273})^{1{,}81} \tag{6.6.5}$$

Where by:

R_{D} = Gas constant of the water vapour = 462 Nm/(kgK)

T = Temperature in the chamber, K

p = Air pressure in the chamber, hPa,

p_0 = Atmospheric pressure = 1013.25 hPa

The value obtained in equation 6.6.5 is replaced in to equation 6.6.4 to obtain μ. Finally, the value of μ is substituted in to equation 6.6.1 and the s_d-value of the compressed earth blocks is determined. Results are presented in table 6.31.

Table 6.31 Results of s_d-values for all specimens

S.No	**Specimen Reference and s_d-value**					
1	**SC**	**SC-0**	**SC-0.25**	**SC-0.50**	**SC-0.75**	**SC-1-0**
	s_d-value, m	0.0790	0.1103	0.0949	0.1098	0.1002
2	**CaC**	**CaC-0**	**CaC-1.5**	**CaC-2.5**	**CaC-5.0**	**CaC-7.0**
	s_d-value, m	0.0790	0.0979	0.1041	0.1038	0.1012
3	**CeC**	**CeC-0**	**CeC-5**	**CeC-9**	**CeC-12**	**-**
	s_d-value, m	0.0790	-	0.1170	0.1258	-
4	**C-SC**	**C-SC-0**	**C-SC-0.5-5**	**C-SC-0.5-9**	**C-SC-0.5-12**	**-**
	s_d-value, m	0.0790	0.1250	0.1247	0.1190	-

Observation of table 6.31, informs that the s_d-value for compressed earth blocks, whether reinforced or not, is basically the same, and lies between 0.079 – 0.1258 m. These results show that all the specimens tested can be classified to belong to "diffusion open layer" category since all the values lie in the range $s_d \leq 0.5$ m (DIN 4108-3 (07-2001)). In practical understanding, it can be interpreted that earthen building materials have thermal capacities and water vapour transmission properties superior to those of counterpart materials e.g. concrete and fired bricks and should therefore be preferred for house construction since they provide improved energy efficiency and indoor air quality.

6.7 Development of Simple Field Testing Method for Earth Blocks

One of the objectives of the current work, as earlier indicated in section 2.2, was to develop a simple method by which strength of earth blocks could be determined in the absence of laboratory facilities in the rural areas of Kenya. This has been accomplished by determining a conversion function between standard laboratory tests and a much simpler testing method i.e. total dead weight test. The overall procedure is described by the scheme in figure 6.53. Determination of compressive strength of sisal reinforced earth blocks catalogued and discussed in section 6.1, is only feasible where laboratory equipment is available.

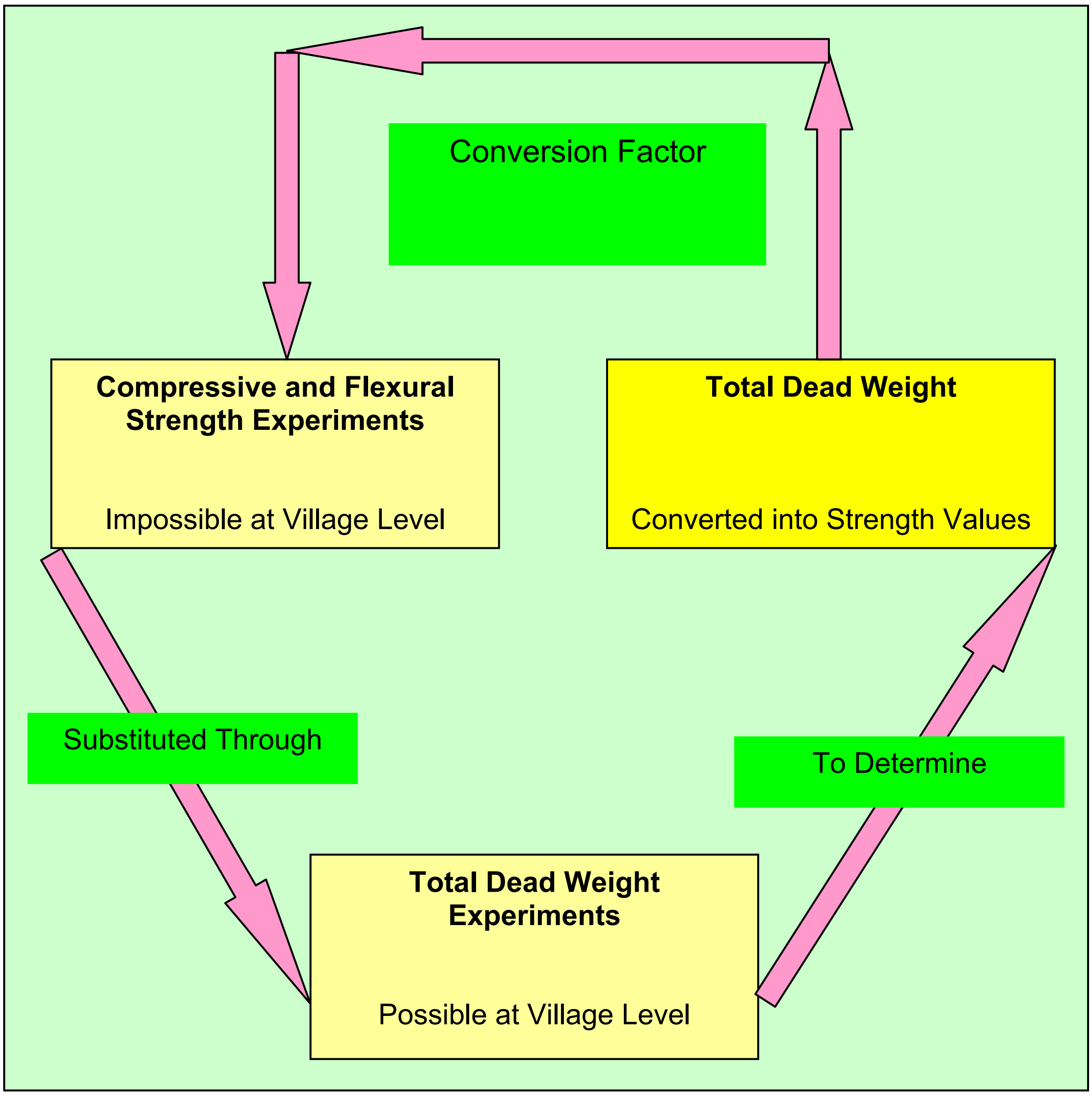


Figure 6.53 Conversion factor determination process

In the proposed procedure, compression strength experiments are substituted through the so called “total dead weight experiments”, which can be held in the absence of the normally expensive laboratory equipment. Results of the loading experiments are then correlated to compression strength ones through a computed conversion factor.

Total dead weight experiments are done by subjecting an earth block sample to a load until the sample raptures as shown in figures 6.54 – 6.55. A bucket is attached to the soil block sample by a string tied on the middle of the block. Sand is then poured into the bucket; this is done in batches of about 0.5 kg at intervals of approximately 1 minute up to the time the block sample collapses. The weight of the bucket and sand therein is taken and recorded. The process is repeated for all the 6 sisal – soil mix proportions illustrated in section 6.1.

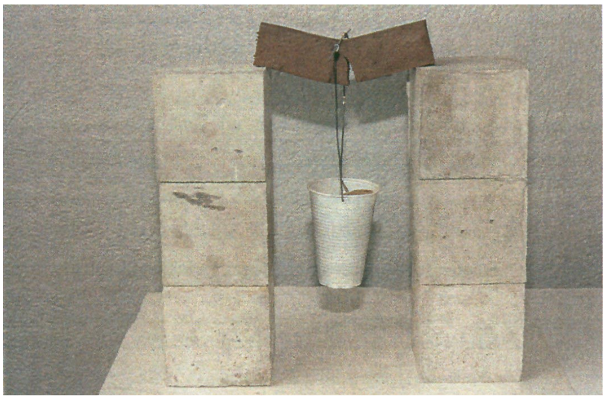


Figure 6.54 Preliminary total dead weight experiments

Figure 6.55 total dead weight experiments

For each sisal-soil proportion, the weight required to bring the sample block to breaking or to rapture has been measured. Results for sisal-reinforced blocks are outlined in figure 6.56 and figure 6.57 as well as in table 6.32 and table 6.33. Change in the total dead weight with increase in sisal content is similar to change in compressive strength with increasing sisal levels, displayed in figure 6.56 and 6.57. This similarity in behaviour of the two trends provided the motivation to assume that a positive relationship between strength and total dead weight against sisal levels exists.

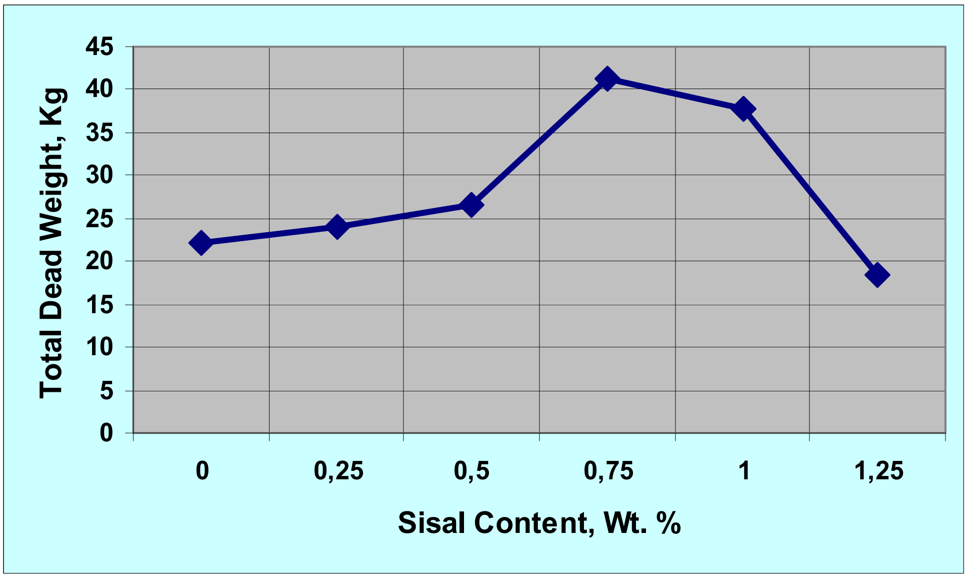


Figure 6.56 Total dead weight as a function of sisal content

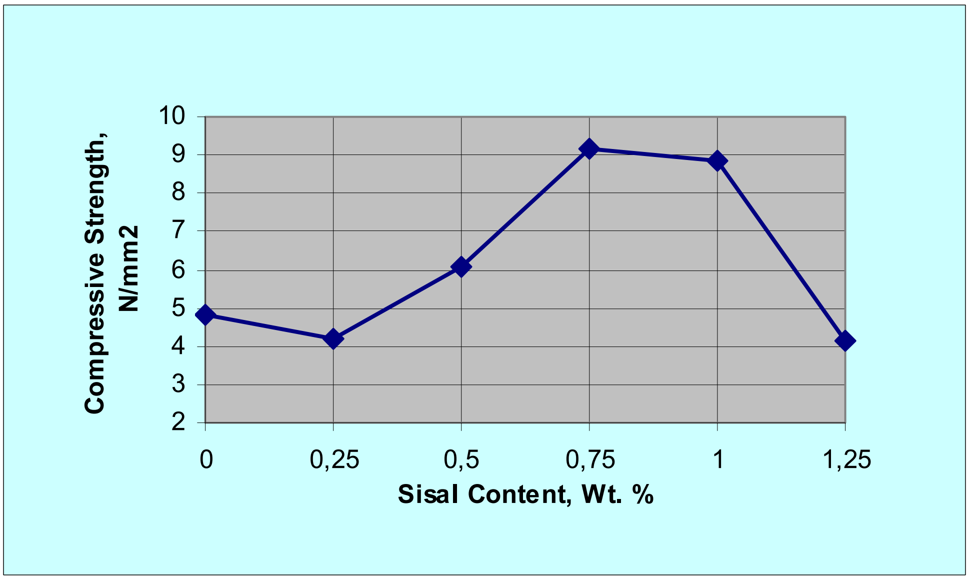


Figure 6.57 Compressive strength as a function of sisal content

6.7.1 Conversion Factor Model

A correlation is made between the compressive strength values denoted as y and the measurements of the total dead weight obtained at block rapture denoted as x. The correlation factor k_1 has then been obtained for each mix composition using equation 6.7.1. The correlation factor k_1 is found to lie between 4.365357 and 5.747085; a mean value of k_1 is computed to be 4.66 with a standard deviation of 0.546791.

