OPTIMIZATION OF SOIL-LIME AND CEMENT MIXES FOR COMPRESSED EARTH STABILIZED BLOCKS FOR LOW-COST HOUSING IN EAST AFRICA (KENYA)

A THESIS IN

Civil Engineering

Presented to the Faculty of the University
of Missouri at Kansas City in partial fulfillment of
the requirements of the degree

MASTER OF SCIENCE

By

KENNETH THENYA WACHIRA

B.S. Kansas State University – Manhattan, 2000

Kansas City, Missouri

2018

OPTIMIZATION OF SOIL-LIME AND CEMENT MIXES FOR COMPRESSED EARTH STABILIZED BLOCKS FOR LOW-COST HOUSING IN EAST AFRICA (KENYA)

Kenneth Wachira, Candidate for the Master of Science Degree

University of Missouri at Kansas City, 2018

ABSTRACT

The population of East Africa (Kenya) has continued to increase steadily due to rural urban migration. This has created a large population influx of low-income earners which has resulted in lack of low-cost affordable housing. Low-cost housing has always been in short supply and the large urban population has only exacerbated the situation. Furthermore, these economic migrants are poor and look to the governments for assistance in housing. The lack of adaptation of new construction techniques and use of locally available low-cost building materials has made housing to be scarce. Cement is two to three times the cost of construction lime in East Africa, thus the need to maximize the use of lime. Conventional building materials (fired bricks and concrete blocks) have proved to be expensive and unsustainable; stabilized earth is the cheapest of the materials locally available. There is a huge incentive to investigate the use of sustainable and appropriate technologies that are affordable in local communities.

This study research project looks at enhancing the use of soil-cement normally used for compressed stabilized earth blocks (CSEBs) with the addition of lime. Also investigated is the relationship between soil properties, stabilizers (lime & cement). Areas considered are:

- Proportions between soil and stabilizer will be optimized taking into consideration the specific characteristics of soil.

- The use of lime and cement in a two-stage mixing process; reduce the shrink swell of high Plasticity Index (PI) soils by reducing the PI with lime (cure for 24 hrs.). Then provide strength with cement to ensure blocks are dense and durable with regular surfaces and edges.

Phase 1 testing revealed improvements in the samples dry and wet compressive strength, abrasive strength and capillary absorption, compared to the control soil-cement sample. Phase 2 testing entailed further mix design optimization of the samples with the highest properties tested in phase 1 by reducing the cementitious (lime and cement) materials used in the mix designs.

APPROVAL PAGE

The following faculty listed as appointed by the Dean of the School of Computing and Engineering, have examined a thesis entitled "Optimization of Soil-Lime and Cement Mixes for Compressed Earth Stabilized Blocks for Low-Cost Housing in East Africa (Kenya)," presented by Kenneth T. Wachira, a candidate for the Master of Science Degree, and certify in their opinion it is worthy of acceptance.

Supervisory Committee

John T. Kevern, Ph.D., Committee Chair

Department of Civil Engineering

Jerry Richardson, Ph.D.

Department of Civil Engineering

Megan Hart, Ph.D.

Department of Civil Engineering

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENTS

The author wishes to thank the following people for their contribution in achieving the aims of this study.

First and foremost, I would like to extend my deepest gratitude and thanks to my supervisor Associate Professor Dr. John Kevern P.E. for his guidance, patience and commitment throughout the entire process of my research. Dr. John Kevern corrected my writing and financially supported my research.

I would also like to thank the other graduate students in the department who were always willing to help me and show me how to use various equipment's in the laboratory. My research would not have been possible without their help.

Finally, I would like to thank my wife, Matanda for encouraging and standing by me throughout this process and my children (Jabulani & Mayamiko Wachira) for being patient and enduring all the times I was away.

CHAPTER 1. OVERVIEW

In East Africa (Kenya) and many developing countries earth has been a traditional building material for housing. The population in developing countries in East Africa (Kenya) as an example has been growing rapidly and the need for housing continues to increase drastically especially in urban areas due to migration.

Conventional construction methods in East Africa use fired bricks, concrete blocks, timber and steel for construction which are high energy embodiment materials and contribute greatly to environmental degradation.

Traditional adobe blocks are most commonly used for construction of very low-income earners. Adobe blocks are made by mixing mud with straw and left in the "forms" for a short time and then the blocks are removed and allowed to cure for about four weeks. The same mud "mortar" is used to hold together the blocks. Below is Table 1: Advantages and Disadvantages of Adobe Blocks for construction.

Table 1: Advantages and Disadvantages of Adobe Blocks

Advantages	**Disadvantages**
Easy and Simple to make blocks	No dimensional accuracy, rough looking and break or chip easily
Adobe blocks make attractive walls compared to rammed earth	Not very well suited for tropical climates
No skill necessary and familiarity with users	

To meet the demand of low-cost housing, earth is well poised to be the primary building material, it is cheaply and readily available in communities who construct their own houses. Conventional construction materials are too expensive and require a lot of technical know-how.

In the early 1980s new kinds of unfired blocks were introduced in East Africa (Kenya), with the help of a mechanical machine with a mold to compress the soil and produce a block. The blocks are dried in the sun before using in construction, hence the name "compressed earth block". Later on, stabilizers (cement, lime, asphalt emulsion) were introduced. Nearly any kind of soil can be made better by the addition of stabilizers (Peace Corps, 1981) , stabilizers ensure

- The particles of the soil are cemented together so the block will be stronger
- They can "waterproof" the soil so that it will not absorb water.
- They can keep the soil from shrinking and swelling.

The most commonly used stabilizers are cement and lime; cement is the most commonly used, rarely if ever is the combination of both used due to lack of technical know-how. Cement and lime have similar effect on the properties of cohesive soils. They reduce the swelling potential, plasticity index, liquid limit and increase the shear strength of soils. The concept of using both stabilizers in a two-stage mixing process offers the possibility of cheaply producing CSEBs well suited for low-cost housing.

New technologies are being developed to use for soil stabilization of road beds which can be implemented for use in CSEBs making. Some of the more promising ones are:

I. Use of enzymes in soil stabilization, this could be bio-enzymes or patented enzymes which area proprietary.

II. Low-cost cements consist of mixing cement with pozzolans (natural & artificial) to extend the use of cement. The higher the reactivity of the pozzolans the higher the percentage it can be used to replace cement.

III. Use of Polymers mainly geopolymers. This consists of the use of Sodium Hydroxide (NaOH) or Potassium Carbonate, (K_2CO_3). When mixed with soil and subject to low temperatures a polymerization reaction takes place which causes the hardening of the blocks. A geopolymer low temperature geopolymeric setting block, (LTGS, Patent 80 20386, public domain 1980) as explained by (Davidovitts, 1988) is made from lateritic clay earth that reacts with a geopolymer.

IV. Nanotechnology in cements is currently being explored by a lot of researchers in the construction industry. The most reported research work regarding application of nanotechnology in cement-based materials is either related to coating or enhancement of mechanical and electrical properties. Active research is also focused on areas dealing with cement and concrete. (Kumar, Mathur, & Kumar, 2011)

Another area of interest is on concrete with nanoparticles. Nanoparticles can enhance the characteristics of concrete i.e. strength or durability at the same time reducing the high energy embodiment of concrete ingredients. Mechanical properties of cement-based materials with nano-SiO2 (Silicon Dioxide); TiO2 (Titanium Dioxide) and Fe2O3 (Iron III Oxide) are currently being studied. Experimental results demonstrated an increase in compressive and flexural strength of mortars containing nano-particles (Ashish Sharma, 2011).

The scope of study of this thesis is to enhance the optimization of the soil-lime and cement mixes for use in compressed stabilized blocks. This study looks at using lime and cement in a two-stage process to extend the use of cement. This study will also examine the relationship between stabilizers (lime and cement) in relation to the soil properties. Determine stabilizer quantities and test physical characteristics of blocks (density, compressive strength, water absorption and abrasion). This will enable development of durable compressed stabilized earth blocks for low cost housing.

The research objective is to find ways in which lime can be used to extend the use of cement in soil stabilization. Cement is a highly priced commodity and is about two to three times as expensive as lime depending on where you are in Kenya or East Africa. The objective is to optimize the use of lime by using it to reduce the shrink swell and PI of the soil and using cement to generate the compressive strength of the blocks. Areas of interest will include:

- To develop a laboratory mixture design using lime and cement and a testing protocol for the blocks and ensure they have the necessary performance characteristics.
- Determine the percentage of lime and cement to be used depending on the soil type and quality.

Overall this study attempts to improve CSEBs as a building material and so summarize information on the best ways to stabilize a wide array of soils.

Chapter one is an introduction of earth as a building material and the dearth of affordable low-cost housing in Kenya and neighboring countries in East Africa. It also looks at the prevailing technologies of compressed earth stabilized blocks (CSEBs) production.

Chapter two looks at the literature review of the CSEBs and compressed earth blocks (CEBs); there use and experimental work done to improve them. It also looks at the history of CEBs and the importance they have had in low cost housing. The introduction of various stabilizers to produce CSEBs, compaction techniques and curing methods used. Various compression techniques used in block production are also explained. This chapter also discusses the various quality control standards which are being adopted in the CSEBs production for standardization.

Chapter three describes the structure of the thesis, experimental design, and Phase 1 and 2 sample preparation of mix designs. Preliminary laboratory testing, mixing, optimal water content, molding pressure, curing conditions and presents standard tests done on the cylinders.

Chapter four presents the results of all the experiments that were carried out and the inferred conclusions from the tests. Also, discussed is the comparison of the results to African Regional Standards for Compressed Earth Blocks where applicable and other accepted standards for CSEBs.

Chapter five discusses the conclusion and future research recommendation areas. It also discusses the limitations of the research.

CHAPTER 2. LITERATURE REVIEW

Introduction

Earth for Compressed earth blocks (CEBs) has been used as a building material in Africa and other parts of the world for centuries. Notably rammed earth walls, cob & wattle walls have been used to construct structures which are still currently in existence. CEBs are susceptible to environmental conditions in which they are used. In tropical countries with wet climates the CEBs are prone to shrink and swell due to inherent clay soils present in the blocks. This greatly reduces the life of the structure. Fired bricks are also popular this time but required the cutting of trees to build a kiln for the bricks which has led to massive deforestation. In the late 80s stabilizers started being used, mainly lime and cement. These blocks were referred to as Compressed Stabilized Earth Blocks (CSEBs). Earlier on the type of stabilizers to be used depended on whether you are in a rural or urban setting. Cement was easier to acquire in the urban areas and lime more easily accessible in the rural areas. The cement factories are based around growing urban areas and the lime is sourced from ground kiln where limestone calcination occurs. A lot of experimental work has been done to improve CSEBs in the following areas:

- By investigating the best type of stabilizer to use for different type of soils.
- Type of compaction techniques, whether static or dynamic and amount of force imparted in the block.
- Using different types of enzymes and alkali activators for some soils
- How to increase the durability of CSEBs which is the biggest drawback in their use.
- Different curing methods which have a direct impact on the durability of the CSEBs.

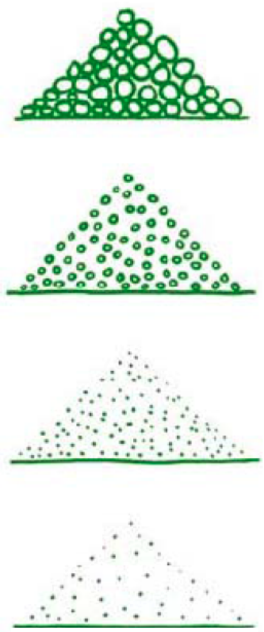
Various stabilizers as discussed at the end of this chapter have been incorporated in the making of CSEBs. The most commonly used ones are cement, lime and sometimes pozzolans like fly ash and sugarcane bagasse ash are used as extenders for the stabilizers. The use of fly ash is not common in African countries due to lack of coal burning power plants. Sugarcane bagasse is available in areas where they grow sugarcane and can be obtained from the factory cheaply. The available quantities could also be marginal and seasonal.

Soil Preparation and Characteristics

Different types of soils are found in different areas of the same region. Figure 1: Soil Types & Colors (Schildkamp, 2009) shows the different types of soils which can vary differently from texture to color.

Figure 1: Soil Types & Colors (Schildkamp, 2009)

Soil structure affects the mechanical behavior of the soil when used in block production and eventually in the quality of the products (blocks and mortar for rendering and filling joints). The four classifications of soils are gravels, sands, silts and clays. By blending and identifying the proportions of each type, block quality can be effectively controlled. Figure 2: Grain Sizes (Schildkamp, 2009) shows the various grain sizes of soils.



Gravels- Particle diameters greater than 2 mm, may be rounded or jagged. Have no noticeable amounts of swell and shrinkage. No cohesion. Excessive gravels may interfere with the block press.

Sands- Particle diameters between 2 and .06 mm (metric), typically made of quartz or silica. Have minimal amount of swell and shrinkage. No cohesion. Sands play an important role in forming a cement matrix in the blocks.

Silts- Particle diameters between .06 and .002 mm, subject to some amounts of swelling and shrinkage. Some cohesion. Excessive amounts of silts are considered detrimental to finished block quality.

Clays- Particle diameters less than .002 mm, clays are subject to significant amount of swelling and shrinkage. High amounts of cohesion. Some clay is required for block production, but excessive amounts are considered detrimental to finished block quality.

Figure 2: Grain Sizes (Schildkamp, 2009)

The best soils to use are the ones that don't contain any organic matter, these types of soils are classified as regular top soil and are usually dark in color. Figure 3: Typical Soil Profile shows a typical soil profile, the best soil to use is in Zone (2) (Adam & Agib, 2001).