$$Y \times K_1 = X \qquad 6.7.1$$

Equation 6.7.2 gives the established conversion model. This model can be applied by local people in the villages to evaluate the compression strength of manufactured earth blocks in the absence of laboratory facilities that would otherwise directly measure compression strength.

$$Y \times 4.66 = X \qquad 6.7.2$$

From investigations of the present work, it can therefore be deduced that:

$$\text{Compressive Strength} \times 4.66 = \text{Total Dead Weight}$$

Table 6.32 Results of the total dead weight against compression strength

Specimen Reference	**Compressive Strength, (y) N/mm^2**	**Ultimate Breaking Load,(x) Kg**	**Conversion factor, (k_1) $K_1 = x/y$**
SC-0	4.798	22.205	4.627247
SC-0.25	4.18	24.03	5.747085
SC-0.50	6.08	26.525	4.365357
SC-0.75	9.14	41.275	4.515247
SC-1	8.87	37.81	4.263284
SC-1.25	4.16	18.49	4.443376

A second correlation is made between the flexural strength values denoted as δ and the measurements of total dead weight obtained at block rapture denoted as β, table 6.33. The correlation factor k_2 is then obtained for each mix composition using equation 6.7.3. The correlation factor k_2 is found to lie between 21.75294118 and 32.04, a mean value of k is computed to be 25.4747 with a standard deviation of 3.65

Table 6.33 Results of the total dead weight against flexural strength

Specimen Reference	**Flexural Strength, δ N/mm^2**	**Ultimate Breaking Load,(β), Kg**	**Conversion factor, (k_2) $K_2 = \beta/\delta$**
SC-0	0.992	22.205	22.38407258
SC-0.25	0.75	24.03	32.04
SC-0.50	1.035	26.525	25.62801932
SC-0.75	1.63	41.275	25.32208589
SC-1	1.47	37.81	25.72108844
SC-1.25	0.85	18.49	21.75294118

$$\delta \times k_2 = \beta \tag{6.7.3}$$

Equation 6.7.4 hence gives the established conversion model with respect to the flexural strength, thus:

$$\delta \times 25.47 = \beta \tag{6.7.4}$$

It can therefore be deduced that:

$$\text{Flexural Strength} \times 25.47 = \text{Total Dead Weight}$$

A more accurate interpretation of the model is given in figure 6.58b

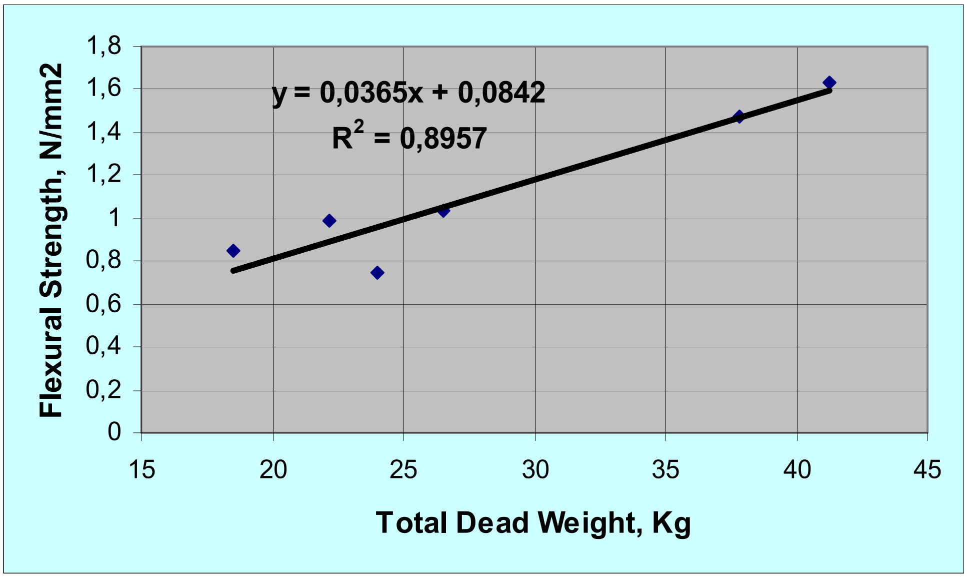


Figure 6.58a Flexural strength against total dead weight

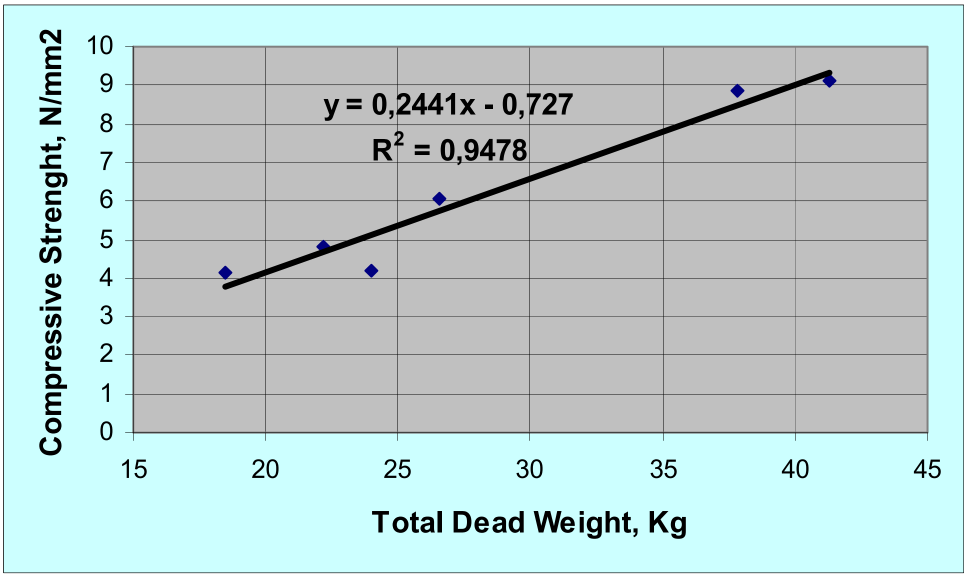


Figure 6.58b Compressive strength against total dead weight

According to (Walker, 2004), who has done extensive research in the area of compressed earth blocks (see section on references), total dead weight tests are more reflective of the flexural (modulus of rapture) strength than to compressive strength; based on this, equation 6.7.4 would be more recommended for application as the conversion model.

7.0 Conclusions and Recommendations

Influence of sisal vegetable fibres, cement, sisal-cement and cassava powder on the durability of compressed earth blocks were studied in this investigation. The main conclusions to be drawn from the experimental work reported in this dissertation can be summarised as follows:

1. Tests carried out here have established that it is possible to reinforce earth blocks with sisal fibres, cassava, cement and a combination of sisal and cement. Mixing of the above mentioned ingredients with soil can be recommended as an efficient procedure for processing house construction bricks for rural Africa population; where (especially) sisal and cassava is readily available. It is noted hereby that amongst the mix compositions, the ideal strength values are outlined in figure 7.1.

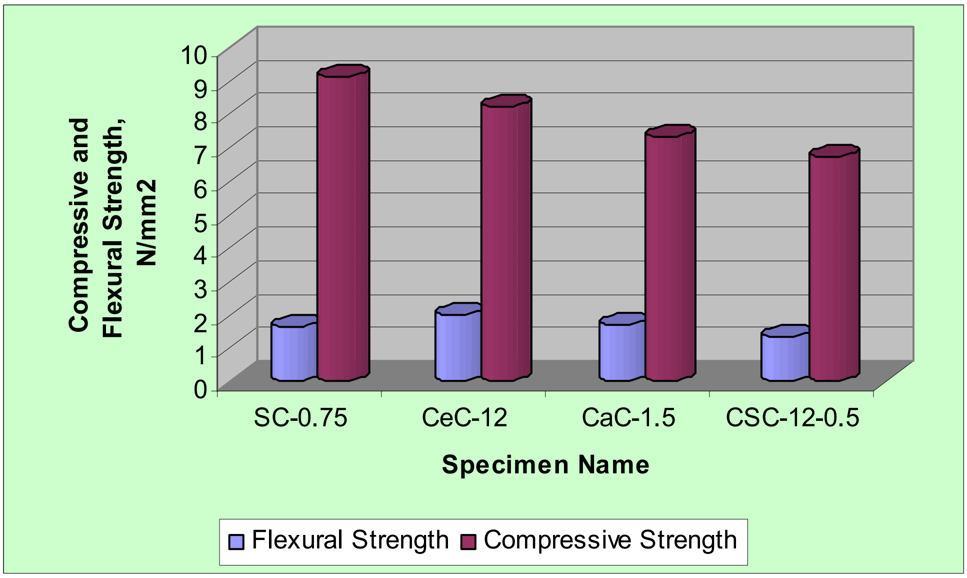


Figure 7.1 Comparison in ideal strength for each block type

Table 7.1 and figure 7.2 depict the percentage increase in strength for the ideal mix of different block types; this increase in strength is in comparison to the plain (non-reinforced) earth blocks.

Table 7.1 Summary of the ideal strength values

Block Type	**Stabiliser Type and optimum Content**	**Improvement in Strength for Ideal mix proportions**			
		Compressive Strength, N/mm^2	**Percentage Improvement in Strength**	**Flexural Strength, N/mm^2**	**Percentage Improvement in Strength**
SC	**0.75% Sisal**	9.14	**+90.5**	1.63	**+64.3**
CeC	**12% Cement**	8.24	**+71.7**	2.00	**+101**
CSC	**0.5% Sisal and 12% Cement**	6.75	**+40.7**	1.36	**+37.1**
CaC	**1.5% Cassava**	7.3625	**+53.5**	1.71155	**+72.5**

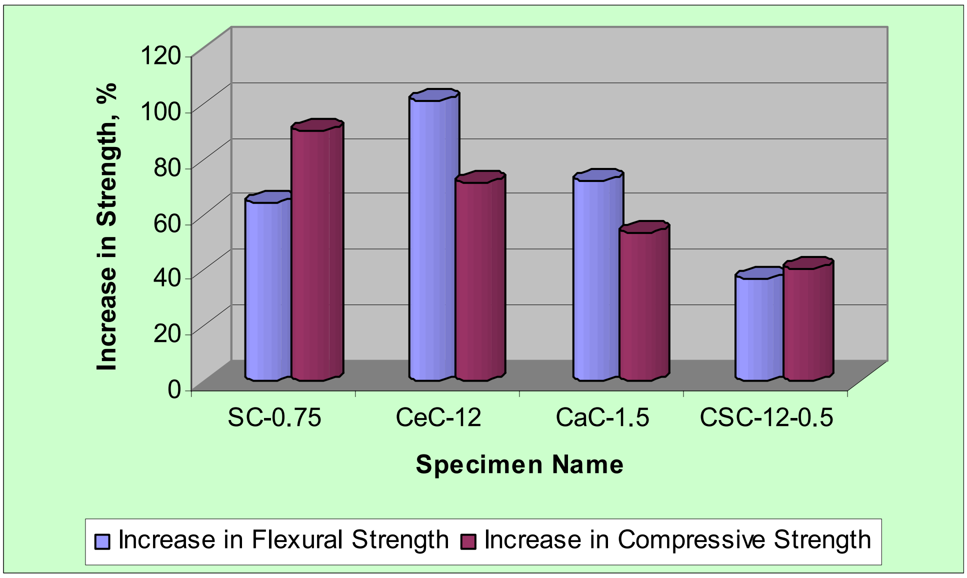


Figure 7.2 Comparison in strength increase for each block type

From table 7.1 and figure 7.2, it can be deduced as follows:

- Optimum compressive strength is obtained by reinforcement of the soil sample with 0.75% sisal fibres by weight of soil. In this case the compressive strength improves by 90.5% and flexural strength improves by 64.3% compared with the plain earth block,

- amounts of sisal fibres exceeding 1.0% are detrimental to strength,
- optimum compressive strength is obtained by stabilisation of the soil sample with 12% cement by weight of soil. In this case the compressive strength improves by 71.7% and flexural strength improves by 101%,
- optimum compressive strength is obtained by stabilisation of the soil sample with 0.5 % sisal and 12% cement by weight of soil. In this case the compressive strength improves by 40.7% and flexural strength improves by 37.1%.

Illustration of strength comparison between various types mix compositions investigated in the present work is summarized in figure 7.3 to figure 7.8.