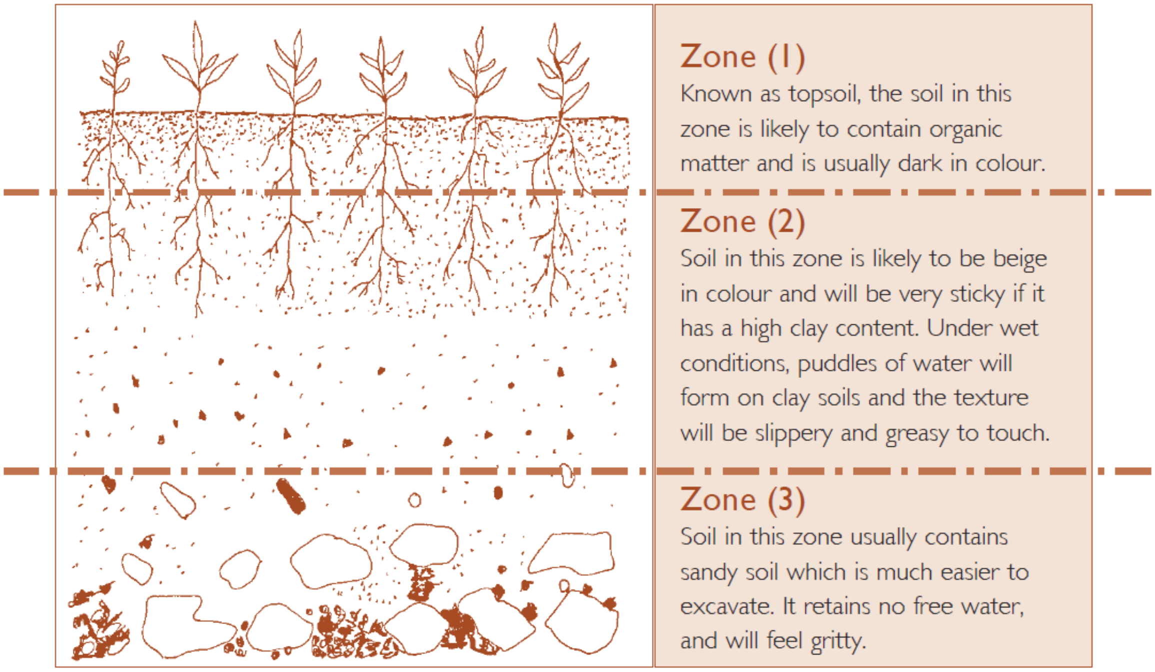


Figure 3: Typical Soil Profile (Adam & Agib, 2001)

Soil Testing

Soil composition/structure tests are divided into two areas:

I. Qualitative

- Visual Examination
- Smell Test
- Sedimentation Test

II. Quantitative

- Linear Shrinkage (Alock's Test)

The linear shrinkage test, or Alcock's test, is performed using a wooden box, 60 cm long, 4 cm wide and 4 cm deep. Grease the inside surfaces of the box before filling it with moist soil with an optimum moisture content (OMC). Ensure that the soil is pressed into all corners of the box using a small wooden spatula that can also be used to smooth the surface. Expose the filled box to the sun for a period of three days or in the shade for seven days. After this period measure the length of the hardened and dried soil as compared to (Guillard & Houben, 1994) the length of the box and calculate the shrinkage length of the soil (Houben H. V.).

Washing Test

Rub the hands with some slightly moistened soil. If the hands are easy to rinse clean this implies that the soil is sandy. If the soil appears to be powdery and the hands can be rinsed clean easily the soil is silty. If the soil has a soapy feel and the hands cannot be rinsed easily the soil is clayey (Guillard & Houben, 1994).

Most of the literature on production of CSEBs referenced a particular type of soil and how the characteristics of the soil influenced the stabilizer to be used. Another paper by (Walker & Stace, 1997) made the CSEBs from dark-red residual kaolinite clay soil with well-graded sand. Kaolinite clay is soft, white and has low shrink swell capacity. In Figure 4: White Kaolinite Clay shows a mined clay kaolinite sample. Heat transforms the kaoline into various states for example (dry, metakaolin, spinel etc.)

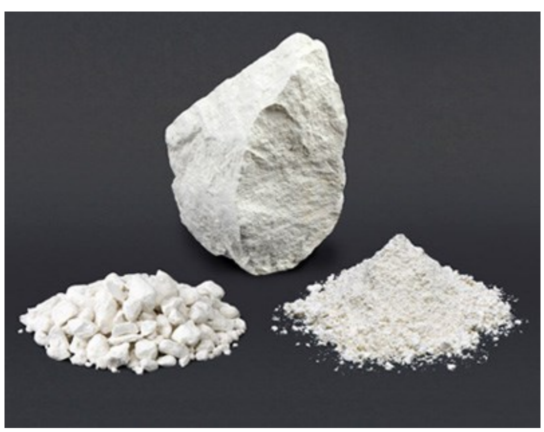


Figure 4: White Kaolinite Clay (Hosokawa Micron Powder Systems, 2018)

Other soils were black cotton soils, red sand ironstone soils, and laterite and lateritic soils (Adam & Agib, 2001) which can be used in block production. Soil blending/grading as a means of obtaining a suitable soil for using for CSEBs has also been widely researched. The soil is tested and if found to be lacking in one type of soil classification, for example sand, then sand can be added. The most referenced item was the clay content which needs to be around 20 % for cement stabilization and about 35% for lime stabilization (Rai). A distinction was also made on using fine- and coarse-grained soils to achieve certain characteristics in the blocks. For example, (Venkatarama, Lal, & Rao, 2007) investigated the optimum soil grading/blending to achieve strength and durability characteristics in CSEBs manufacture. Coarse blended soils with different grading limits were used by (Walker & Stace, 1997) in the manufacture of CSEBs. There results showed a considerable rise in compressive strength and increased mass loss in the durability test as the clay content was increased in the mix designs. The findings also indicated for soil clay contents between (15-30%) cement contents between 5-10% were adequate for stabilization.

The gaps found in the literature review for recommending optimum soil grading limits for the CSEBs production are as follows (Latha & Venkatarama, 2014):

a. There are only limited studies which attempt to specify the exact soil grading limits for CSEBs manufacture. These studies specify optimum clay fraction for only coarse-grained soils.
b. The reasons for the optimum clay fraction yielding maximum strength are not discussed.
c. There are no attempts to specify optimum grading limits considering fine grained soils (especially soils with high silt fraction) for the production of CSEBs.

Mixing

Mixing of the soil-cement was either done manually or by machine in a laboratory. The first step is dry mixing followed by wet mixing. Dry mixing entails mixing the soil and cement on a dry, flat hard surface. This ensures a homogenous mix both in color and texture. The procedure is illustrated in Figure 5: Dry Mixing Procedure.

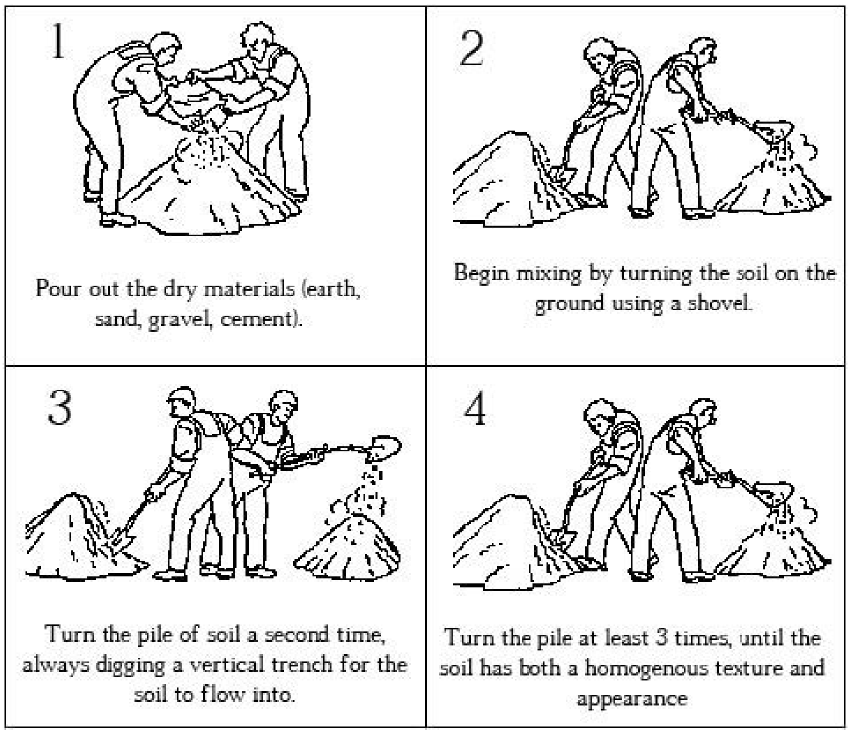


Figure 5: Dry Mixing Procedure (Rigassi, CRATerre-EAG, 1985)

Wet mixing involves mixing the soil-cement/lime mixture with water to hydrate the mixture. Once the soil-cement/lime mixture is homogenous, the molding process should begin immediately. Effect of retention time versus compressive strength is shown in Figure 6: Effect of Retention Time on 28-day Compressive Strength , retention time, the time from first hydration to compression, on block strength (Kerali & Thomas, 2002).

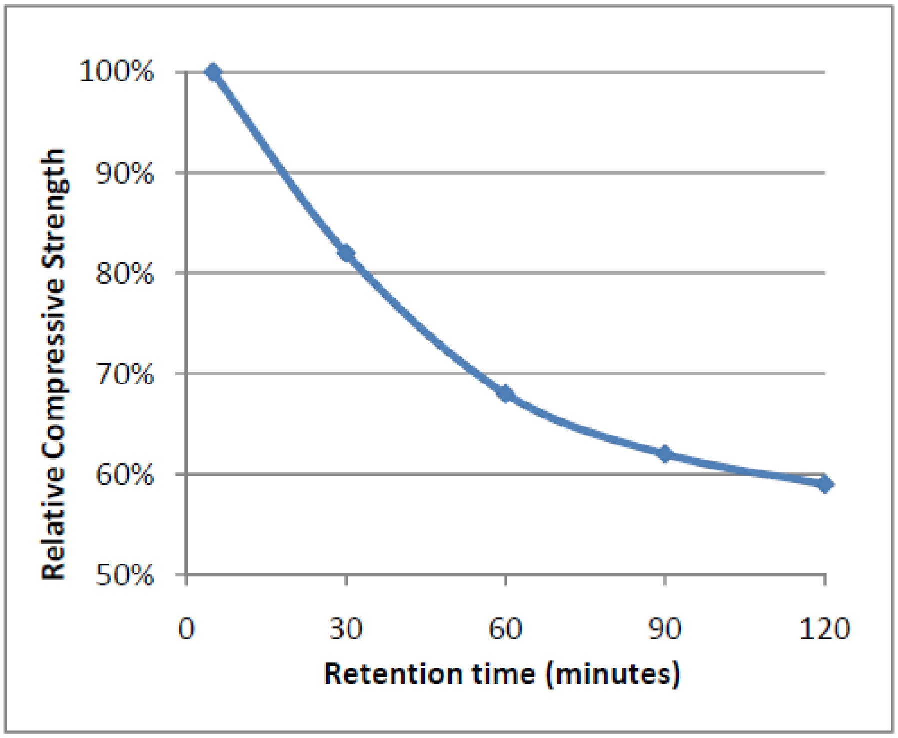


Figure 6: Effect of Retention Time on 28-day Compressive Strength (Kerali & Thomas, 2002)

Any soil-cement/lime mixture which has been in the open for more than an hour should not be used. This is because hydration of cement products has started, and the mix cannot be re-tempered. A standard proctor test is as a benchmark to determine the optimum moisture content (OMC) of a soil. The OPC is a starting point for water needed to be added to the soil mixtures. The Drop Test was used to determine the OMC of the soil-cement/lime mixture. The Drop Test is described as shown in Figure 7: Drop Test Procedure (Proto, Sanchez, Rowley, Thompson, & Moss, 2010).

Drop Test

1. Take a handfull of moistened soil and shape it into a ball using a moderate amount of pressure.

2. Drop the ball of soil onto a hard surface from a height of 1 m.

3. Observe the reaction of the ball.

Observed Result	Conclusion
Ball shattered or broke into more than 7 pieces	Soil is too dry
Ball broke into 4-6 pieces	Water content suitable for compression
Ball broke into 3 or less pieces, or didn't break at all	Soil is too wet

4. Repeat Drop Test at least 3 times to get an average result.

Figure 7: Drop Test Procedure (Proto, Sanchez, Rowley, Thompson, & Moss, 2010)

Compaction

Compaction techniques depended on whether a static or dynamic machine was being used to produce the blocks. The molding pressures were also dependent of the machine type. The wet mixture was weighed, and a known container volume is used to load the mixture into the press. This maintains the density and dimensional accuracy of the molded block. Simple hand operated block press is shown in Figure 8: Hand Operated Block Press (Linyi Fulang Trading Co. Ltd., 2018). The hand operated machines produce blocks with minimum block dry densities of at least 1700 kg/m^3-2200 kg/m^3 (Adam & Agib, 2001).

Figure 8: Hand Operated Block Press (Linyi Fulang Trading Co. Ltd., 2018)

An example of a highly static machine was Auram Press 3000 (Auroville Earth Institute, n.d.) which has a very high compression ratio and can produce 850 blocks per day. Figure 9: Auram Press 3000 shows a typical Auram Press 3000.