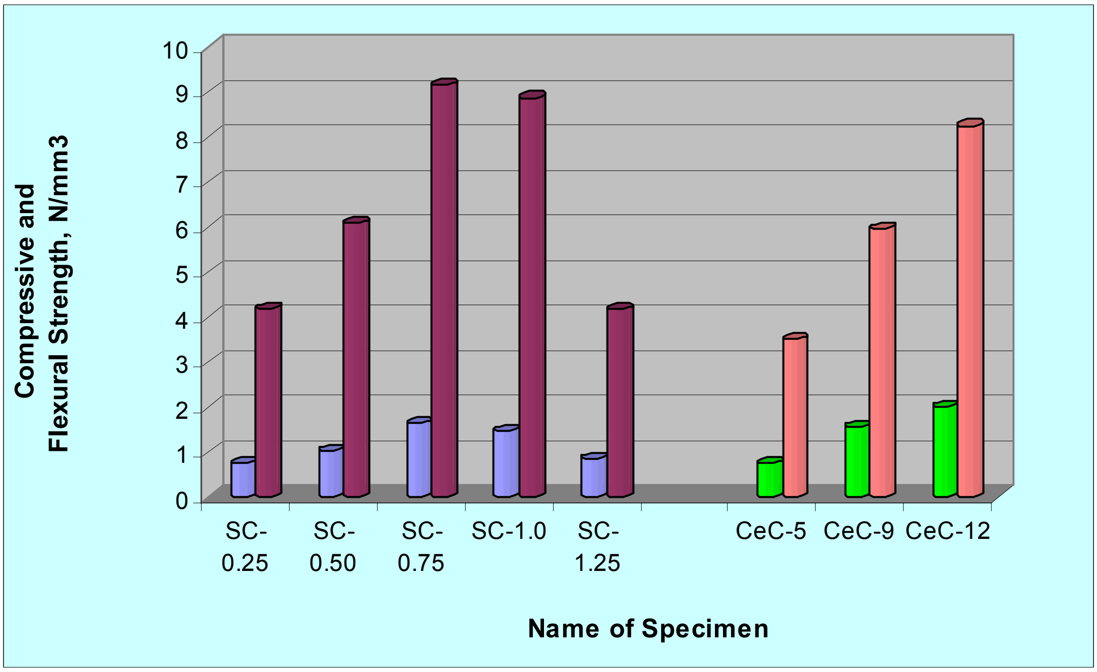


Figure 7.3 Comparison of sisal reinforced and cement stabilised blocks

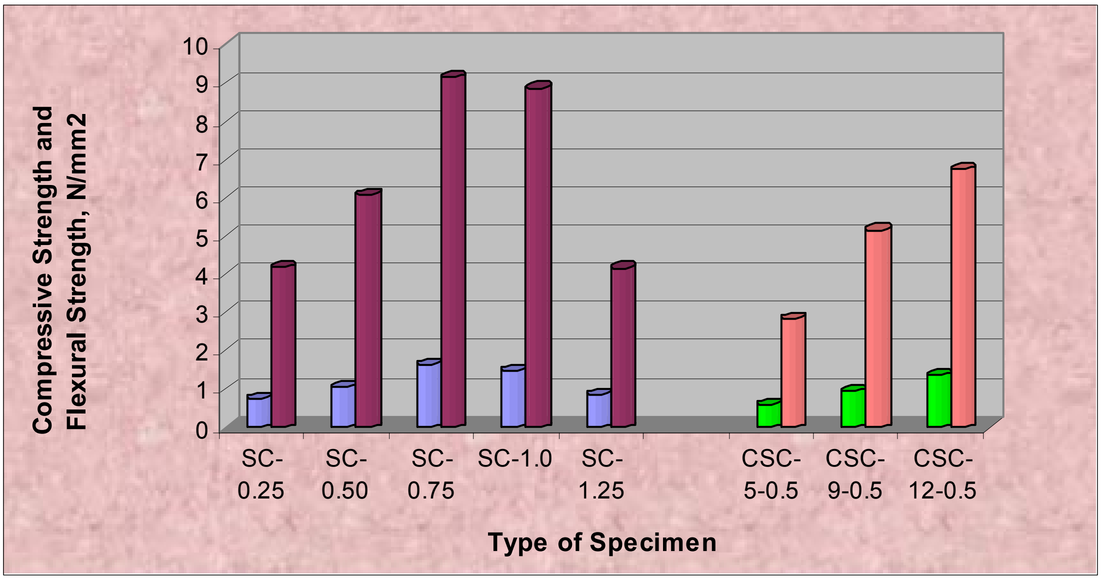


Figure 7.4 Comparison of sisal reinforced and cement-sisal stabilised blocks

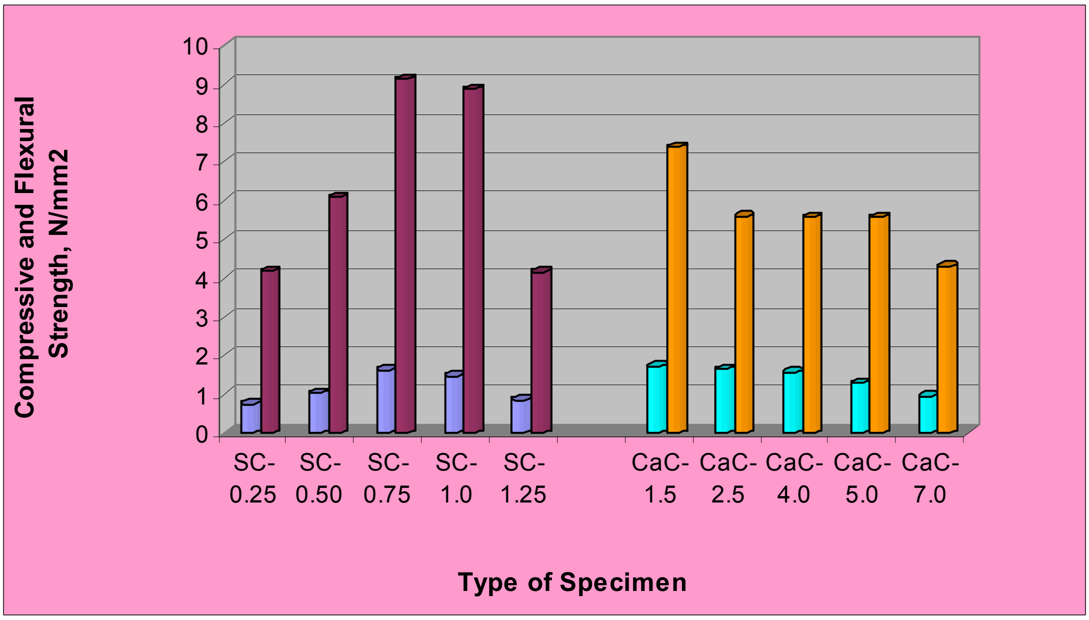


Figure 7.5 Comparison of sisal reinforced and cassava stabilised blocks

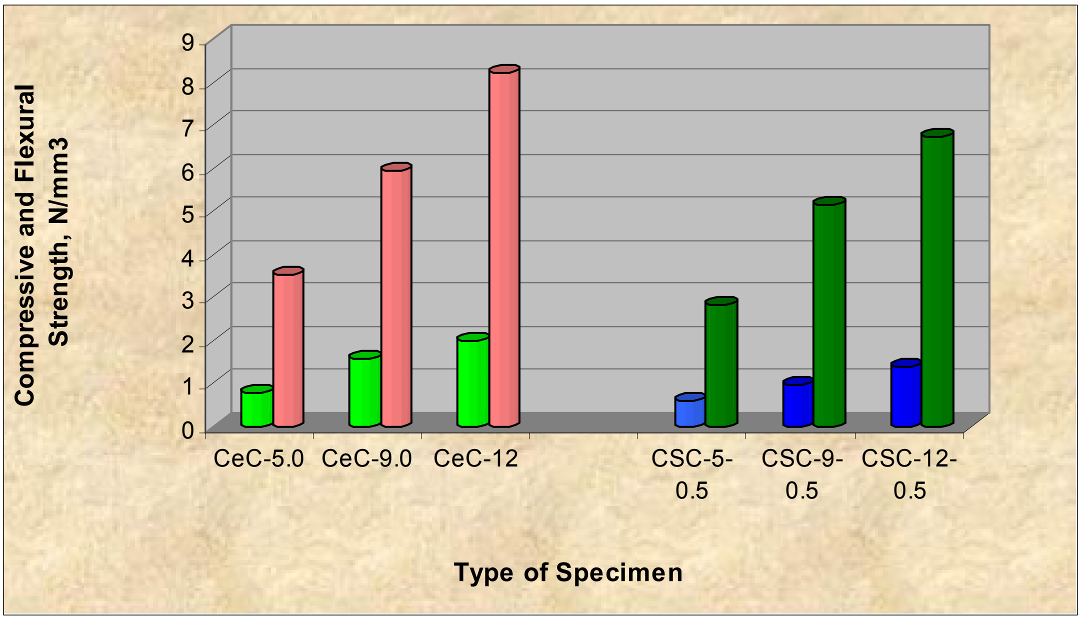


Figure 7.6 Comparison of cement and cement-sisal stabilised blocks

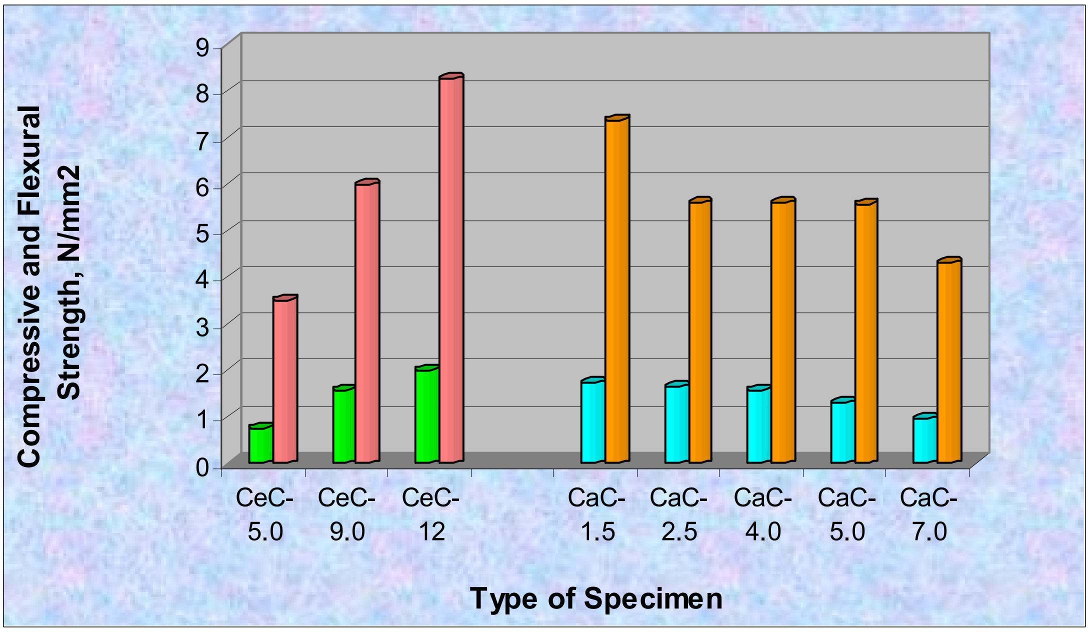


Figure 7.7 Comparison of cement and cassava stabilised blocks

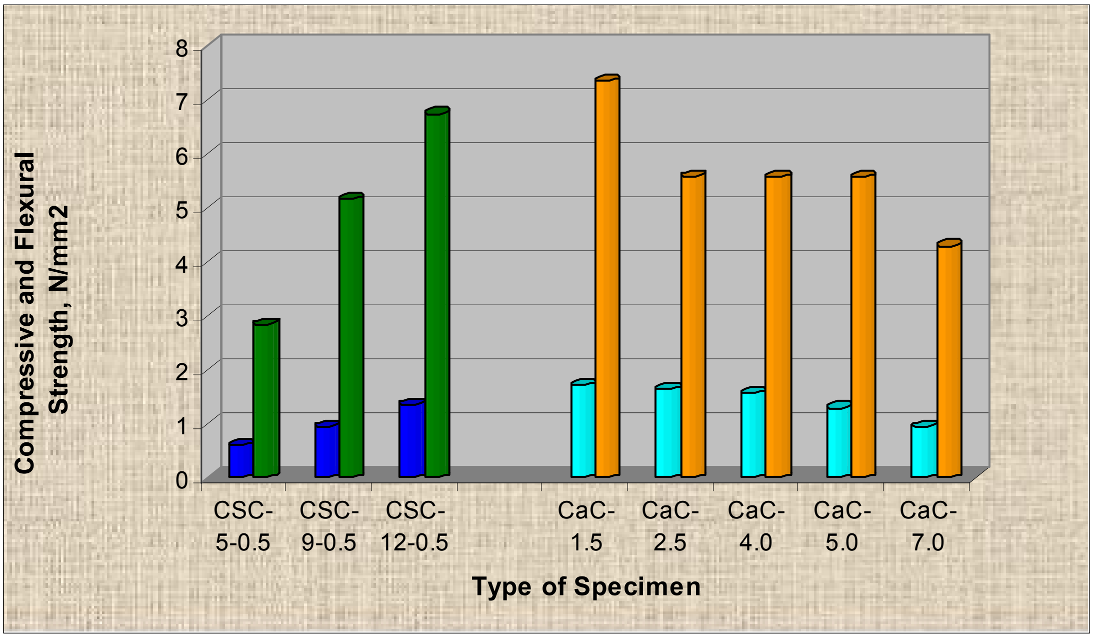


Figure 7.8 Comparison of cement-sisal and cassava stabilised blocks

2. The present work has evaluated compressed earth blocks in terms of both practical block density and theoretical block density. For the first time therefore compressed earth blocks have been characterised with respect to theoretical density, unlike past workers who have seen this property only in terms of practical density. It is important to note that a relationship between two densities has been established, thus, theoretical density is in general about one and a half (1.5) times greater than the corresponding practical density, equation 7.2

$$\text{Practical Density} \times 1.5 = \text{Theoretical Density} \tag{7.1}$$

A strong linear correlation ($R^2 \geq 0.98$) between the stabilizers and the theoretical density has been established, equation 7.2, 7.3 and 7.4

$$\rho_t = -26.64 \text{ Sisal Content} + 2661.2 \tag{7.2}$$

$$\rho_t = -0.3494 \text{ Cement Content} + 2663.7 \tag{7.3}$$

$$\rho_t = -17.123 \text{ Cassava Content} + 2665.4 \qquad (7.4)$$

Unlike research results presented by past workers that base the evaluation of porosity of earthen building materials through density measurements, this project has been able to directly determine the porosity of samples prepared as per section 5.0

3. The present work has developed a new earthen building material. The mixture of soil (earth) with cassava powder for the purpose of constructing walls for houses is not yet recorded in literature. Cassava powder is crushed from a root tuber which is available in plenty in the tropical countries. This material is to be classified as GreenEarth-1.5, figure 7.9.

   The material can replace the expensive cement which is traditionally used for soil stabilization. Addition of cassava powder in the range of 1.5% by weight of dry soil provides strength that is more than two times that recommended by many researchers mentioned in section 2.3.

Figure 7.9 CaC classification and trade mark

Figure 7.10 SC classification and trade mark

4. Material obtained by reinforcement of the soil sample with 0.75% sisal fibres with the effect that the compressive strength improves by 90.5% is hereby classified as GreenClay-0.75, figure 7.10.

5. This technical report proposes a method of indirectly evaluating strength and therefore durability characteristics of manufactured earth blocks in rural areas of Africa in absence of the normally expensive laboratory facilities; this method is discussed in section 6.7.

   The primary advantage of the proposed method, which entails loading earth block samples with a weight till rapture, is that it can easily be adapted at village level by people who have little scientific knowledge of compressed blocks. A conversion factor between this developed method and the conventional way of determining strength i.e. compressive and flexural strength has been established; the model is presented in equation 7.5 and 7.6

$$\text{Flexural Strength} \times 25.47 = \text{Total Dead Weight} \tag{7.5}$$

$$\text{Compressive Strength} \times 4.66 = \text{Total Dead Weight} \tag{7.6}$$

6. Water vapour transmission performance of compressed earth blocks, prior unrecorded in literature, has been determined. As a result it is possible to discuss the fact that earthen building materials have better thermal capacities based on a value scientifically established.

Although this research finding is intended to be consumed in Africa for rural population, it may be used anywhere in the world where natural fibres and cassava are to be found in plenty.

It should however, be mentioned that the roof construction should be done in such way that rain does not directly pound the compressed earth blocks when applied for building of walls.

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Appendices

Appendix A Strength and Density Interrelationship

Table A.1 Strength values and percentage change

Block Type	Stabiliser Type and Content	Change in Strength			
		Compressive Strength, N/mm^2	Change in Strength*, %	Flexural Strength, N/mm^2	Change in Strength*, %
SC	**Plain Block**	4.798	**-**	0.992	**-**
	0.25% Sisal	4.181	-12.8	0.751	-24.3
	0.5% Sisal	6.076	**+26.6**	1.035	**+4.3**
	0.75% Sisal	9.14	**+90.5**	1.63	**+64.3**
	1.0% Sisal	8.868	**+84.8**	1.473	**+48.5**
	1.25% Sisal	4.161	-13.3	0.850	-14.3
CeC	**5% Cement**	3.505	-26.9	0.750	-24.4
	9% Cement	5.965	**+24.3**	1.566	**+57.8**
	12% Cement	8.24	**+71.7**	2.00	**+101**
CSC	**0.5% Sisal and 5% Cement**	2.843	-40.7	0.583	-41.2
	0.5% Sisal and 9% Cement	5.16	**+7.5**	0.934	-5.8
	0.5% Sisal and 12% Cement	6.75	**+40.7**	1.36	**+37.1**
CaC	**1.5% Cassava**	7.362	**+53.5**	1.711	**+72.5**
	2.5% Cassava	5.593	**+16.5**	1.637	**+65.0**
	4% Cassava	5.576	**+16.2**	1.557	**+57.0**
	5% Cassava	5.565	**+16.0**	1.283	**+29.3**
	7.0% Cassava	4.298	-10.4	0.945	-4.7

Table A.2 Ratio of flexural to compressive strength

S.No.	Sample Name	Flexural Strength, N/mm^2	Compressive Strength, N/mm^2	Ratio of Flexural to Compressive Strength	
				Gross	Mean
	Sisal stabilised compressed earth blocks				
1	SC-0	0.992	4.79875	4.83745	5,591126
2	SC-0.25	0.75125	4.18125	5.565724	
3	SC-0.5	1.035	6.07625	5.870773	
4	SC-0.75	1.63075	9.14125	5.60555	
5	SC-1.0	1.473	8.86875	6.020876	
6	SC-1.25	0.8505	4.16125	4.89271	
7	**Cement stabilised compressed earth blocks**				
8	CeC-0	0.992	4.79875	4.83745	4.196685
9	CeC-5	0.75075	3.505	4.668665	
10	CeC-9	1.5665	5.965	3.807852	
11	CeC-12	2.00375	8.2425	4.113537	
12	**Cement-Sisal reinforced compressed earth blocks**				
13	CSC-0	0.992	4.79875	4.83745	5.125949
14	CSC-5-0.5	0.58325	2.843125	4.874625	
15	CSC-9-0.5	0.9345	5.16	5.521669	
16	CSC-12-0.5	1.35525	6.75125	4.981553	
17	**Cassava stabilised compressed earth blocks**				
18	CaC-0	0.992	4.79875	4.83745	4.036621
19	CaC-1.5	1.7115	7.3625	4.301782	
20	CaC-2.5	1.6375	5.59375	3.416031	
21	CaC-4	1.557333	5.576667	3.580908	
22	CaC-5	1.283	5.565	4.33749	
23	CaC-7	0.945333	4.298333	4.546897	

Table A.3 Comparison of practical and theoretical density

Block Type	**Stabiliser Type and Content**	**Theoretical Density, kg/m^3**	**Practical Density, kg/m^3**	**Change in Practical Density*, %**
SC	**Plain Block**	2663.7	1792.97	-
	0.25% Sisal	2653.5	1800.78	+0.44
	0.5% Sisal	2645.2	1857.42	+3.6
	0.75% Sisal	2640.8	1895.51	+5.7
	1.0% Sisal	2635.6	1883.79	+5.1
	1.25% Sisal	2628.7	1738.28	-3.1
CeC	**5% Cement**	2661.2	1689.45	-5.8
	9% Cement	2662.1	1686.52	-6.0
	12% Cement	2658.6	1689.45	-5.8
CSC	**0.5% Sisal and 5% Cement**	2650.5	1644.53	-8.3
	0.5% Sisal and 9% Cement	2661.1	1640.63	-8.5
	0.5% Sisal and 12% Cement	2664.4	1674.32	-6.6
CaC	**1.5% Cassava**	2644	1781.25	-0.65
	2.5% Cassava	2619.5	1765.62	-1.5
	4% Cassava	2595.2	1753.90	-2.2
	5% Cassava	2583.4	1740.23	-3.0
	7.0% Cassava	2544.1	1635.31	-8.8

**+ implies % improvement in density in comparison to the non-reinforced earth block*

- implies % drop in density in comparison to the non-reinforced earth block.