Figure 9: Auram Press 3000 (Aureka - Machinery for Sustainable Construction, 2014)

An example of a dynamic compaction machine was the Automatic Terstamatic Press (Appro-Techno SPRL, 2017), this machine has a theoretical capacity of block production of 6,480 blocks. An example of the press is shown in Figure 10: Automatic Terstamatic Press (Appro-Techno SPRL, 2017)

Figure 10: Automatic Terstamatic Press (Appro-Techno SPRL, 2017)

Curing

The wet CSEBs in all instances were covered with plastic sheeting or tarps to prevent sudden loss of moisture after molding. Curing is essential for eventual strength of the blocks. The rate of moisture evaporates from the surface should not be greater than the rate at which it can diffuse through the fine pores of the green brick (International Labour Office and the United Industrial Developement Organization, 1984). When the surface moisture loss is sudden the blocks are susceptible to cracking. Figure 11: Effect of Curing Conditions on 28-day Compressive Strength (Kerali & Thomas, 2002).

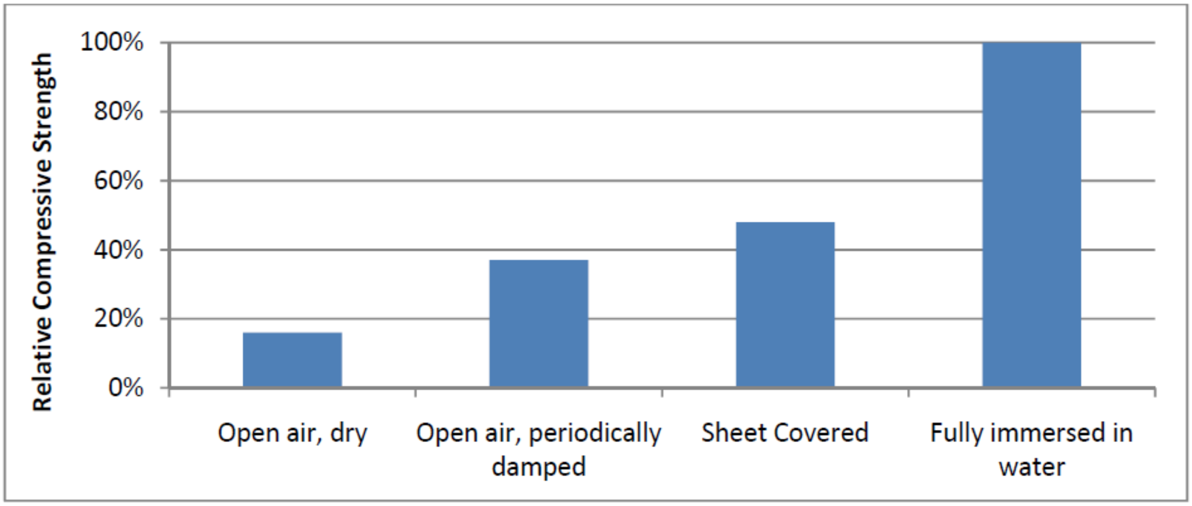


Figure 11: Effect of Curing Conditions on 28-day Compressive Strength (Kerali & Thomas, 2002)

After two or three days, depending on the local temperatures, cement stabilized blocks complete their primary cure. They can be removed from their protective cover and stacked in a pile as shown in Figure 12: Curing of Blocks (Adam & Agib, 2001).

Figure 12: Curing of Blocks (Adam & Agib, 2001)

The blocks should be sprinkled with water daily and then covered with protective covering. The required duration of curing varies from soil to soil and, more significantly, which type of stabilizer is used. With cement stabilization, it is recommended to cure blocks for a minimum of three weeks. The curing period for lime stabilization should be at least four weeks. Compressed stabilized earth blocks should be fully cured and dry before being used for construction (Adam & Agib, 2001).

Testing of CSEBs

After curing and before the CSEBs are used in construction they should undergo testing to make sure they are of a satisfactory quality. The standards of testing used for the cylinders were the ones adopted by the African Regional Standards (ARS) for Compressed Earth Blocks. Under the ARS there are several guides/documents adopted as standards for CSEBs. The document referenced for this work is ARS 671: 1996 – Compressed earth blocks definition, classification and designation of compressed earth blocks.

The ARS standards were silent on the standards for the abrasive strength and thus a manual commissioned by the United Nations in 1958 titled " Manual on Stabilized Soil Construction for Housing (Fitzmaurice, 1958) was used as the standard for abrasive strength test parameters. There are a lot of tests for different properties of the blocks; the testing to be adopted reflects the type of climate where the blocks will be used. For example, if they will be used in tropical areas with high rainfall, they should be tested for moisture susceptibility using two or more different tests.

Cost of CSEBs

The cost of CSEBs is an important factor in their usage in developing countries. In the developing countries their cost might be high due to the amount of cement and type of machinery needed to manufacture them. The cost of labor is cheap relative to the cost of materials. The cost of CSEBs will vary a great deal from county to country and even from one area to another within the same country. Unit production costs will differ in relation to local conditions (Adam & Agib, 2001).

Causes for cost variations include (Adam & Agib, 2001).

- Availability of soil, whether it is available on site or must be transported to the site.
- Suitability of the soil for stabilization, and thus the type, quality and quantity of stabilizer needed. It may also be necessary to buy sand if the soil has an excessively high linear shrinkage.
- Current prices of materials, especially stabilizers (cement).
- Whether the blocks are to be made in rural or urban areas, size and type of equipment used, and quality required.
- Current wage rates, and productivity of the labor force.

In the rural villages, blocks can be communally manufactured, and soil would be available at the site of construction thus further reducing the cost of the CSEBs.

It was observed that production of CSEBs is competitive with other widely accepted building materials which have high energy embodiment. For example, the comparable cost of various sub-structure and superstructure items of a rural house in Mozambique are shown in Table 2: Direct Cost Comparison for Rural House Model.

Table 2: Direct Cost Comparison for Rural House Model (Kuchena & Usiri, 2009)

Phase	Costs (MTn) 26 MTn ≡ US$ 1		
	Stabilised Soil Blocks	Concrete Blocks	Industrial Clay Bricks
Foundation	8,465.00	9,981.00	9,981.00
Walling	9,410.00	23,030.00	19,430.00
Windows, Doors	11,660.80	11,660.80	11,660.80
Roofing	11,852.00	11,852.00	11,852.00
Finishes	2,430.00	8,480.00	8,480.00
Total	***43,817.80***	***65,003.00***	***61,430.00***

CSEBs are about 32% lower in cost than the concrete blocks and about 29% lower in cost than the industrial clay bricks.

Socio-Economic Factors

Despite earth being used for housing in developing countries especially in the rural areas, it invokes a negative connotation as being a poor man's building materials. A major hindrance in adaptation of the CSEBs is a lack of standards from a national level. The technology is appreciated but the quality control is the biggest drawback limiting its usage to alleviate extreme housing shortages in developing countries especially in Africa.

A lot of low-income housing projects initiated by the governments (Kenya & Malawi) do not take advantage of CSEBs as a viable material for construction.

In Sudan, community buildings have been using CSEBs so that local people can see for themselves the quality and durability of the material and experience, first hand, the quality of construction CSEBs can offer (i.e. El Haj Yousif prototype model school) shown in Figure 13: El Haj Yousif School Under Construction (Adam & Agib, 2001).

Figure 13: El Haj Yousif School Under Construction (Adam & Agib, 2001)

Over the years various organizations have improved on the design of the low-cost housing using CSEBs. One of the organizations is Habitat Verde which has designed aesthetically pleasing structures. Figure 14: CSEB House (Habitat Verde, 2014) shows a low-cost house built with CSEBs.

Figure 14: CSEB House (Habitat Verde, 2014)

This kind of projects have enabled to burnish the image of CSEBs and improve their use in local communities. The quality of the dwelling is outstanding and attractive to prospective home buyers or renters.

Research Background

The overall research am doing looks at stabilizing soil with lime and cement in a two-stage process. The first step is mixing the soil with lime and letting it mellow for 24 hours to reduce the shrink and swell of the soil and lower the plasticity index (PI) of the soil. The second step involves mixing the soil-lime with cement to impart strength through bonding in the soil-lime and cement matrix.

The research am undertaking is important in this field since it aims at optimizing the design mixes for soil, lime and cement mixes. It delves into more details on the viability and variability of the various mix designs. The various mixes have different amounts of lime and cement; which must meet the baseline standard tests for soil-blocks. These are; general appearance tests, dimension accuracy, mass, apparent density, dry and wet compressive strengths, abrasive strength and, capillary absorption. When the blocks can demonstrably meet these standards, they can be effectively used for building low-cost housing without any impacts to the longevity of the structure.

Am interested in this topic since it would have a profound impact on the quality of the soil blocks produced for low cost housing. Poor quality of the soil blocks is the main hindrance of their use in low or medium cost housing projects. The lack of technological knowledge in soil testing and medium cost of cement contribute to the production of poor-quality blocks by use of low amounts of cement. By encouraging the use of basic soil characteristic tests and extending the use of cement by using lime which is 2 to 3 times cheaper than cement depending on where you are building (rural or urban).

Various soils require or can be stabilized with different stabilizers present in the area. The literature review will discuss the most commonly used methods of stabilization which are:

I. Lime Stabilization

II. Cement Stabilization

III. Mechanical Stabilization

IV. Asphalt/Bitumen Stabilization

Lime Stabilization

Limes are available in either quicklime (calcium oxide-CaO), hydrated lime (calcium hydroxide-Ca $(OH)_2$ or lime slurry (calcium hydroxide in water). The lime slurry is easy to transport and has minimal dust production when being used. Lime makes one of the best stabilizers for most type of clays. Lime can be used with almost any soil with a plasticity index of (PI) of 12 and greater (Wolfskill, Lyle A. ; Agency for International Development, 2005). Lime can be used to treat soils in two different ways, either through chemical stabilization or modification.

Chemical stabilization would be more applicable to soil-block making while modification is used to stabilize the subgrade of construction areas where the subgrade is susceptible to movement due to presence of highly expansive soils. The physical and chemical properties of various soils are changed by adding lime. The soils with too much clay are best suited for lime stabilization. In Figure 15: Untreated Plastic Clay to Lime-Treated Cla (National Lime Association, 2004) is shown after initial mixing and mellowing.

Figure 15: Untreated Plastic Clay to Lime-Treated Clay (National Lime Association, 2004)

The types of soils best suited for chemical stabilization are the highly plastic clays. The blocks made with lime stabilization (chemical) are mainly made from sandy or gravely soils. Soil-blocks made only with lime take about 5-6 times as long to gain full strength as compared to soil-cement blocks.

Lime modification entails drying of soil by mixing lime with about 1-3 percent lime, this process is mainly used by Contractors at construction sites to enable them to create a platform for continuing construction operations. The major difference between chemical and lime stabilization is no structural credit is given to the lime modified layer during design of the subgrade. After initial mixing, the calcium ions (Ca^{++}) from hydrated lime migrate to the surface of the clay particles and displace water and other ions. The soil becomes friable and granular, making it easier to work and compact (Figure 16: Lime Flocculating Clay). At this stage the plasticity index of the soil decreases dramatically, as does its tendency to swell and shrink. The process is called flocculation and agglomeration, generally occurs in a matter of hours (National Lime Association, 2004). In Figure 16: Lime Flocculating Clay a depiction of the lime flocculating clay shows the granular nature of the clay soil.

Figure 16: Lime Flocculating Clay (National Lime Association, 2004)

Some of the research papers discussed the use of lime to breakdown the highly plastic clays before using them for soil-block production. The only drawback discussed in the research papers was the time it takes for the blocks to gain strength and be ready to be used in construction. Highly expansive and high clay soils are most suitable for stabilization with lime. Although, other soils benefit from lime stabilization to lesser degree than other soils. Fine-grained clay soils (with a minimum of 25 percent passing the #200 sieve (74 mm) and a

Plasticity Index greater than 10) are candidates for stabilization. Generally, adding 2-4 percent lime by weight of dry soil will suffice (National Lime Association, 2004). If desired an Atterberg test can be done on the soil-lime mixture to determine the new PI.

Cement Stabilization

Cement can be used alone to stabilize a wider range of soils, but it works best with sandier and gravely soils. The mixture is known as soil-cement. For effective use of cement all the soil clods must be broken down to increase the surface area for cement to work, it is not preferred for highly clayey soils due to their physical structure. After the soil has undergone basic soil mechanic tests, cement can used on the soil if it has a plasticity index of between 0 to about 12.

To determine the amount of cement to use in a soil a linear shrinkage mold is used which is filled with mud (soil and water). The mold is left out in the sun for three days or seven days under the shade. The shrinkage of the soils is measured and from standard tables you can tell what percentage of cement to stabilize a soil effectively. This was the most common method of soil stabilization from the literature review. The only drawback is that cement is expensive and not readily available in rural-urban settings.

Mechanical Stabilization

Mechanical stabilization of soil can be achieved by applying a dynamic or static force to the soil-block mass. From the literature research this was not a commonly used method of soil-block construction due to the lack of a stabilizer use in the soil. The soils mostly used with this method had a high clay content for it to act as the cementing agent.

The soil and water mixture were put in dynamic block maker or wooden molds and then let to dry out in the open covered with plastic sheeting to prevent sudden loss of moisture. After two weeks all the moisture has been lost and the blocks could be used for construction. The research indicated these blocks were highly susceptible to cracking and moisture absorption since the surface of the blocks was not sealed.

Mechanical stabilization was used mostly for rammed earth construction. This technique was used mainly by dynamically ramming the clay-based soil inside some formwork to hold the wall up during construction. When mechanical stabilization was used in conjunction with a stabilizer the soil-blocks were durable and of high quality which is ideal for housing construction.

Asphalt/Bitumen Stabilization

Asphalt is normally mixed with water and it is known as an asphalt emulsion. After drying the asphalt separates back from the solution leaving a thin film on the soil grains which provides the cementitious material for the soil-blocks. Other types of asphalt that have been used are called cutbacks which have been mixed with gasoline, kerosene etc. to make them thinner so that they can be used without being heated up. Asphalt works well with sandy gravely soils, because the soil particles will be covered with asphalt thus giving them the adhesion quality to stick with one another.

This technology is used to stabilize low-volume gravel and macadamized unpaved roads. By mixing the bitumen binders and subsequently compacting the (consolidation), the grain structure is permanently sealed (cemented). The load distribution of the stabilized layer is about 2-2.5 times greater than that of unbound foundation. (Blumer, 1977)

The literature did not reveal a lot of use for asphalt/bitumen for soil-block use due to its scarcity and cost. No further work seemed to be going on in this field.

Test Methods

This literature review has shed light on the type of research available concerning compressed earth stabilized blocks and the testing methods employed in different countries. The literature review helped to direct the research project into an area where there was not much research. For example, most papers looked at how cement or lime performed with various types of soils (clayey, sandy, silty or gravely). The cement or lime would be mixed in various percentages of the dry weight of the soil. The test methods adopted for this research were the one which would be relevant to the climate in Kenya which comprise of tropical, arid, semi-arid and experiences long and short rainy seasons.

There were inconsistencies with the testing standard parameters from one country to another. Some papers looked at wet durability testing (spraying water jet) and others looked at dry durability testing by brushing the blocks with a wire brush. The wire brushes used were different sizes, thus a normalization of the data would have to be undertaken to compare the parameters. An example of the different standards from various countries is shown in Table 3: Summary of Durability Results Obtained from Various Sources :

Table 3: Summary of Durability Results Obtained from Various Sources (Ipinge, 2012)

Country (Author, Date)	Compactive Effort (MPa)	Clay Content (%)	PI (%)	Cement Content (%)	Wet Strength (MPa)	Dry Strength (MPa)	Absorption by water Uptake Test (%)	Abrasion by Wet/Dry Durability Test (%)
South Africa (Blight, 1994)	10	12	-	0	-	0.9	-	-
				4	-	4.17	4.2	14.6
				6	-	4.2	2.75	11.7
				8	-	7.93	2.72	10.6
Zimbabwe (Walker,1997)	4	9	10	5	1.6	3.67	14.6	4.9
			10	10	3.2	7.11	13.1	0.7
		40	35	5	0.3	0.3	27.3	75.7
			35	10	0.95	2.13	25.9	25.7
Algeria (Guettala et al, 2005)	15	18	14	5	9	15.4	8.27	1.4
				8	12.7	18.4	7.35	1.25
South Africa (Pave, 2009)	10	-	-	5	3.1	6.1	-	-
		-	-	7	4.8	8.2	-	-
		-	-	10	9	13.6	-	-

From the results it is apparent various parameters are used to derive the data from different countries for example the compaction effort and the quantity of clay in the design mixes vary making standardization difficult. Testing on dry compressive strength was also assessed differently; the two metrics used were compressive and flexural strength (modulus of rupture). Compressive strength results were more prevalent than flexural strength which is an easier test in the field since it doesn't require expensive machinery.

The modulus of rupture test could be performed on site or in the laboratory. This test is based on the principle of a "Three Point Bending Test". This test ensures that the brick will fail in tension rather than in shear which would be characterized with a diagonal crack from the supports. The Masonry Standards Joint Committee (MSJC) gives the allowable rupture load (Mr.) as 30 psi. The New Mexico Earthen Building Materials Code specifies that the minimum flexural strength (Mr.) is 50 psi. The test can be setup as shown in Figure 17: Modulus of Rupture Test Set-Up.

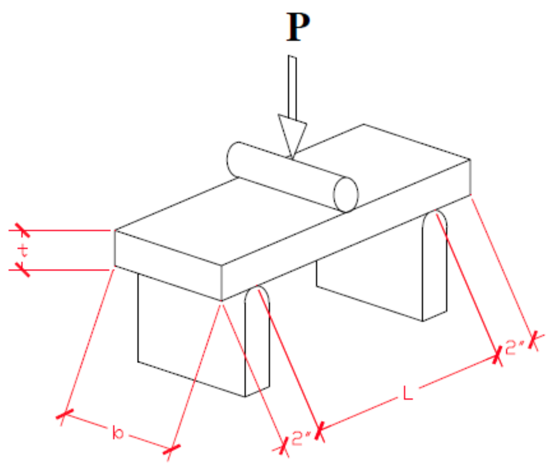


Figure 17: Modulus of Rupture Test Set-Up (Chen, 2009)

The following equation is used to calculate the modulus of rupture:

$$Mr.\ (psi) = 3\,P\,L \,/\, 2\,b\,t \qquad \textit{(Equation 1)}$$

P = Force at failure (rupture lbs.)

L = Distance Between Supports (in)

B = Width (in)

t = Thickness (in)

In Figure 18: Modulus of Rupture Field Test Set-Up depicts, the weight of a person being applied to a brick. The weight of the person and the size of the brick are corelated to represent a modulus of rupture of 30 psi. The field test is quick and gives consistent results.

Figure 18: Modulus of Rupture Field Test Set-Up (Chen, 2009)

Another test from the literature review which had different modes of testing was the capillary absorption test. Some papers used the testing standards for the ASTM D559 (Standard Test Method of Wetting and Drying Compacted Soil-Cement Mixtures) and the African Regional Standards (ARS) 674-677.

Due to the ease of setup and time required the capillary absorption test described in ARS 674-677 was referenced with different setups and methodologies described. The principle of the test is to report absorption values in percentage mass (mass of water absorbed/mass of the block before wetting), this value being one of the standardized classifications for CSEBs (Adam & Agib, 2001). The setup as described in ARS 674-677 is as shown in Figure 19: Capillary Absorption Test .

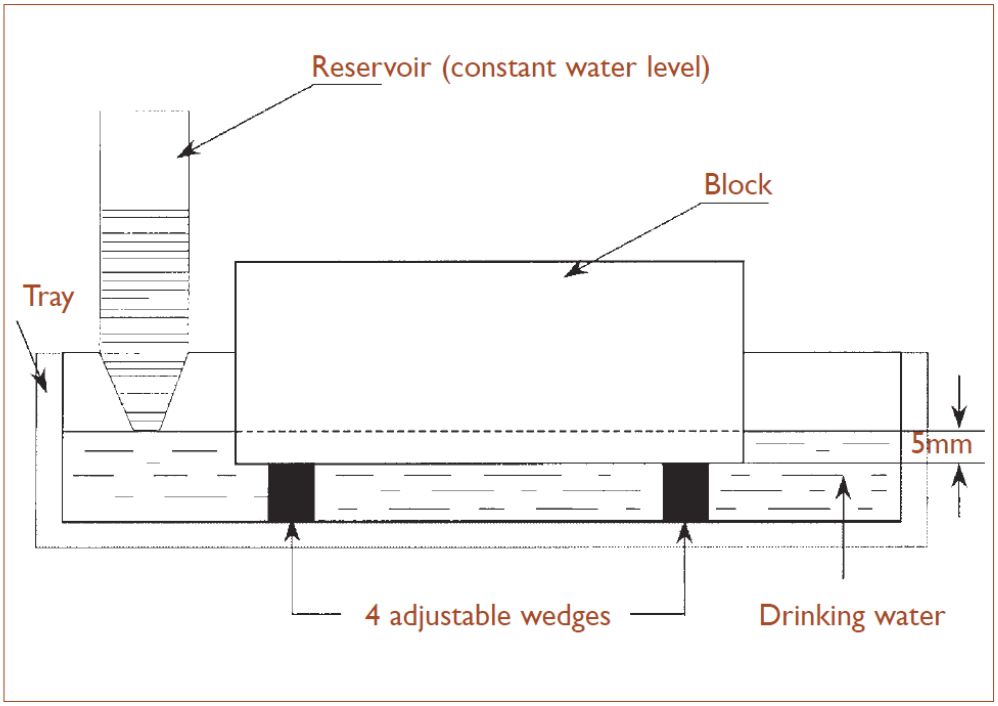


Figure 19: Capillary Absorption Test (Adam & Agib, 2001)

Another test discussed in the literature review was the Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures (ASTM D559). This test method covered the procedures for determining the soil-cement losses, water content changes, and volume changes (swell and shrinkage) produced by repeated wetting and drying of hardened soil-cement specimens. The specimens are compacted in a mold, before cement hydration, to maximum density at optimum water content using the compaction procedure for the Proctor Test (ASTM - D559, 2015). This test was used to ascertain the durability performance of CSEBs.

Durability performance was also determined by carrying out an Abrasive Strength Test described in Compressed Earth Blocks: Testing Procedures (Tech Series Guide No. 16). African Regional Standards for Compressed Earth Blocks give the abrasive strength values in percentage mass (mass loss of mater/mass of block before abrasion), this value being one of the standardized classifications of CSEBs. An abrasion coefficient can be calculated; which expresses the ratio of the surface to the quantity of the material removed by brushing and is proportional to the abrasive strength. The abrasion coefficient gives a more significant value which is also easier to compare regardless of the configuration of the CSEBs (Adam & Agib, 2001). In Figure 20: Steel Wire Brush is shown loaded with a 3kg weight.

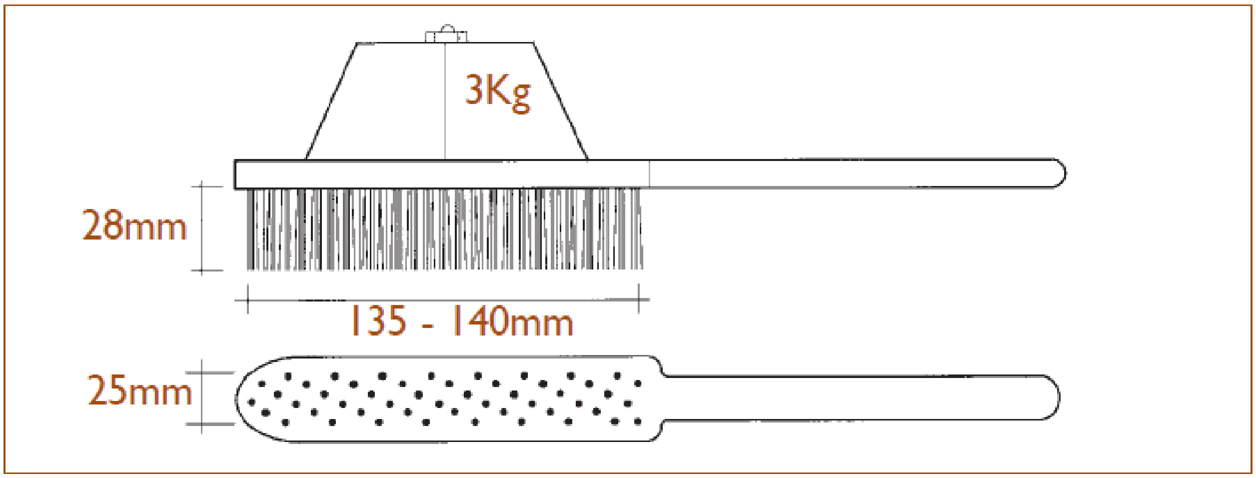


Figure 20: Steel Wire Brush (Adam & Agib, 2001)

Another, weakness, was that there was no consistent literature on the testing of the soil Atterberg limits after adding lime in the literature reviewed. Due to lack of consistent standards which can be utilized by those in the industry of CSEBs, various conferences have been held to assist in normalization of the standards. A set of standards being used in 24 African countries has been prepared in collaboration with CRATerre-EAG with assistance from ARSO (African Regional Standard Organization) and the URA (Associated Research Unit) geo-materials laboratory of the National Scientific Research Center (CNRS) no 1652 of the Lyon National School of State Public Works (ENTPE) (Houben & Rigassi, 1999).

The next steps for research would be to undertake extensive testing of design mixes using the two-stage stabilization process on various types of soils. Another effort would be to standardize the test results for compressed earth blocks at least from one region to another if not from country to country. This baseline standards would be further refined by the respective countries to better conform to their environmental and prevailing sustainable and appropriate technology.

The focus of this research was to look at the efficacy of common stabilizers (cement and lime) used in combination and how this research could be applied to stabilize different kind of soils by using a matrix to determine the quantities of stabilizers to be used. The overall strength of the literature review is that cement and lime can used to stabilize a whole range of soils (clayey, silty, sandy or gravely). These types of soils can be found everywhere and blending of soils can also be done to achieve a soil which can be suitably stabilized.

Adoption of the two-stage mixing of soil with stabilizer would aid in sustainability efforts in reducing the consumption of high energy embodied materials like cement. Testing the efficacy of construction grade lime would also promote local industries and increase the market share of the product.

CHAPTER 3. EXPERIMENTAL DESIGN

Introduction

Unfired earth has been used as a traditional building material in Africa since before colonization in the early 1800s. One of the most common techniques is the use of sun dried or kiln fired adobe bricks with mortar (Sturm, Ramos, Lourenco, & Campos-Costa, 2014). Fired bricks require a lot of firewood in Africa and are one of the causes or deforestation. The governments are strongly discouraging this behavior and urging the people to adapt more appropriate and sustainable materials, for low-cost housing construction. As a result of this, stabilized soil has gained prominence for block production. Stabilized soil has been used in construction of road sub-bases for decades, and people are familiar with the overall concept. CINVA RAM press was the first machine developed to compact soil into a high-density block in Columbia during 1952 (Reddy & Gupta, 2005).

Stabilization materials vary from place to place but the main ones are cement and lime. Cement must be imported or is locally available in Kenya. The cost of cement is prohibitive since it's not only the cost of cement it also includes the transportation cost. Lime can be obtained from limestone rocks fired in ground kilns. This can be done locally and thus mitigates a lot of the costs related to cement. The cost difference between cement and lime is about 2-3 times depending on where your project is located (rural or urban). Thus, there is a high incentive to extend the use of cement in block production with another stabilizer.