Appendix B Sisal Stabilized Compressed Earth Blocks (SC): Compressive Strength

Specimen Reference	Ultimate Load, (F) kN		Compressive Strength, N/mm2		
	Gross	Gross	Gross	Gross	Mean
SC-0-0-1	7.68	5.57	4.8	3.48	4.798
SC-0-0-2	7.01	8.38	4.38	5.24	
SC-0-0-3	7.97	7.74	4.98	4.84	
SC-0-0-4	8.59	8.49	5.37	5.3	
SC-0.25-0-1	7.5	4.89	4.69	3.06	4.18
SC-0.25-0-2	8.44	7.3	5.27	4.56	
SC-0.25-0-3	4.98	6.72	3.11	4.2	
SC-0.25-0-4	7.06	6.64	4.41	4.15	
SC-0.50-0-1	9.59	8.99	6	5.62	6.08
SC-0.50-0-2	8.93	7.92	5.58	4.95	
SC-0.50-0-3	10.37	10.48	6.48	6.55	
SC-0.50-0-4	10.26	10.9	6.62	6.81	
SC-0.75-0-1	14.54	14.2	9.09	8.87	9.14
SC-0.75-0-2	16.11	14.89	10.07	9.31	
SC-0.75-0-3	14.87	14.31	9.3	8.94	
SC-0.75-0-4	15.31	12.76	9.57	7.98	
SC-1-0-1	14.74	14.04	9.21	8.78	8.87
SC-1-0-2	14.4	13.2	9	8.25	
SC-1-0-3	15.53	12.5	9.7	7.81	
SC-1-0-4	14.78	14.33	9.24	8.96	
SC-1.25-0-1	6.91	6.47	4.32	4.04	4.16
SC-1.25-0-2	6.15	6.33	3.84	4	
SC-1.25-0-3	6.62	7.4	4.14	4.62	
SC-1.25-0-4	7.48	5.86	4.67	3.66	

Appendix C Sisal Stabilized Compressed Earth Blocks (SC): Flexural Strength

Specimen Reference	Dry Block Density, Kg/m3	Ultimate Load, (F) kN	Dry Flexural Strength, N/mm2	
		Gross	Gross	Mean
SC-0-0-1	1792.99	0.373	0.874	0.992
SC-0-0-2		0.373	0.874	
SC-0-0-3		0.456	1.069	
SC-0-0-4		0.491	1.151	
SC-0.25-0-1	1800.78	0.284	0.666	0.75
SC-0.25-0-2		0.359	0.841	
SC-0.25-0-3		0.295	0.691	
SC-0.25-0-4		0.345	0.807	
SC-0.50-0-1	1857.42	0.425	0.995	1.035
SC-0.50-0-2		0.415	0.969	
SC-0.50-0-3		0.452	1.06	
SC-0.50-0-4		0.476	1.116	
SC-0.75-0-1	1895.51	0.612	1.434	1.63
SC-0.75-0-2		0.792	1.856	
SC-0.75-0-3		0.757	1.774	
SC-0.75-0-4		0.622	1.459	
SC-1-0-1	1883.79	0.598	1.402	1.47
SC-1-0-2		0.515	1.206	
SC-1-0-3		0.752	1.763	
SC-1-0-4		0.649	1.521	
SC-1.25-0-1	1738.28	0.37	0.867	0.85
SC-1.25-0-2		0.281	0.658	
SC-1.25-0-3		0.363	0.851	
SC-1.25-0-4		0.438	1.026	

Appendix D Practical Dry Block Density of Sisal Reinforced Blocks

Specimen Reference	**Mass of Dry Block, g**		**Dry Block Volume, $cm3*10^{-6}$**	**Dry Block Density, Kg/m3**
	Gross	**Mean**		
SC-0-0-1	455	459	256000	1792.97
SC-0-0-2	464			
SC-0-0-3	456			
SC-0-0-4	461			
SC-0.25-0-1	455	461	256000	1800.78
SC-0.25-0-2	472			
SC-0.25-0-3	452			
SC-0.25-0-4	465			
SC-0.50-0-1	474	475.5	256000	1857.42
SC-0.50-0-2	464			
SC-0.50-0-3	482			
SC-0.50-0-4	482			
SC-0.75-0-1	494	485.25	256000	1895.51
SC-0.75-0-2	490			
SC-0.75-0-3	474			
SC-0.75-0-4	483			
SC-1-0-1	485	482.25	256000	1883.79
SC-1-0-2	484			
SC-1-0-3	476			
SC-1-0-4	484			
SC-1.25-0-1	447	445	256000	1738.28
SC-1.25-0-2	435			
SC-1.25-0-3	452			
SC-1.25-0-4	446			

Appendix E Determination of True Block Density

An ULTRAPYCNOMETER is specifically designed to measure the exact volume and density ρ_t of solid objects by employing Archimedes' principle of fluid displacement and Boyle's law to determine the volume. An inert gas, Helium, of small atomic dimensions ensures penetration of all pores. The ULTRAPYCNOMETER contains an empty cell of volume V_c where a sample is sealed. By opening the solenoid valves to the sample cell, the system is brought to ambient pressure P_a after being purged with helium. The state of the system is then defined as

$$P_a V_c = n R T_a \tag{1}$$

Where n is the number of moles of gas occupying volume V_c at P_a, R is the gas constant and T_a is ambient temperature in Kelvin. When the solid sample of volume V_p is placed in the sample cell, equation (1) can be written as

$$P_a \, (V_c - V_p) = n_1 \, R T_a \tag{2}$$

When pressurized to some pressure above ambient, the state of the system is given by

$$P_2 \, (V_c - V_p) = n_2 \, R T_a \tag{3}$$

Where P_2 indicates the pressure above ambient and n_2 represents the total number of moles of gas contained in the sample cell. When the solenoid valve opens to connect the added volume V_A to that of the cell, the pressure will fall to lower value P_3 given by

$$P_3 \, (V_c - V_p + V_A) = n_2 \, R T_a + n_A \, R T_a \tag{4}$$

Where n_A is the number of moles of gas contained in the added volume when at ambient pressure. The term P_aV_A can be used in place of n_ART_a in equation (4), yielding

$$P_3 \, (V_c - V_p + V_A) = n_2 \, R T_a + P_a \, V_A \tag{5}$$

Substituting P_2 (V_c – V_p) from equation (3) for n_2RT_a changes equation (5) to

$$P_3\ (V_c - V_p + V_A) = P_2\ (V_c - V_p) + P_a V_A \tag{6}$$

or

$$(P_3 - P_2)\ (V_c - V_p) = (P_a - P_3)\ V_A \tag{7}$$

Then,

$$V_c - V_p = \frac{(P_a - P_3)\ V_A}{P_3 - P_2} \tag{8}$$

Equation (8) is further reduced by adding and subtracting P_a from P_3 and P_2 in the denominator, giving

$$V_p = V_c - \frac{(P_a - P_3)\ V_A}{(P_3 - P_a) - (P_2 - P_a)} \quad = \quad V_c + \frac{V_A}{1 - \dfrac{P_2 - P_a}{P_3 - P_a}} \tag{9}$$

Since P_a is made to read zero, that is, all pressure measurements are relative to P_a which is zeroed prior to pressurizing, equation (9) becomes

$$V_p = V_c + \frac{V_A}{1 - (P_2 / P_3)} \tag{10}$$

Equation (10) is the working equation employed by the ULTRAPYCNOMETER.

Appendix F Cement Stabilized Compressed Earth Blocks (CeC): Compressive Strength

Specimen Reference	Ultimate Load (F), kN		Dry Compressive Strength, MPa		
	Gross	Gross	Gross	Gross	Mean
CeC-0-0-1	7.68	5.57	4.8	3.48	4.79
CeC-0-0-2	7.01	8.38	4.38	5.24	
CeC-0-0-3	7.97	7.74	4.98	4.84	
CeC-0-0-4	8.59	8.49	5.37	5.3	
CeC-5-0-1	5.44	6.43	3.4	4.02	3.50
CeC-5-0-2	4.84	4.84	3.03	3.03	
CeC-5-0-3	6.4	7.17	4	4.48	
CeC-5-0-4	4.86	4.86	3.04	3.04	
CeC-9-0-1	10.63	9.75	6.64	6.09	5.96
CeC-9-0-2	8.64	8.33	5.4	5.21	
CeC-9-0-3	8.42	8.52	5.26	5.32	
CeC-9-0-4	11	11.08	6.88	6.92	
CeC-12-0-1	8.54	10.44	5.34	6.53	8.24
CeC-12-0-2	11.62	12.47	7.26	7.8	
CeC-12-0-3	15.68	15.07	9.8	9.42	
CeC-12-0-4	15.48	16.19	9.67	10.12	

Appendix G Cement Stabilized Compressed Earth Blocks (CeC): Flexural Strength

Specimen Reference	Dry Block Density, Kg/m3	Ultimate Load, (F) kN	Flexural Strength, MPa	
			Gross	Mean
CeC-0-0-1	1792.97	0.373	0.874	0.99
CeC-0-0-2		0.373	0.874	
CeC-0-0-3		0.456	1.069	
CeC-0-0-4		0.491	1.151	
CeC-5-0-1	1689.45	0.344	0.807	0.75
CeC-5-0-2		0.237	0.556	
CeC-5-0-3		0.382	0.895	
CeC-5-0-4		0.31	0.745	
CeC-9-0-1	1686.52	0.714	1.674	1.56
CeC-9-0-2		0.551	1.292	
CeC-9-0-3		0.595	1.396	
CeC-9-0-4		0.812	1.904	
CeC-12-0-1	1689.45	0.647	1.517	2.00
CeC-12-0-2		0.753	1.764	
CeC-12-0-3		0.962	2.254	
CeC-12-0-4		1.06	2.48	

Appendix H Cement Stabilized Compressed Earth Blocks (CeC): Dry Block Density

Specimen Reference	Mass of Dry Block, g		Dry Block Volume, mm3	Dry Block Density, Kg/m3
	Gross	Mean		
CeC-0-0-1	455	459	256000	1792.97
CeC-0-0-2	464			
CeC-0-0-3	456			
CeC-0-0-4	461			
CeC-5-0-1	437	432.5	256000	1689.45
CeC-5-0-2	426			
CeC-5-0-3	431			
CeC-5-0-4	436			
CeC-9-0-1	436	431.75	256000	1686.52
CeC-9-0-2	428			
CeC-9-0-3	437			
CeC-9-0-4	426			
CeC-12-0-1	460	432.5	256000	1689.45
CeC-12-0-2	428			
CeC-12-0-3	424			
CeC-12-0-4	418			

Appendix I Cement-Sisal Stabilized Compressed Earth Blocks (C-SC): Compression Strength