The scope of the research endeavors to look at other materials which may be used with cement for soil stabilization. One of the materials readily available at reasonable costs in rural and urban areas is lime. Industrial qualities contain between 90 and 99% "of active lime" while artisanal lime may contain between 55 and 75%, the rest consisting of unburnt or excessively burnt material (GATE, 1994).

The research focuses on design optimization of soil-lime and cement mixes by incorporating a two-stage mixing process. The soil is first dried, pulverized and then ground to pass a No. 20 sieve (0.841mm). In the first stage of mixing, the soil is mixed with hydrated lime at certain percentages and left to mellow for 24 hours before mixing the soil-lime mixture with cement to make cylinders. In the second stage cement is added to the soil-lime mixture to provide the strength for the cylinders. The cylinders are then tested for general appearance, dry & wet compressive strength, capillary absorption and abrasion. The testing is compared to baseline acceptable standards to ensure that the mix designs are viable and meet or exceed the prevailing standards for CSEBs in the local industry.

It was determined that in the event the results are very promising after Phase 1 testing; then Phase 2 testing would be set by further optimizing the mix designs which met the industry standards for the various properties being tested and were above the control sample. Phase 2 mix designs would be set up by using 9% of cementitious materials (lime and cement combined) and another mix design would have half of the cementitious material (4.5%) be se-up by being used in the cylinder production. If phase 1 results were not favorable and were nominally higher than the control sample, then it would be determined that an improvement of the mix designs would be a viable proposition instead of just using cement along for block production.

Soil Testing

The mix design optimization was divided into two phases. Phase 1 was to set-up the various mix designs and compare them to the African Regional Standard (ARS) tests for CSEBs and other pertinent standards. Phase 1 entailed evaluating the best mix design and optimizing it further by reducing the stabilizing material (lime & cement) used in the cylinders and comparing the results to the standards to ensure durability and strength of the cylinders are acceptable and meet or exceed the various standards.

Stabilizers

The stabilizers chosen for this research were cement and lime which are available in East Africa, Kenya. Cement used for the research consisted of Type 1 – Normal Portland Cement which is locally available. The hydrated lime is locally available with an "available lime" of above 90%. A high clay content soil obtained from a highway project in Lawrence, Kansas which was used to formulate the mix designs.

Linear Shrinkage (Alock's Test)

The test was performed using a mold made of wood 60 cm long x 4cm wide and 4 cm deep. The soils used in the Alock's Test (Adam & Agib, 2001) was dried and ground to pass a sieve size (Mesh) of No. 20. The sides of the mold were greased, and the mold filled with soil at about wet optimum moisture content (OMC). The mold was then placed in the sun for three days. Thereafter the length of the hardened soil was measured and compared to the length of the mold to calculate the shrinkage length of the soil. Shown in Figure 21: Linear Shrinkage Mold Samples (3) which were prepared to measure the linear shrinkage of the mix soil design.

Figure 21: Linear Shrinkage Mold Samples

After three days in the sun there was an appreciable shrinkage of the soil as shown in Figure 22: Soil Sample Shrinkage in Mold all the samples were measured, and an average was determined. The average reading was 31 mm from the samples.

Figure 22: Soil Sample Shrinkage in Mold

I. Sieve Analysis and Particle-Size Analysis

A sieve analysis of the soil was carried out to determine the particle size distribution of the soil material passing through a series of vertical stacked sieves which progressively had smaller mesh sizes. The hydrometer analysis was used to determine the distribution of finer particles. The test was carried out per the ASTM D422 – Standard Test Method for Particle- Size Analysis of the Soils. A set of the equipment used in the sieve analysis is shown in Figure 23: Sieve Analysis Equipment. It shows the sieves used, sieve shaker, and weighing balances used for the experiment.

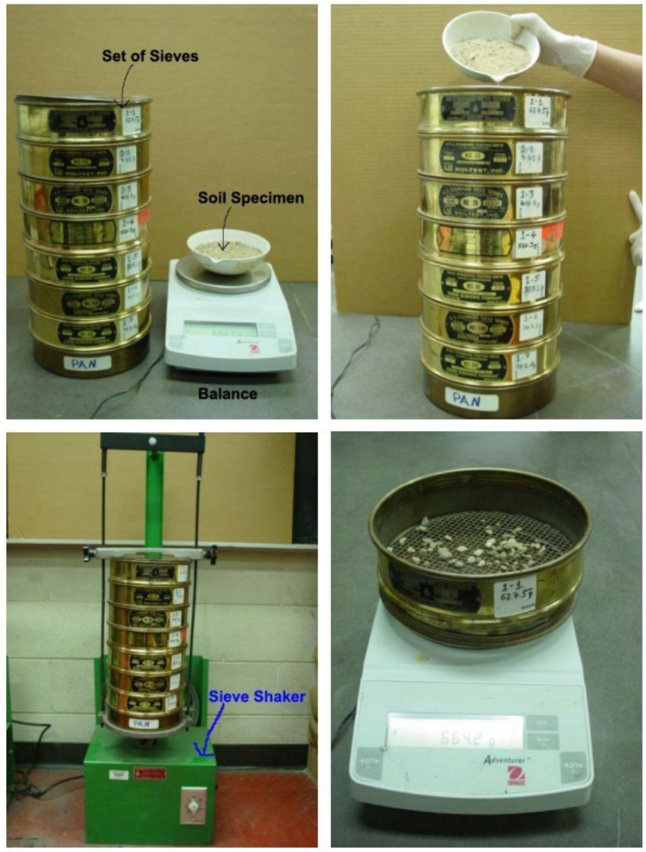


Figure 23: Sieve Analysis Equipment (Reddy K. R., 2002)

The sieve analysis results are shown in Figure 24: Sieve Analysis Results below.

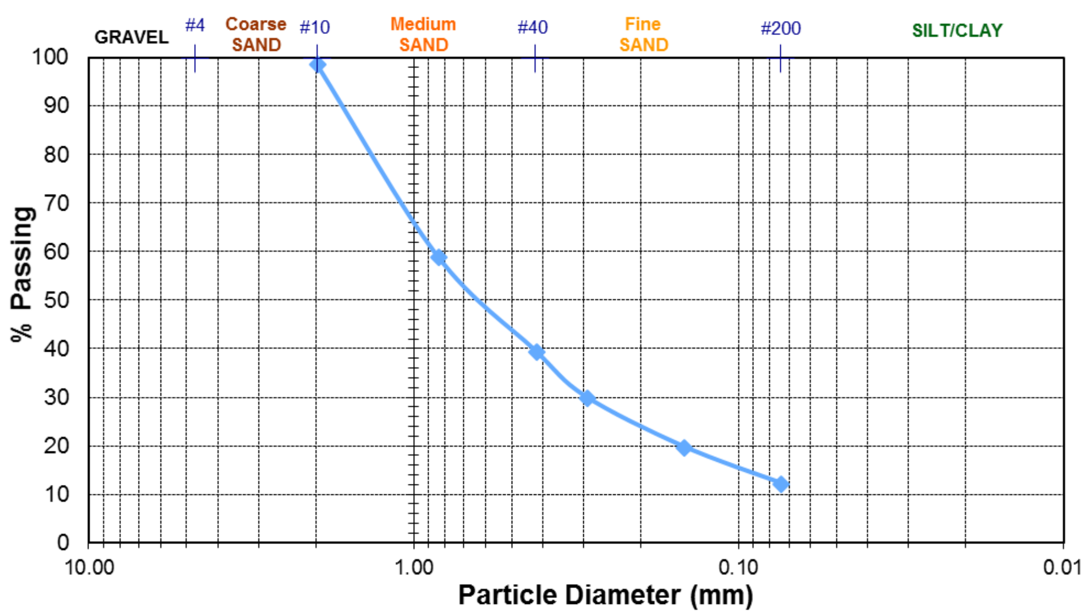


Figure 24: Sieve Analysis Results

Hydrometer Analysis

The fine soil from the bottom of the pan after the sieve analysis was used for particle size analysis. The hydrometer analysis procedure used was as determined in ASTM D422. The equipment used is as shown in Figure 25: Particle Size Analysis Equipment .

Figure 25: Particle Size Analysis Equipment (Reddy K. R., 2002)

The results of the particle size experiment are as shown in Figure 25: Particle Size Analysis Equipment were combined with the sieve analysis results.

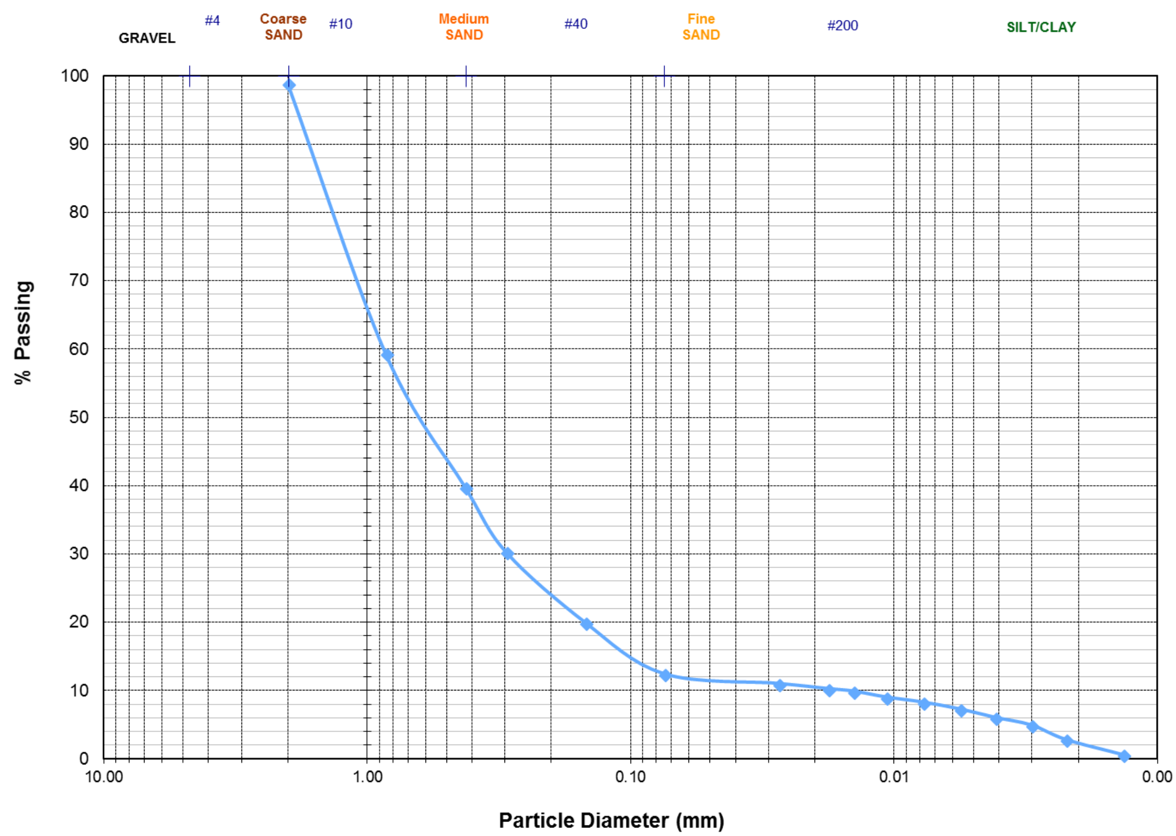


Figure 26: Particle Size Analysis Results

The results from Figure 25: Particle Size Analysis Equipment indicate that the soil consists of: Coarse fragment = 1%, Sand = 86% and Silt/Clay = 13%

ii) Protor Compaction Test

The proctor test was used to determine the optimum water content of the soil at which it can reach its maximum dry density. The test carried out was the standard proctor per ASTM D698 Standard Test Methods for Laboratory Compaction. The soil was air dried and placed in a mold and compacted in three layers with 25 blows per layer from a standard hammer of 5.5 pound dropped from a height of 12 inches. At the end of the test a sample is removed, and the water content and dry density are determined. A set of results are then plotted dry unit weight versus water content. From the curve the maximum dry density and optimum water content were determined. The equipment and illustration of the compaction procedure is shown in Figure 27: Proctor Mold Equipment.

Figure 27: Proctor Mold Equipment (Geotechdata.info, 2016)

The results of the proctor test are shown in Figure 28: Standard Proctor Curve.

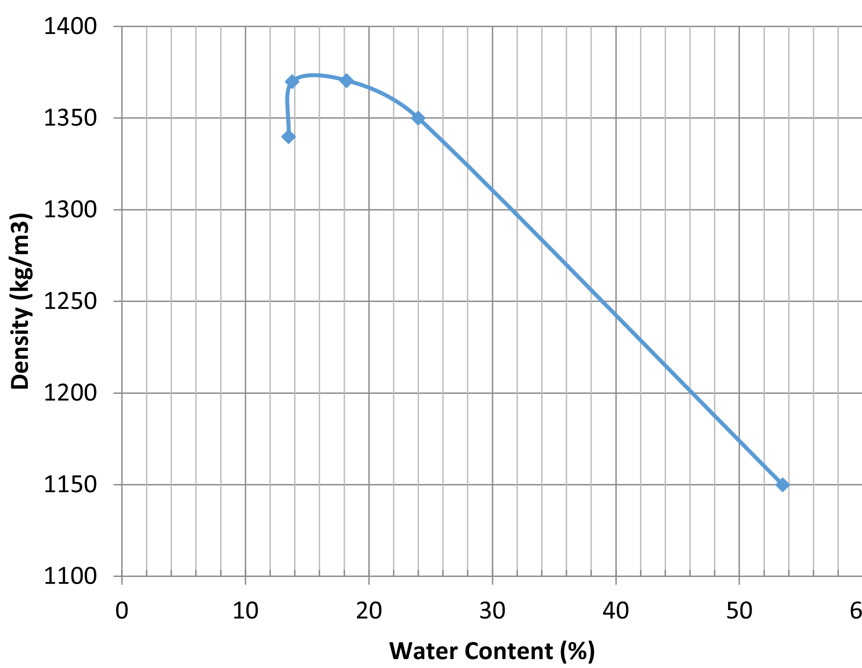


Figure 28: Standard Proctor Curve

Soil Type and Testing

The following tests were conducted on the soil to determine its properties and characteristics. Atterberg limits of the soil are as shown in

Table 4: Atterberg Limits *Result* are as follows:

Table 4: Atterberg Limits Result

Atterberg Limits of Soil	
Liquid Limit (LL)	70.98
Plastic Limit (PL)	23.73
Plasticity Index (PI) = LL - PL	47.25

The soil was classified using the Unified Soil Classification System (USCS) and found to be high plasticity GC (Clayey Gravel with Sand).