Specimen Reference	**Ultimate Load, (F) kN**		**Compression Strength, MPa**		
	Gross	Gross	Gross	Gross	Mean
C-SC-0-0-1	7.68	5.57	4.8	3.48	4.798
C-SC-0-0-2	7.01	8.38	4.38	5.24	
C-SC-0-0-3	7.97	7.74	4.98	4.84	
C-SC-0-0-4	8.59	8.49	5.37	5.3	
C-SC-5-0.25-1	6.13	6.12	3.83	3.83	3.60
C-SC-5-0.25-2	6.19	5.78	3.87	3.61	
C-SC-5-0.25-3	5.86	5.39	3.66	3.37	
C-SC-5-0.25-4	4.86	6.13	3.04	3.83	
C-SC-9-0.25-1	7.45	6.8	4.66	4.25	4.60
C-SC-9-0.25-2	7.73	7.63	4.83	4.77	
C-SC-9-0.25-3	7.47	7.17	4.67	4.48	
C-SC-9-0.25-4	8.06	7.36	5.06	4.06	
C-SC-12-0.25-1	8.83	10.69	5.52	6.68	6.06
C-SC-12-0.25-2	9.04	10.94	5.65	6.84	
C-SC-12-0.25-3	8.71	10.93	5.44	6.83	
C-SC-12-0.25-4	8.79	9.64	5.49	6.03	
C-SC-5-1-1	4.28	4.91	2.675	3.07	2.84
C-SC-5-1-2	4.32	4.72	2.7	2.95	
C-SC-5-1-3	4.3	3.85	2.69	2.41	
C-SC-5-1-4	4.75	5.25	2.97	3.28	
C-SC-9-1-1	9	7.96	5.63	4.97	5.16
C-SC-9-1-2	7.9	8.06	4.94	5.04	
C-SC-9-1-3	8.9	8.19	5.56	5.12	
C-SC-9-1-4	7.84	8.19	4.9	5.12	
C-SC-12-1-1	10.64	9.76	6.65	6.1	6.75
C-SC-12-1-2	10.24	8.69	6.4	5.43	
C-SC-12-1-3	13.05	10.72	8.15	6.7	
C-SC-12-1-4	10.68	12.66	6.67	7.91	
C-SC-5-0.75-1	4.3	3.68	2.69	2.3	2.37
C-SC-5-0.75-2	3.74	4.21	2.34	2.63	
C-SC-5-0.75-3	3.15	3.7	1.97	2.31	
C-SC-5-0.75-4	3.77	3.88	2.36	2.42	
C-SC-9-0.75-1	7.35	6.86	4.6	4.29	4.51
C-SC-9-0.75-2	7.87	8.6	4.92	5.38	
C-SC-9-0.75-3	7.15	5.8	4.47	3.63	
C-SC-9-0.75-4	7.29	6.83	4.56	4.27	
C-SC-12-0.75-1	10.45	9.83	6.53	6.14	6.43

C-SC-12-0.75-2	9.65	10.94	6.03	6.84	
C-SC-12-0.75-3	11.18	10.22	6.98	6.39	
C-SC-12-0.75-4	10.47	9.63	6.54	6.02	
C-SC-5-1-1	4.13	3.48	2.58	2.18	2.6
C-SC-5-1-2	3.78	4.26	2.36	2.66	
C-SC-5-1-3	5.26	4.73	3.29	2.96	
C-SC-5-1-4	3.43	4.21	2.14	2.63	
C-SC-9-1-1	6.75	8.08	4.22	5.05	4.33
C-SC-9-1-2	7.16	7.66	4.48	4.79	
C-SC-9-1-3	6.96	7.33	4.35	4.58	
C-SC-9-1-4	5.79	5.79	3.62	3.62	
C-SC-12-1-1	9.39	10.23	5.87	6.4	5.99
C-SC-12-1-2	10.14	10.79	6.34	6.74	
C-SC-12-1-3	10.17	9.64	6.35	6.02	
C-SC-12-1-4	7.37	9	4.61	5.63	
C-SC-5-1.25-1	4.44	3.88	2.78	2.42	2.86
C-SC-5-1.25-2	5.62	4.37	3.51	2.73	
C-SC-5-1.25-3	4.38	5.54	2.74	3.46	
C-SC-5-1.25-4	4.24	4.24	2.65	2.65	
C-SC-9-1.25-1	7.67	6.44	4.79	4.02	4.72
C-SC-9-1.25-2	8.21	7.59	5.13	4.74	
C-SC-9-1.25-3	7.75	7.52	4.84	4.7	
C-SC-9-1.25-4	8.16	7.19	5.1	4.49	
C-SC-12-1.25-1	8.5	9.95	5.31	6.22	5.49
C-SC-12-1.25-2	8.02	8.92	5.01	5.58	
C-SC-12-1.25-3	8.24	9.76	5.15	6.1	
C-SC-12-1.25-4	9.35	7.56	5.85	4.73	

Appendix J Cement-Sisal Stabilized Compressed Earth Blocks (C-SC): Flexural Strength

Specimen Reference	**Dry Block Density, Kg/m3**	**Ultimate Load, (F) kN**	**Flexural Strength, MPa**	
			Gross	Mean
C-SC-0-0-1	1792.97	0.373	0.874	0.992
C-SC-0-0-2		0.373	0.874	
C-SC-0-0-3		0.456	1.069	
C-SC-0-0-4		0.491	1.151	
C-SC-5-0.25-1	1689.94	0.307	0.718	0.63
C-SC-5-0.25-2		0.202	0.473	
C-SC-5-0.25-3		0.3	0.703	
C-SC-5-0.25-4		0.262	0.615	
C-SC-9-0.25-1	1666.01	0.417	0.978	0.95
C-SC-9-0.25-2		0.38	0.891	
C-SC-9-0.25-3		0.36	0.844	
C-SC-9-0.25-4		0.46	1.078	
C-SC-12-0.25-1	1678.22	0.534	1.251	1.23
C-SC-12-0.25-2		0.494	1.158	
C-SC-12-0.25-3		0.516	1.21	
C-SC-12-0.25-4		0.557	1.306	
C-SC-5-1-1	1644.53	0.265	0.621	0.58
C-SC-5-1-2		0.254	0.596	
C-SC-5-1-3		0.237	0.556	
C-SC-5-1-4		0.239	0.56	
C-SC-9-1-1	1640.625	0.363	0.85	0.93
C-SC-9-1-2		0.4	0.938	
C-SC-9-1-3		0.447	1.048	
C-SC-9-1-4		0.385	0.902	
C-SC-12-1-1	1674.31	0.555	1.302	1.36
C-SC-12-1-2		0.46	1.077	
C-SC-12-1-3		0.741	1.737	
C-SC-12-1-4		0.557	1.305	
C-SC-5-0.75-1	1540.52	0.244	0.571	0.52
C-SC-5-0.75-2		0.2	0.468	
C-SC-5-0.75-3		0.233	0.546	
C-SC-5-0.75-4		0.211	0.495	
C-SC-9-0.75-1	1621.58	0.415	0.972	0.91
C-SC-9-0.75-2		0.435	1.019	
C-SC-9-0.75-3		0.357	0.836	

C-SC-9-0.75-4		0.341	0.798	
C-SC-12-0.75-1	1634.27	0.581	1.362	1.30
C-SC-12-0.75-2		0.607	1.422	
C-SC-12-0.75-3		0.513	1.201	
C-SC-12-0.75-4		0.526	1.233	
C-SC-5-1-1	1611.32	0.211	0.494	0.53
C-SC-5-1-2		0.242	0.566	
C-SC-5-1-3		0.276	0.648	
C-SC-5-1-4		0.18	0.423	
C-SC-9-1-1	1620.11	0.343	0.805	0.83
C-SC-9-1-2		0.351	0.822	
C-SC-9-1-3		0.402	0.942	
C-SC-9-1-4		0.321	0.751	
C-SC-12-1-1	1651.36	0.479	1.123	1.22
C-SC-12-1-2		0.556	1.302	
C-SC-12-1-3		0.579	1.357	
C-SC-12-1-4		0.47	1.101	
C-SC-5-1.25-1	1619.14	0.214	0.502	0.61
C-SC-5-1.25-2		0.275	0.646	
C-SC-5-1.25-3		0.306	0.717	
C-SC-5-1.25-4		0.239	0.56	
C-SC-9-1.25-1	1612.30	0.422	0.988	1.01
C-SC-9-1.25-2		0.494	1.157	
C-SC-9-1.25-3		0.369	0.864	
C-SC-9-1.25-4		0.437	1.023	
C-SC-12-1.25-1	1616.21	0.587	1.375	1.17
C-SC-12-1.25-2		0.447	1.047	
C-SC-12-1.25-3		0.569	1.333	
C-SC-12-1.25-4		0.397	0.93	

Appendix K Cement-Sisal Stabilized Compressed Earth Blocks (C-SC):

Table K1 Cement-Sisal Stabilized Compressed Earth Blocks (C-SC): Dry Block Density

Specimen Reference	Mass of Dry Block, g		Dry Block Volume, mm3	Dry Block Density, Kg/m3
	Gross	Mean		
C-SC-0-0-1	455	459	256000	1792.97
C-SC-0-0-2	464			
C-SC-0-0-3	456			
C-SC-0-0-4	461			
C-SC-5-0.25-1	442	432.625	256000	1689.94
C-SC-5-0.25-2	423.5			
C-SC-5-0.25-3	437			
C-SC-5-0.25-4	428			
C-SC-9-0.25-1	428	426.5	256000	1666.01
C-SC-9-0.25-2	431			
C-SC-9-0.25-3	420.5			
C-SC-9-0.25-4	426.5			
C-SC-12-0.25-1	432.5	429.625	256000	1678.22
C-SC-12-0.25-2	424.5			
C-SC-12-0.25-3	432			
C-SC-12-0.25-4	429.5			
C-SC-5-0.5-1	419.5	421	256000	1644.53
C-SC-5-0.5-2	411.5			
C-SC-5-0.5-3	422			
C-SC-5-0.5-4	431			
C-SC-9-0.5-1	407.5	420	256000	1640.625
C-SC-9-0.5-2	421			
C-SC-9-0.5-3	425			
C-SC-9-0.5-4	426.5			
C-SC-12-0.5-1	432.5	428.625	256000	1674.31
C-SC-12-0.5-2	430.5			
C-SC-12-0.5-3	422			
C-SC-12-0.5-4	429.5			
C-SC-5-0.75-1	396	394.375	256000	1540.52
C-SC-5-0.75-2	392			
C-SC-5-0.75-3	391.5			
C-SC-5-0.75-4	398			
C-SC-9-0.75-1	415	415.125	256000	1621.58

C-SC-9-0.75-2	413			
C-SC-9-0.75-3	412.5			
C-SC-9-0.75-4	420			
C-SC-12-0.75-1	421	418.375	256000	1634.27
C-SC-12-0.75-2	420			
C-SC-12-0.75-3	421.5			
C-SC-12-0.75-4	411			
C-SC-5-1-1	412	412.5	256000	1611.32
C-SC-5-1-2	414			
C-SC-5-1-3	407			
C-SC-5-1-4	417			
C-SC-9-1-1	410	414.75	256000	1620.11
C-SC-9-1-2	424			
C-SC-9-1-3	414			
C-SC-9-1-4	411			
C-SC-12-1-1	420	422.75	256000	1651.36
C-SC-12-1-2	419			
C-SC-12-1-3	425			
C-SC-12-1-4	427			
C-SC-5-1.25-1	413	414.5	256000	1619.14
C-SC-5-1.25-2	417			
C-SC-5-1.25-3	405			
C-SC-5-1.25-4	423			
C-SC-9-1.25-1	422	412.75	256000	1612.30
C-SC-9-1.25-2	417			
C-SC-9-1.25-3	418			
C-SC-9-1.25-4	394			
C-SC-12-1.25-1	410	413.75	256000	1616.21
C-SC-12-1.25-2	412			
C-SC-12-1.25-3	414			
C-SC-12-1.25-4	419			

Table K.2 Decrease in density in comparison to plain earth block

Block Type	**Stabiliser Type and Content**	**Practical Density, kg/m^3**	**Change in Practical Density*, %**
CSC	**Plain Block**	1792.97	-
	0.5% Sisal and 5% Cement	1644.53	-8,3
	0.5% Sisal and 9% Cement	1640.63	-8,5
	0.5% Sisal and 12% Cement	1674.32	-6.6

**+ implies % improvement in density in comparison to the non-reinforced earth block*

- implies % drop in density in comparison to the non-reinforced earth block.

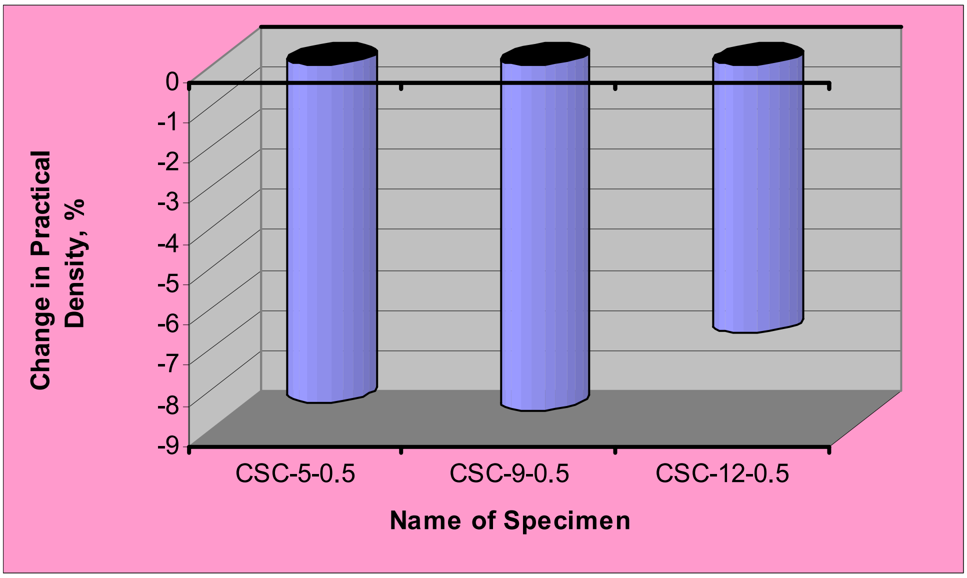


Figure K.1 Change in practical dry block density

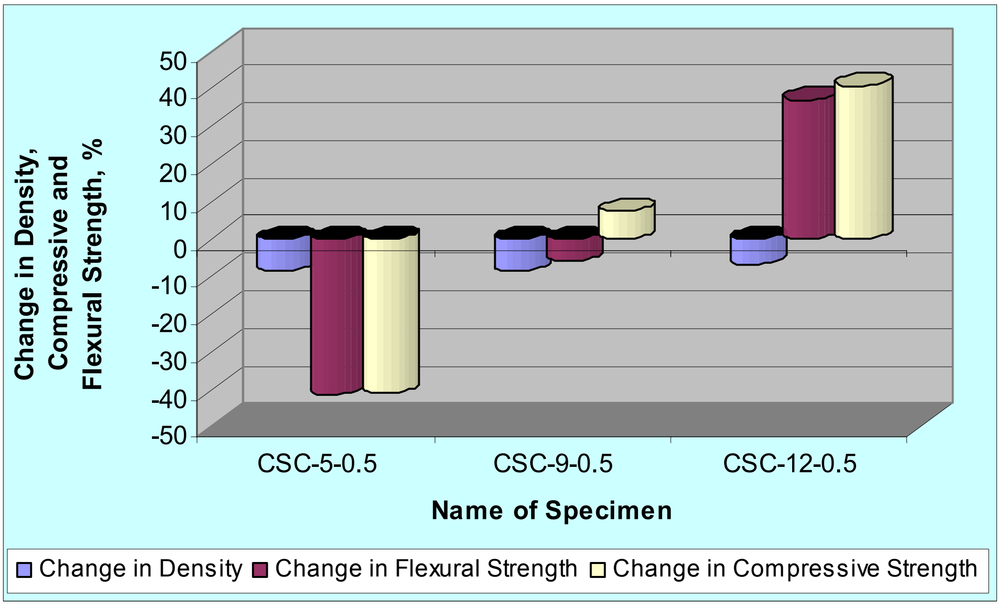


Figure K.2 Change in strength as a reflection of change in density

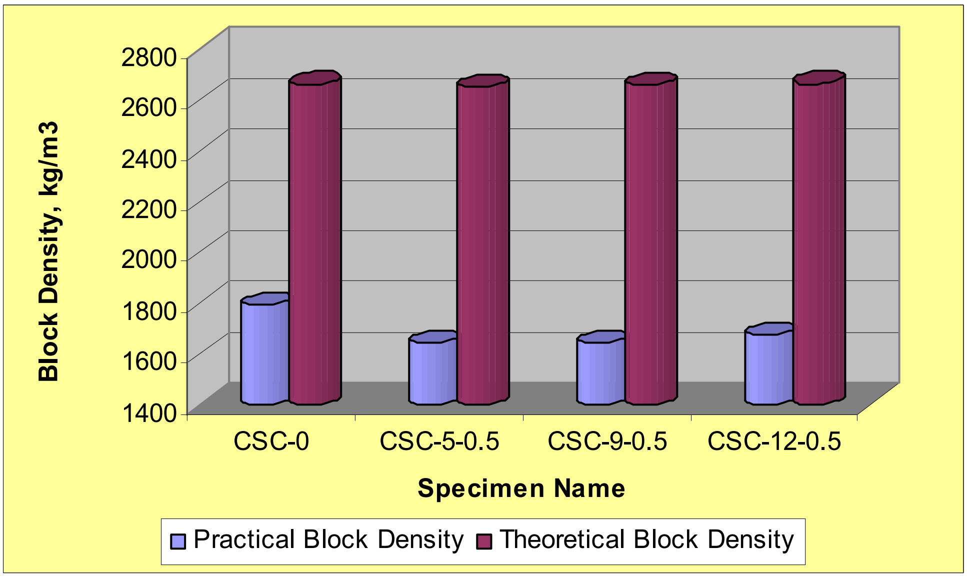


Figure K.3 Comparison between theoretical and practical density

Appendix L Cassava Stabilized Compressed Earth Blocks (CaC): Compressive Strength

Specimen Reference	Ultimate Load. (F), kN		Dry Compressive Strength, MPa		
	Gross	Gross	Gross	Gross	Mean
CaC-0-0-1	7.68	5.57	4.8	3.48	4.79
CaC-0-0-2	7.01	8.38	4.38	5.24	
CaC-0-0-3	7.97	7.74	4.98	4.84	
CaC-0-0-4	8.59	8.49	5.37	5.3	
CaC-1.5-0-1	11.49		7.18	7.20	7.3625
CaC-1.5-0-2	11.31		7.07	7.04	
CaC-1.5-0-3	11.16		7.97	8.00	
CaC-1.5-0-4	11.56		7.23	7.21	
CaC-2.5-0-1	8.47	11.65	5.3	7.28	5.593
CaC-2.5-0-2	7.98	11	4.99	6.38	
CaC-2.5-0-3	7.81	8.97	4.88	5.6	
CaC-2.5-0-4	7.9	8.61	4.94	5.38	
CaC-4-0-1	8.92	7.81	5.57	4.88	5.576
CaC-4-0-2	9.74	9.47	6.09	5.92	
CaC-4-0-3	7.38	10.23	4.61	6.39	
CaC-4-0-4					
CaC-5-0-1	9.16	8.82	5.72	5.51	5.56
CaC-5-0-2	10.36	10.38	6.47	6.49	
CaC-5-0-3	7.95	8.39	4.97	5.25	
CaC-5-0-4	8.3	7.86	5.19	4.92	
CaC-7-0-1	7.4	6.28	4.63	3.92	4.298
CaC-7-0-2	7.12	6.84	4.45	4.28	
CaC-7-0-3	6.69	6.92	4.18	4.33	
CaC-7-0-4					
CaC-10-0-1	6.01	6.09	3.75	3.8	3.84
CaC-10-0-2	5.93	5.96	3.71	3.73	
CaC-10-0-3	6.13	6.69	3.83	4.18	
CaC-10-0-4	6.48	5.95	4.05	3.72	
CaC-15-0-1	4.08	3.82	2.55	2.39	2.46
CaC-15-0-2	4.18	3.98	2.61	2.49	
CaC-15-0-3	3.63		2.27		
CaC-15-0-4					
CaC-20-0-1	2.61	2.65	1.63	1.66	1.57
CaC-20-0-2	2.56	2.33	1.6	1.46	
CaC-20-0-3	2.3	2.57	1.44	1.61	
CaC-20-0-4	2.58	2.59	1.61	1.62	

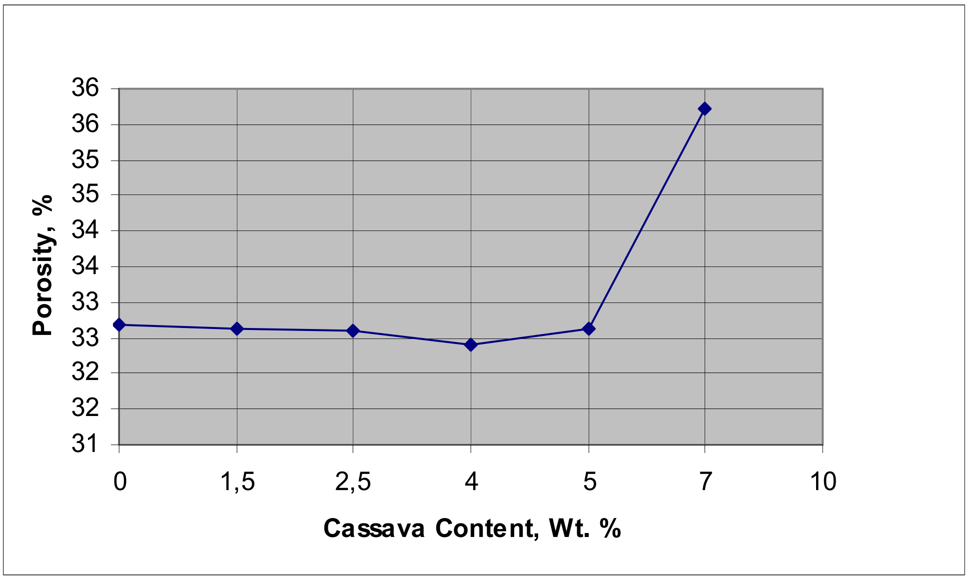
Appendix M Cassava Stabilized Compressed Earth Blocks (CaC): Flexural Strength Test

Specimen Reference	Dry Block Density, g/mm3	Ultimate Load, (F) kN	Flexural Strength, MPa	
		Gross	Gross	Mean
CaC-0-0-1	1792.97	0.373	0.874	0.99
CaC-0-0-2		0.373	0.874	
CaC-0-0-3		0.456	1.069	
CaC-0-0-4		0.491	1.151	
CaC-1.5-0-1	1781.25	0.729	1.707	1.7115
CaC-1.5-0-2		0.729	1.716	
CaC-1.5-0-3				
CaC-1.5-0-4				
CaC-2.5-0-1	1765.625	0.53	1.243	1.6375
CaC-2.5-0-2		0.815	1.91	
CaC-2.5-0-3		0.877	2.055	
CaC-2.5-0-4		0.575	1.342	
CaC-4-0-1	1753.9	0.56	1.312	1.557
CaC-4-0-2		0.65	1.524	
CaC-4-0-3		0.783	1.836	
CaC-4-0-4				
CaC-5-0-1	1740.23	0.47	1.102	1.28
CaC-5-0-2		0.454	1.064	
CaC-5-0-3		0.733	1.718	
CaC-5-0-4		0.533	1.248	
CaC-7-0-1	1635.31	0.435	1.018	0.945
CaC-7-0-2		0.388	0.91	
CaC-7-0-3		0.387	0.908	
CaC-7-0-4				
CaC-10-0-1	1649.90	0.326	0.763	0.80
CaC-10-0-2		0.359	0.842	
CaC-10-0-3		0.34	0.797	
CaC-10-0-4		0.351	0.823	
CaC-15-0-1	1541.99	0.275	0.645	0.57
CaC-15-0-2		0.231	0.541	
CaC-15-0-3		0.236	0.554	
CaC-15-0-4		0.235	0.551	
CaC-20-0-1	1439.45	0.2	0.468	0.33
CaC-20-0-2		0.131	0.308	
CaC-20-0-3		0.148	0.348	
CaC-20-0-4		0.089	0.209	