Soil-Lime Atterberg limits

The percentages of lime to be mixed with soil were 2%, 4%, 6%, 8% & 10%, these mixes would provide a full array of reactions with the soil.

Table 5: Results of Atterberg Limit Testing - Soil-Lime (%) - Phase 1

Soil Property	Soil – Lime (%)					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
	0%	2%	4%	6%	8%	10%
Plastic Limit (PL)	23.73	35.29	38.73	39.08	39.69	40.27
Liquid Limit (LL)	71.43	58.68	55.49	52.69	52.09	51.69
Plasticity Index (PI)	47.70	23.39	16.76	13.61	12.40	11.42

The graph in Figure 29: Atterberg Limits of Soil-Lime shows the relationship between Atterberg Limits (%) and the lime percent used in the various design mixes.

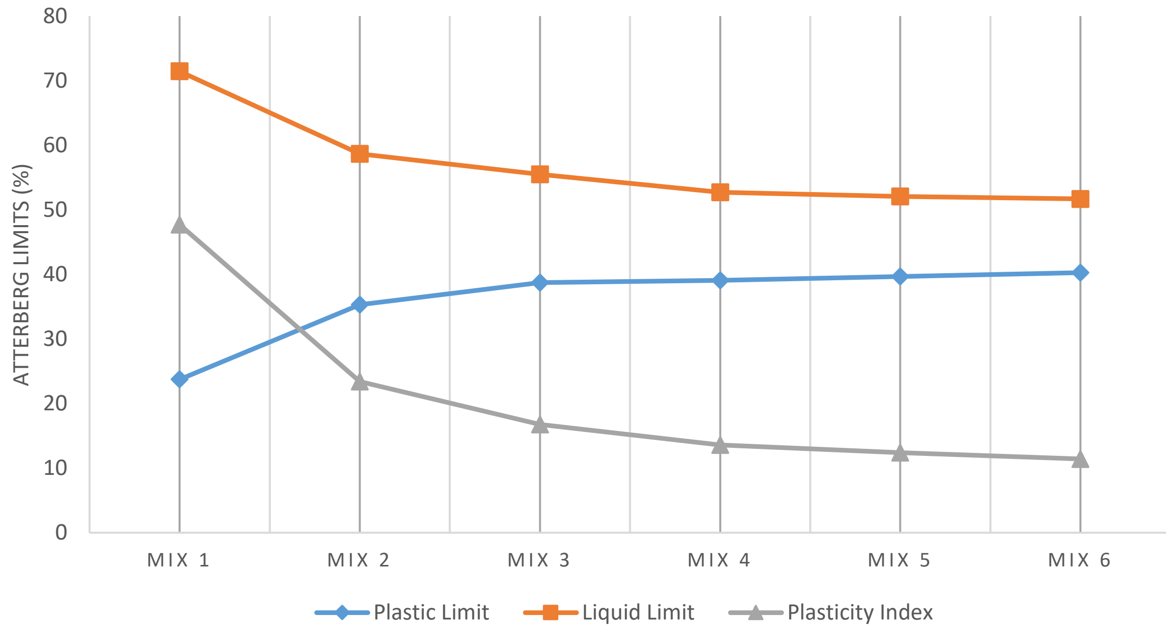


Figure 29: Atterberg Limits of Soil-Lime

Soil-Lime Mix Design

The mix designs were setup to be molded in two phases. Phase 1 was molding the cylinders per the matrix set-up in Table 8: Design Mix Set-Up. Phase 2 entailed reducing the cementitious material (lime and cement) to 9% to further optimize the mix designs.

The soil as determined from the particle size analysis and USCS classification had a high clay content therefore it was a good candidate for lime stabilization. The cement content for the control sample was determined from the linear shrinkage mold testing results which are interpreted from a standard cement to soil ratio. As determined earlier the linear shrinkage form the mold was 31mm. From the results the cement to soil was determined to be 1:14 parts (7.14%). The various cement to soil ratios are shown in Table 6: Cement to Soil Ratio.

Table 6: Cement to Soil Ratio (Adam & Agib, 2001)

Measured Shrinkage (mm)	Cement to Soil Ratio
Under 15	1:18 Parts (5.56%)
15-30	1:16 Parts (6.25%)
30-45	1:14 Parts (7.14%)
45-60	1:12 Parts (8.33%)

Therefore, the control sample was made with 7.14% cement content by weight. A matrix was developed to calculate the descending amounts of cement to use with the five lime percentages picked at an increment of 2% to 10%. The cost of one bag of cement was used as the standard and the cement was replaced by 2,4,6,8,10% of lime by weight. The prices shown in the Table 7: Cement & Lime Costing Matrix are the cost of lime and cement in Kenya.

Table 7: Cement & Lime Costing Matrix

Mix	**Assume 100 Cylinders = 270,000 grams**	**Lime**	**Cost of Lime $ 3.50 per 50 Kg bag**	**Cement Percent**	**Cost of Cement $ 9.52 per 50 kg Bag**	**Cost of Cement & Lime**
1	270,000.00	0%	$0.00	7.14%	$3.67	$3.67
2	270,000.00	2%	$0.38	6.40%	$3.29	$3.67
3	270,000.00	4%	$0.76	5.67%	$2.91	$3.67
4	270,000.00	6%	$1.13	4.93%	$2.54	$3.67
5	270,000.00	8%	$1.51	4.20%	$2.16	$3.67
6	270,000.00	10%	$1.89	3.46%	$1.78	$3.67

The design mixes were setup as follows in Table 8: Design Mix Set-Up to capture the full spectrum of possible mixes and results.

Table 8: Design Mix Set-Up

Design Mix Set-Up		
	Lime (%)	Cement (%)
Mix 1	0	7.14
Mix 2	2	6.40
Mix 3	4	5.67
Mix 4	6	4.93
Mix 5	8	4.20
Mix 6	10	3.46

After the mix designs were setup the soil and lime was mixed in the laboratory using a HOBART Legacy HL200 mixer as shown in Figure 30: Hobart Mixer. The soil was mixed in batches and the appropriate lime mixed with the soil by weight.

Figure 30: Hobart Mixer

The soil was first put in the Horbart Mixer and then the lime was added and mixed for two minutes until a uniform color of the soil and lime was attained. Moisture was then added and to the soil-lime and mixed for another two minutes to ensure all the soil-lime attained the optimum moisture content. The soil-lime mixture was then put in bowls and covered to mellow for 24 hours. The progression of soil-lime mixture colors before and after adding moisture is shown in Figure 31: Soil-Lime Mixtures. After adding moisture the soil-lime mixture turns into a dark gray from light gray. Once the mixing was done the soil-lime mixture was covered with plastic sheets to prevent the sudden loss of moisture, which is needed to enable the reaction to continue for the next 24 hours. The moisture was determined to be enough to activate the lime reaction with the clay content in the soil.

Figure 31: Soil-Lime Mixtures

Soil-Lime and Cement Mix

After 24 hours of the soil-lime mellowing the various mixes were mixed with cement by weight per the mix designs in Table 6: Design Mix Set-Up. The soil-lime and cement was mixed in the Hobart mixer for 3 minutes for the six mixes and the resulting mixture was compacted with a gyratory compactor. The gyratory compactor makes a six-inch diameter cylinders with variable heights. Since the research was optimizing the various mix designs the cylinders were ideal for testing unconfined compressive strength and other parameters.

The Hobart Mixer was used to mix the various mixes in batches after adding the appropriate amount of cement and moisture. There was still some residual amount of moisture in the soil- lime therefore, very little moisture was required to bring the soil-lime and cement mixture to dry optimum moisture content. The drop test was used as a guide to check the amount of moisture in the mixture before compaction. The gyratory compactor used to make the cylinders is shown in Figure 32: Gyratory Compactor.

Figure 32: Gyratory Compactor

Approximately 3,600 grams of soil-lime and cement mixture was put in the compaction chamber for the gyratory compactor. This amount of mixture enabled production of a cylinder with a height of 100 mm and a 6-inch (152.40 mm) diameter which is standard. The gyratory compactor exerts a force of a 600kPa on the cylinder.

For each mix design, 8 cylinders were produced to test for density, dry and wet compressive strength, abrasive strength and capillary absorption. In Figure 33: Cylinder Extrusion from Gyratory Compactor shows the method of extrusion of the cylinders after compaction.

Figure 33: Cylinder Extrusion from Gyratory Compactor

A sample of the cylinder specimen ready for curing is shown in Figure 34: Cylinder Specimen for Curing The cylinders were handled with care to avoid any damage and were inspected visually for any defects.

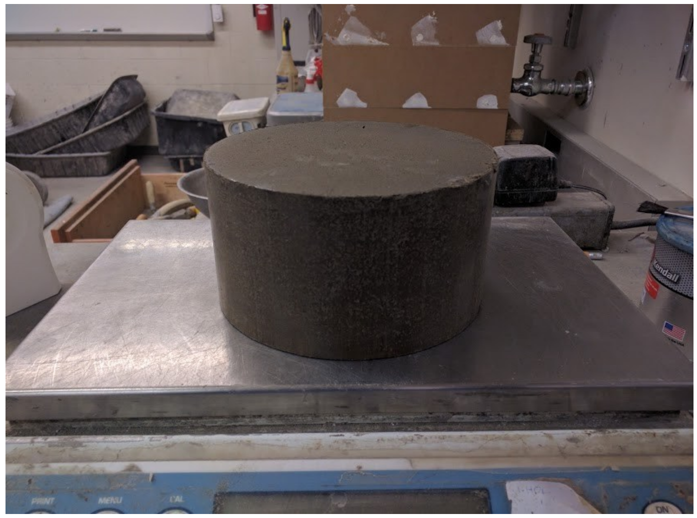


Figure 34: Cylinder Specimen for Curing

This process was repeated until all the mix designs were molded.

Curing Process

The intent for curing process is to keep the cylinders moist for as long as possible to achieve maximum strength. After the specimens were molded, they were stored in a 100% humidity chamber for 25 days and then moved to a 50% humidity environmental chamber for 10 days. The cylinders are shown in the environmental chamber in Figure 35: Cylinders in Environmental Chamber.

Figure 35: Cylinders in Environmental Chamber

The cylinders were weighed then put in the oven at 40º/104º F and weighed daily until the change in weight from consecutive days was less 0.1%. This process took approximately 21-25 days.

Testing

The phase 1 mix designs outlined in Table 8: Design Mix Set-Up were molded and cured accordingly as earlier described. After Phase 1 testing was conducted the results were very favorable and indicated further optimization of the mix designs could be undertaken to close the gap from the best performing mixes to the control sample. Phase 1 design mixes 3, 4, 5, & 6 had more than 9% of cementitious material (lime and cement) in the them and could be further optimized. These design mixes had the highest dry density, dry and wet compressive strengths, low abrasion and capillary absorption. Design mix 6 had the highest quantity of cementitious material with 10% lime and 3.46% cement (13.46%). The quantity of lime and cement were reduced by ratios to match 9% total cementitious material. Cement quantity was determined to be (3.46/13.46 x 9) = 2.31% and the lime was (10/13.46 x9) = 6.69 %.

Design mix 7 was mixed with 6.69% lime and 2.31 % cement and design mix 8 was achieved by halving the cementitious materials in design mix 7 to be 1.16% cement and 3.34% lime. The Phase 2 design mixes are summarized below in Table 9: Phase 2 Design Mixes.

Table 9: Phase 2 Design Mixes

Test Design Mixes		
Design Mix	Lime %	Cement %
7	2.31	6.69
8	1.16	3.34

The same tests as described in Phase 1 testing were conducted for the two mix designs in Phase 2 testing. The experimental design setup of Phase 2 was the same as for Phase 1 testing. Everything was kept the same to enable comparison of the results from the two testing schemes. The results of Phase 1 and 2 testing are tabulated and discussed in Chapter 4.

Phase 1 Testing

During Phase 1 testing the following tests were undertaken for this research:

I General Tests (Adam & Agib, 2001)

a. Textural Characteristics
b. Dimensional Characteristics
c. Geometric Characteristics
d. Appearance Characteristics
e. Physicochemical Characteristics
f. Mechanical, hygrometric and physical characteristics

II Dimensions, Mass and Density

II Dry and Wet Compressive Strengths

III Capillary Absorption

IV Abrasive Strength

I. General Tests

a. Textural Characteristics

All the samples were molded with soil consisting of particles with less than 2 mm. The diameter of the largest particle was restricted to 5 mm.

b. Dimensional Characteristics

Dimensional tolerances were:

Height: +2 to – 3mm;

Diameter: +2 to -3 mm

The nominal dimensions were determined beforehand and entered into the gyratory compactor which ensured the samples were molded as required. Random measurements taken of the height varied within the tolerances given. The diameter was also within the tolerance.

c. Geometric Characteristics

This characteristic is more relevant to a block with flat faces for example stretcher, bed or laying face. The cylinders were checked for surface and edge smoothness and found to be satisfactory.