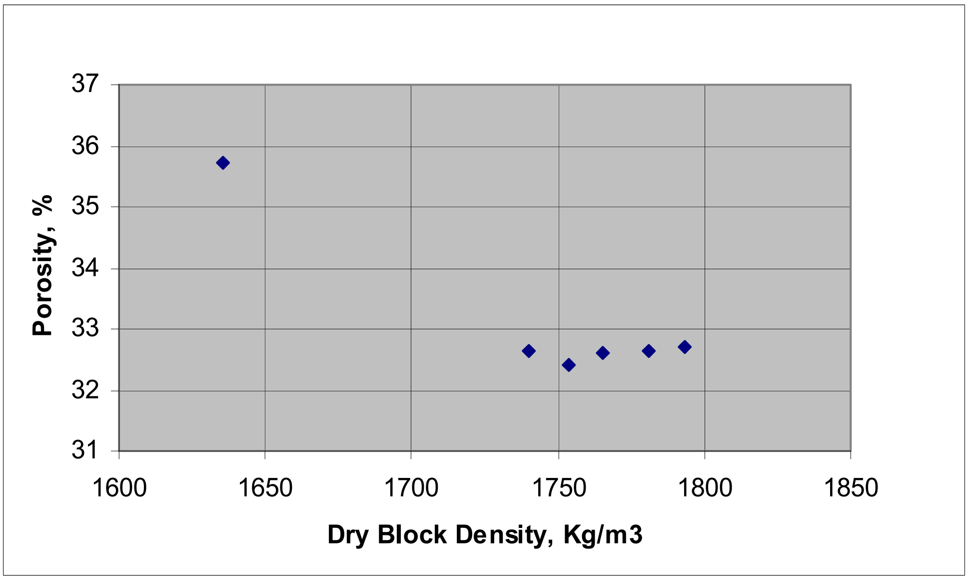
Appendix N Cassava Stabilized Compressed Earth Blocks (CaC): Dry Block Density

Specimen Reference	Mass of Dry Block, g		Dry Block Volume, mm3	Dry Block Density, Kg/m3
	Gross	Mean		
CaC-0-0-1	455	459	256000	1792.97
CaC-0-0-2	464			
CaC-0-0-3	456			
CaC-0-0-4	461			
CaC-1.5-0-1	458	456	256000	1781.25
CaC-1.5-0-2	454			
CaC-1.5-0-3	451			
CaC-1.5-0-4	462			
CaC-2.5-0-1	453	452	256000	1765.625
CaC-2.5-0-2	451			
CaC-2.5-0-3	450			
CaC-2.5-0-4	454			
CaC-4-0-1	449	449	256000	1753.9
CaC-4-0-2	449			
CaC-4-0-3	451			
CaC-4-0-4	447			
CaC-5-0-1	446	445.5	256000	1740.23
CaC-5-0-2	439			
CaC-5-0-3	459			
CaC-5-0-4	438			
CaC-7-0-1	433	434	256000	1635.31
CaC-7-0-2	435			
CaC-7-0-3	440			
CaC-7-0-4	428			
CaC-10-1	424	422.375	256000	1649.90
CaC-10-2	419.5			
CaC-10-3	423.5			
CaC-10-4	422.5			
CaC-15-0-1	396	394.75	256000	1541.99
CaC-15-0-2	398.5			
CaC-15-0-3	395			
CaC-15-0-4	389.5			
CaC-20-0-1	368.5	368.5	256000	1439.45
CaC-20-0-2	371			
CaC-20-0-3	365			
CaC-20-0-4	369.5			

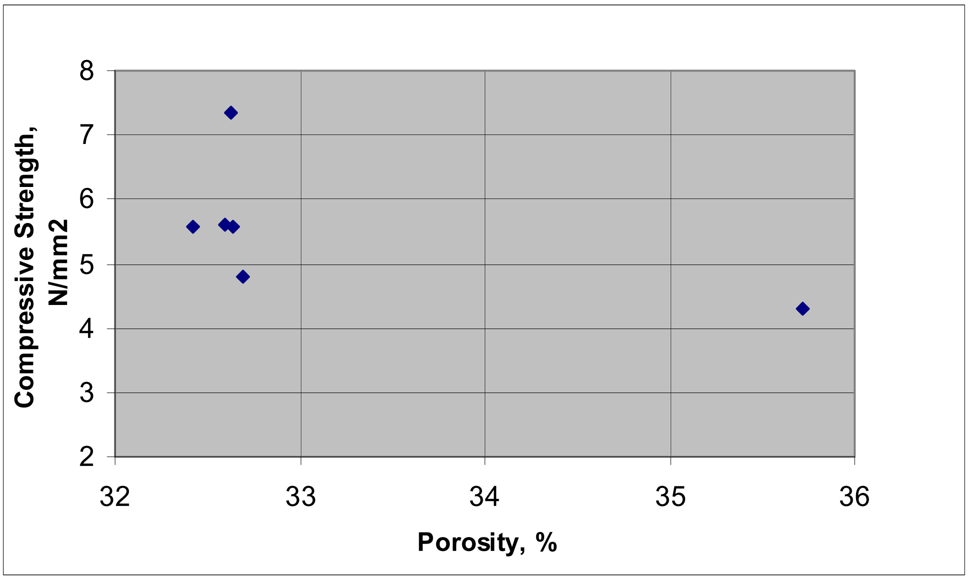
Appendix O Cassava Stabilized Compressed Earth Blocks (CaC): Porosity Cassava Content Relationship



Appendix P Cassava Stabilized Compressed Earth Blocks (CaC): Dry Block Porosity Relationship



Appendix Q Cassava Stabilized Compressed Earth Blocks (CaC): Compressive Strength Porosity Relationship



Appendix R Sisal Stabilized Compressed Earth Blocks (SC): Water Vapour Transmission

S.No.	Date	Specimen Reference and Mean Weight. g			
		SC-0.25	**SC-0.5**	**SC-0.75**	**SC-1.0**
1	05.01.06	339.5095	342.8067	344.902	338.8857
2	07.01.06	342.583	346.9863	348.667	343.3247
3	09.01.06	346.119	350.685	352.0217	347.1053
4	11.01.06	348.886	353.5957	354.7487	350.15
5	13.01.06	351.771	356.681	357.5317	353.2567
6	15.01.06	354.3975	359.4957	360.1383	356.1587
7	17.01.06	356.8885	362.19	362.4653	358.8723
8	19.01.06	359.436	364.832	364.8437	361.5563
9	21.01.06	361.6965	367.316	367.1307	363.977
10	23.01.06	363.9285	369.9617	369.646	366.386
11	25.01.06	366.0215	372.3013	371.7213	368.4047
12	27.01.06	367.9785	374.601	373.6283	370.2913
13	29.01.06	319.605	376.5133	375.2207	371.9073
14	31.01.06	371.375	378.5263	376.9503	373.6413
15	02.02.06	372.765	380.2937	378.2933	375.1727
16	04.02.06	373.9635	381.9697	379.5293	376.5097
17	06.02.06	375.306	383.6667	380.8997	377.9487

Appendix S Cement Stabilized Compressed Earth Blocks (CeC): Water Vapour Transmission

S.No.	Date	Specimen Reference and Mean Weight. g		
		CeC-0	CeC-9	CeC-12
1	05.01.06	354.9353	355.7073	348.898
2	07.01.06	359.2463	358.826	351.7605
3	09.01.06	363.2017	361.6847	354.3905
4	11.01.06	366.352	363.9607	356.582
5	13.01.06	369.5503	366.3613	358.866
6	15.01.06	372.7457	368.618	361.014
7	17.01.06	375.624	370.7557	363.0895
8	19.01.06	378.4433	372.8183	365.122
9	21.01.06	381.0357	374.7353	366.95
10	23.01.06	383.7147	376.763	368.832
11	25.01.06	386.3113	378.6357	370.549
12	27.01.06	389.0843	380.5573	372.318
13	29.01.06	391.618	382.2817	373.9535
14	31.01.06	394.5643	384.295	375.8335
15	02.02.06	397.2387	386.1757	377.5415
16	04.02.06	399.8867	387.811	379.0925
17	06.02.06	402.677	389.703	380.7405

Appendix T Cassava Stabilized Compressed Earth Blocks (CaC): Water Vapour Transmission

S.No.	Date	Specimen Reference and Mean Weight. g			
		CaC-1.5	CaC-2.5	CaC-5	CaC-7
1	05.01.06	348.5625	350.475	348.3277	344.638
2	07.01.06	352.517	354.249	352.0463	348.6717
3	09.01.06	356.066	357.581	355.3957	352.2533
4	11.01.06	358.847	360.24	358.0533	357.177
5	13.01.06	361.8495	363.0805	360.9163	360.123
6	15.01.06	364.658	365.706	363.5873	**362.851**
7	17.01.06	367.277	368.1435	366.0743	**363.4753**
8	19.01.06	369.8445	370.5265	368.5127	**366.0097**
9	21.01.06	372.2015	372.7375	370.746	368.348
10	23.01.06	374.6865	375.1175	373.087	370.7837
11	25.01.06	377.013	376.329	375.2363	373.0063
12	27.01.06	379.293	379.559	377.4233	375.1863
13	29.01.06	381.2845	381.476	379.344	377.0293
14	31.01.06	383.4065	383.5005	381.4007	378.9383
15	02.02.06	385.1705	385.181	383.099	380.5197
16	04.02.06	386.7155	386.655	384.613	381.877
17	06.02.06	388.2975	388.148	386.19	383.2803

Appendix U Cement-Sisal Stabilized Compressed Earth Blocks (CSC): Water Vapour Transmission

S.No.	Date	Specimen Reference and Mean Weight. g		
		C-SC-0.5-5	**C-SC-0.5-9**	**C-SC-0.5-12**
1	05.01.06	338.2363	343.9817	347.903
2	07.01.06	341.9057	346.9703	350.939
3	09.01.06	344.568	349.7593	353.798
4	11.01.06	346.9263	352.0213	356.1047
5	13.01.06	349.425	354.4037	358.5403
6	15.01.06	351.706	356.6437	360.848
7	17.01.06	353.857	358.7827	363.064
8	19.01.06	355.947	360.8557	365.1933
9	21.01.06	357.9	362.7257	367.1163
10	23.01.06	359.9577	364.7023	369.1277
11	25.01.06	361.832	366.5157	370.954
12	27.01.06	363.6393	368.3493	372.8547
13	29.01.06	365.1507	369.9913	374.5947
14	31.01.06	366.7263	371.7987	376.5387
15	02.02.06	368.0283	373.3417	378.2487
16	04.02.06	369.1473	374.721	379.7763
17	06.02.06	370.3113	376.1533	381.3913