Surface Smoothness:

- Sides: the sweep must not exceed 2mm
- Compression surfaces: the sweep must not exceed 3mm

d. Appearance Characteristics

Damage:

- Any broken cylinders
- Any cylinder displaying chipped edges or corners, the overall volume of which exceed 5% of the volume of the cylinder

General Appearance:

The cylinders did not display any systematic defects such as cracks or significant chips of any kind. The general appearance of the cylinders was satisfactory based on the criteria described:

- Holes, punctures and scratches were not found on cylinders. Roughness, the exposed faces can have a grainy and rough appearance.
- Chipped corners and edges do not extend over more than 10 mm, and which do not exceed 10 mm in depth are tolerated on all surfaces.
- Flaking & Spiltting: These were tolerated provided mechanical performance is not affected.
- Cracks, crazing, fissures

  Micro-cracks were tolerated on all the bottom and sides of the cylinders. Conditions of acceptability for all faces (bottom and sides) were:

    - They must not exceed 1 mm in width
    - They must not exceed 40 mm in length
    - They must not exceed 10 mm in depth
    - They must not exceed 3 in number on any one surface

e. Physicochemical characteristics

All the cylinders were found to be satisfactory after being examined for physicochemical characteristics.

Pitting:

No pitting due to bursting of expansive materials was tolerated

Efflorescence:

The cylinders must not display any significant and lasting efflorescence covering more than 1/3 for the total surface of CEBs. A faint whitish film or a thin band are not considered.

f. Mechanical, hygrometric and physical characteristics

Mechanical, hygrometric and physical characteristics were determined by the values shown in the following Table 10: Mechanical, hygrometric and physical characteristics required for ordinary CEBs.

Table 10: Mechanical, hygrometric and physical characteristics required for ordinary CEBs

Designation	Environmental constraint category	Mechanical constraint category	f_b dry N/mm^2	f_b wet N/mm^2	Water absorption %	Abrasion loss of matter %
CEB O 1 D		1	≥ 2	N/A	N/A	N/A
CEB O 2 D	Dry Environment (D)	2	≥ 4	N/A	N/A	N/A
CEB O 3 D		3	≥ 6	N/A	N/A	N/A
CEB O 1 R		1	≥ 2	≥ 1	N/A	N/A
CEB O 2 R	Effect of water by lateral spraying (R)	2	≥ 4	≥ 2	N/A	N/A
CEB O 3 R		3	≥ 6	≥ 3	N/A	N/A
CEB O 1 C		1	≥ 2	≥ 1	≤ 15	N/A
CEB O 2 C	Effect of water by vertical penetration (C)	2	≥ 4	≥ 2	≤ 10	N/A
CEB O 3 C		3	≥ 6	≥ 3	≤ 5	N/A

CEB O - Compressed Earth Blocks Ordinary

All the cylinders met the fb dry and fb wet metrics as will be discussed in the next chapter.

II. Dimensions, Mass and Apparent Density

The mass was determined after the cylinders were oven-dried and it was determined there was no change in weight greater than 0.1% of the initial mass within consecutive 24-hour weight measurements. Each of the cylinders were measured for height and diameter to enable calculation of the volume. Cylinders drying in a convection oven are shown in Figure 36: Oven Drying of Cylinders.

Figure 36: Oven Drying of Cylinders

At this point the cylinders were determined to have reached equilibrium since all the moisture had been expelled from the cylinders. All cylinders were weighed, and their masses recorded in grams. Weighing of the cylinders is shown in Figure 37: Weighing Cylinder Sample.

Figure 37: Weighing Cylinder Sample

The volumes of the cylinders were also calculated to enable the determination of the densities.

III. Dry and Wet Compressive Strengths

As discussed earlier the cylinders were moisture conditioned in an oven at 40º/104º F for about 30 days. After that they were ready to be tested for dry and wet compressive tests. The cylinders needed to be completely devoid of any moisture as discussed earlier before testing. A sample of a cylinder from the oven ready for determination of dry density and compressive strength testing is shown in Figure 38: Dry Cylinder Sample.

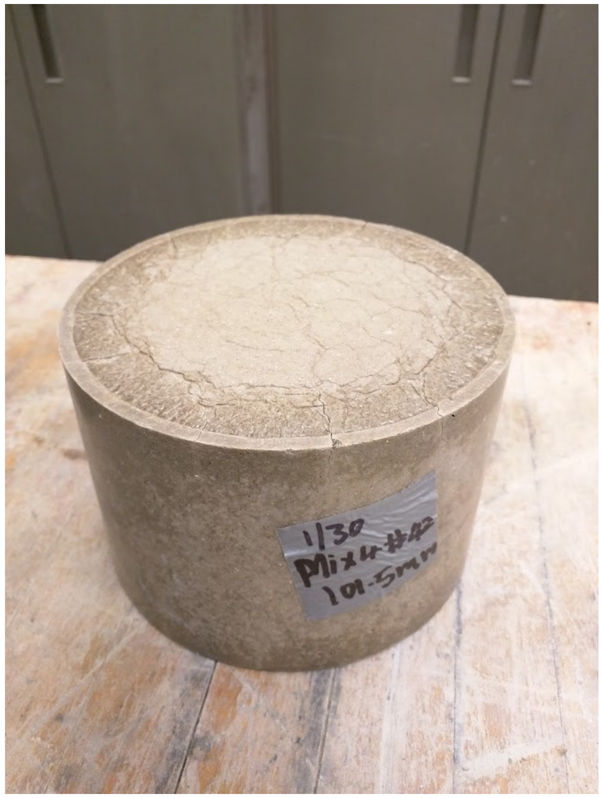


Figure 38: Dry Cylinder Sample

The dry unconfined compressive strength was tested using a Test Mark – Compression Machine. The rate of loading was approximately 320-340 lbs./sec. The machine recorded the load in pounds to needed to cause failure of the specimen. A cylinder sample being tested is shown in Figure 39: Dry Compressive Strength Testing.

Figure 39: Dry Compressive Strength Testing

The surface area of the block was calculated, and the dry compressive strength was determined in MPa. The procedure to test and prepare the samples for wet compressive strength was the same as the one used for dry compressive strength testing. The same Test Mark machine was used for testing the cylinders. Figure 40: Wet Compressive Strength Testing shows a sample being tested for wet compressive strength.

Figure 40: Wet Compressive Strength Testing

Results of Mix 1 and 2 could not be determined since the specimen cylinders split in two before the two hours elapsed, which was the time the samples were submerged in water.

IV. Capillary Absorption

The samples to be used for testing of capillary absorption were moisture conditioned the same way as the samples for dry compressive strength testing. The cylinders were weighed before starting the experiment. The cylinders were then immersed in water to a height of 5 mm. The height of the water was constantly maintained to ensure that it remained at a depth of 5mm, spacers were used to support the samples. During the weighing intervals the cylinder was dabbed to remove any dripping water then immersed back to the water bath. The samples were left partially immersed for a total of six hours. The setup was as shown in Figure 41: Capillary Absorption Testing

Figure 41: Capillary Absorption Testing

V. Abrasive Strength

The cylinders were moisture conditioned in the oven as previously discussed for the other tests. The brushing was applied to the top of the cylinder across the diameter. A wire brush with a 3 kg weight on top was used for the abrasive test. The sample was weighed before the brushing begun and weighed after to determine the loss of mass from brushing. No vertical pressure was applied to the weighted brush while brushing the cylinder specimen.

Phase 2 Testing

As discussed in the beginning of the chapter Phase 2 testing was set-up after examining the results from Phase 1. The mix designs were setup as shown in Table 9: Phase 2 Design Mixes. Phase 2 testing was like Phase 1 to maintain consistency and to be able to compare the results. The results of Phase 2 testing are discussed in chapter 4.

CHAPTER 4. TEST RESULTS AND DISCUSSION

Dimension, Mass Apparent Densities

The mass of the cylinders was determined by weighing all the specimens on the same scale. The density was calculated as the ratio of the mass of the block to its volume which was determined from the height and radius of the specimen. A plot of dry densities in relation to the mix designs is shown in Figure 42: Phase 1 - Dry Densities.

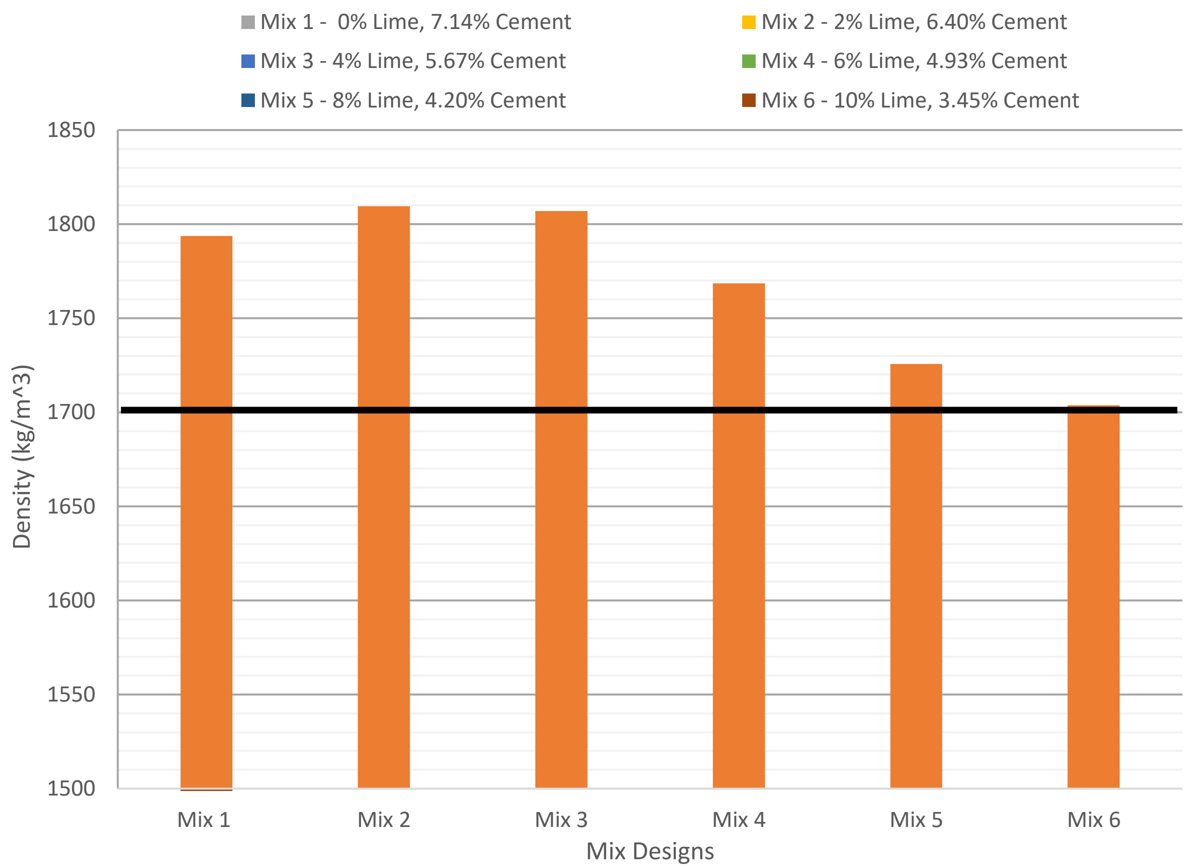


Figure 42: Phase 1 - Dry Densities

As can be seen from the bar graph, that as the quantity of lime increased the dry density decreased. The black line across the bar graphs indicates the baseline density recommended for CSEBs. Some of the reasons that could be attributed for the decreases in the dry density was that; the lime causes the aggregation of the particles (caused by the cation exchange reaction), occupying larger spaces, and hence alters the effective grading of the soils. Secondly, the further drop may be due to the replacement of soil particles in each volume by particles of lime of comparatively low specific gravity (Harichane, Ghrici, & Kenai, 2012).

Phase 2 testing (Mix 7 & 8) of the dry densities is shown in Figure 43: Phase 2 - Dry Densities.

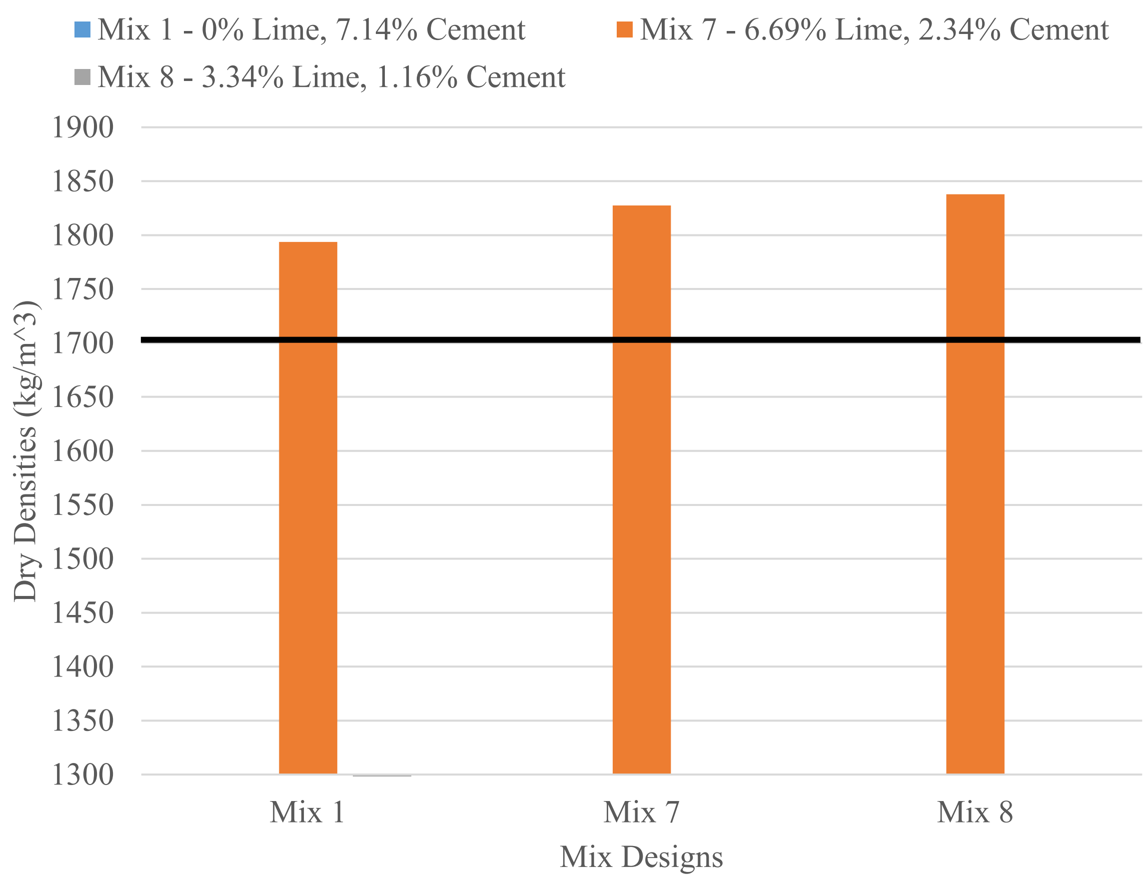


Figure 43: Phase 2 - Dry Densities

The dry densities of Mix 7 & 8 were above the control sample and therefore satisfactory. Mix 8 had lowest cementitious material in it therefore the higher dry density. The densities of CSEBs range in between 1,700 -2,200 Kg/m^3 (Adam & Agib, 2001). All the densities of the samples were above the recommended standard therefore were found to be satisfactory.

Another observation was that there was an increase in the optimum moisture content as the quantity of lime increased, this was due to the lime absorbing most of the moisture in the mixing bowl while mixing. The reaction of soil-lime is exothermic, and this was quite apparent with the mix designs with over 6 percent of lime once there was enough moisture in the mixing bowl to begin the reaction.

Dry and Wet Compressive Strengths

The dry compressive strength was determined from the results of the Test Mark Compression machine. The machine indicated the load at which the cylindrical samples encountered complete failure. The compressive strength was calculated as follows:

$$f_b \text{ dry} = \frac{F_{orce}}{Area}$$

Where:

f_b dry = dry compressive strength in kg/mm^2

Force = Maximum load at failure

Area = surface area of test face (mm^2)

The dry compressive strength was calculated from at least two tests on specimens from the same lot. The results of the dry compressive strengths are shown in Figure 44: Phase 1 - Dry Compressive Strength Results.

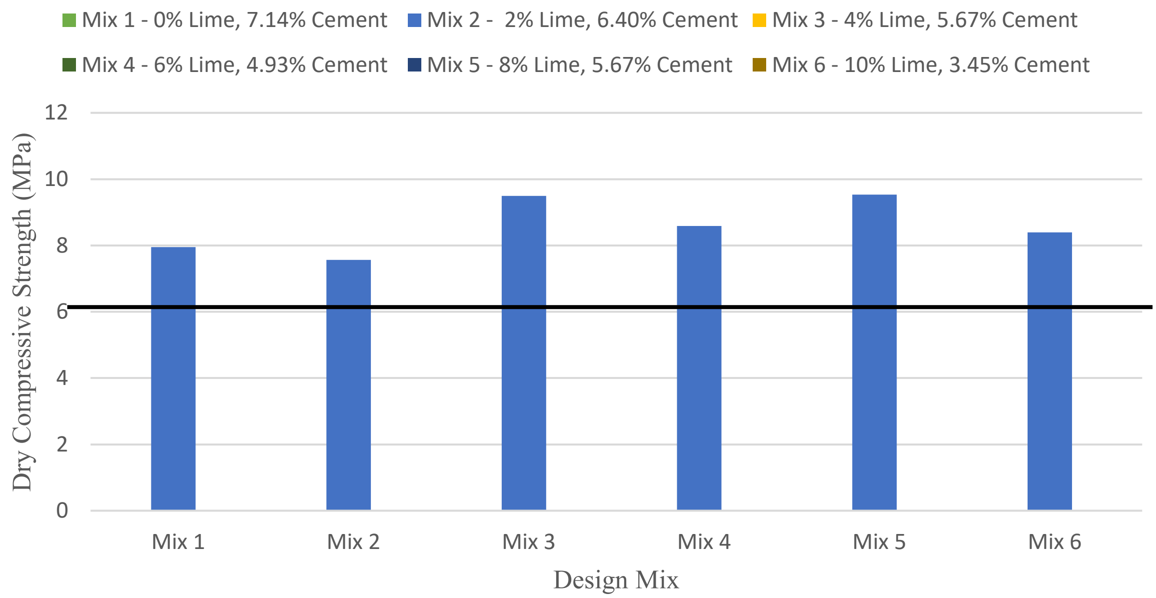


Figure 44: Phase 1 - Dry Compressive Strength Results

The results of dry compressive strength show that as the quantity of cement used in the samples goes down there is a marginal decrease in the dry compressive strength. The presence of lime prevented a precipitous drop in the dry compressive strength with the reduction of cement. Mix 1 was the control sample with only cement and the other mixes had different quantities of lime and cement mixed in them. Mix 2 had a small quantity of lime and less cement than Mix 1 and had the lowest dry compressive strength across all the samples tested. The marginal drop can be attributed due to the presence of lime which was mixed initially with the soil. Mix 3 has the recommended optimum amount for lime from the literature review, therefore has the one of the higher dry compressive strengths. Mix 4 had a slightly lower dry compressive strength than Mix 3 because of the quantity of cement in the mix. Mix 5 had higher dry compressive strength than Mix 4 which is an aberration since with the lesser quantity of cement the dry compressive strength was tending to decrease as can be seen by Mix 6 dry compressive strengths. The necessary quantities of lime for stabilization have been achieved, thus any excess quantity of lime serves the purpose of changing the density of the soil with lime which has lower specific gravity.

The phase 2 testing results for the dry compressive strength are shown in Figure 45: Phase 2 - Dry Compressive Strength Results.

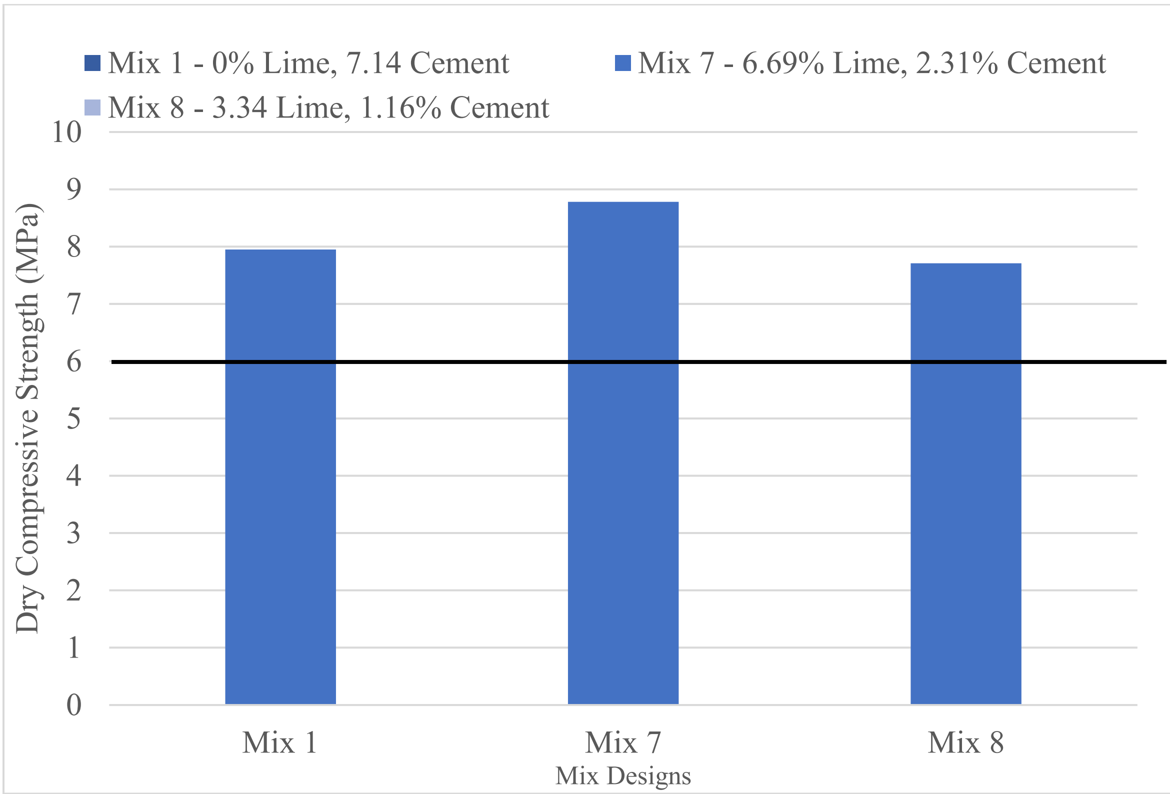


Figure 45: Phase 2 - Dry Compressive Strength Results

The results of Phase 2 testing (Mix 7 & 8) are shown with the control Mix 1 for comparison. Mix 7 which has 9% of cementitious material and has higher dry compressive strength, than the control sample of Mix 1. Mix 8 had half (4.5%) of cementitious material of Mix 7 which had slightly lower dry compressive strength than both the control and Mix 1. The very little cement in the mix was a contributing factor in the low dry compressive strengths.

Wet compressive strengths were determined for the samples after submersion in water for 2 hours. The results for wet compressive strengths are shown in

Figure 46: Phase 1 - Wet Compressive Strength Results for the four samples which did not crack after submersion in water. Mix 1 and 2 cracked and fell apart after being submerged in water for 2 hours and therefore could not be tested.

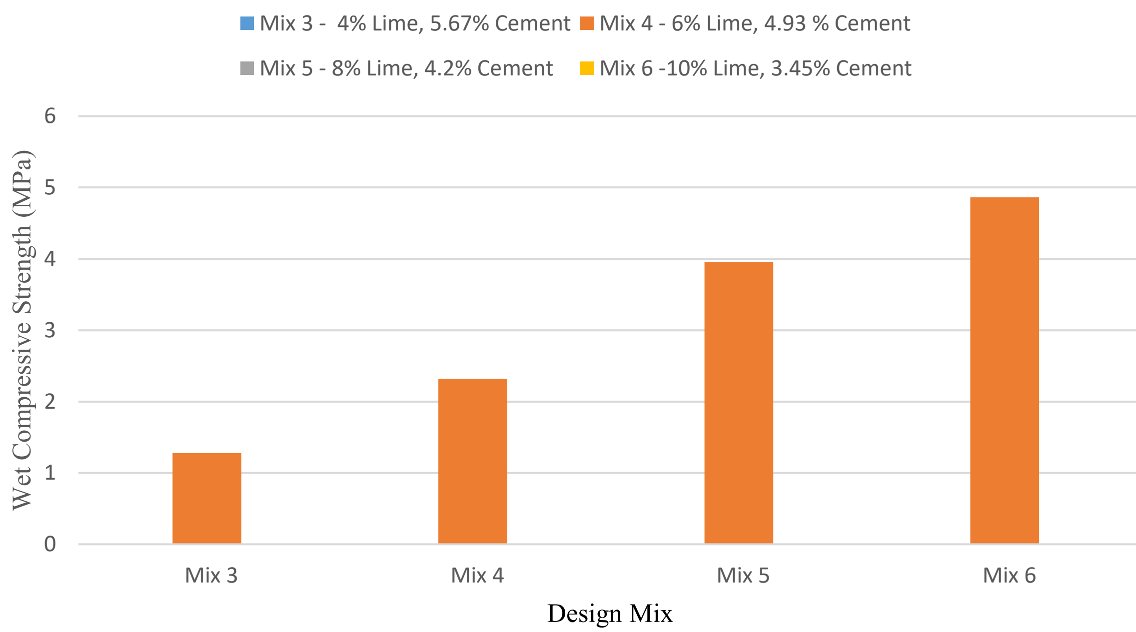


Figure 46: Phase 1 - Wet Compressive Strength Results

The results for samples above the African Regional Standards (A.R.S) which range from (1-40 MPa). Mix 3 which had the lowest wet compressive strength was 1.28 MPa and there was a linear increase to Mix 6 which had maximum strength of 4.86 MPa. The higher the quantity of lime filled the voids and contributed to the higher wet compressive strengths. There was also minimal strength contribution from cement in the mixes.

The results of Phase 2 testing (Mix 7 & 8) were only obtained for Mix 7 since Mix 8 cracked during the 2 hours of submersion in water and could not be tested. Mix 7 had an average wet compressive strength of 1.71 MPa. Mix 7 had 9% of cementitious comprising of

6.69% lime and 2.34% cement. Mix 8 had half the cementitious material of Mix 7, therefore the assumption would be that it would have had a lower wet compressive strength than Mix 7.

Capillary Absorption

Phase 1 testing as explained earlier had six samples which were tested by being constantly immersed in water at 5mm height. The results for Phase 1 testing are shown in Figure 47: Capillary Absorption.

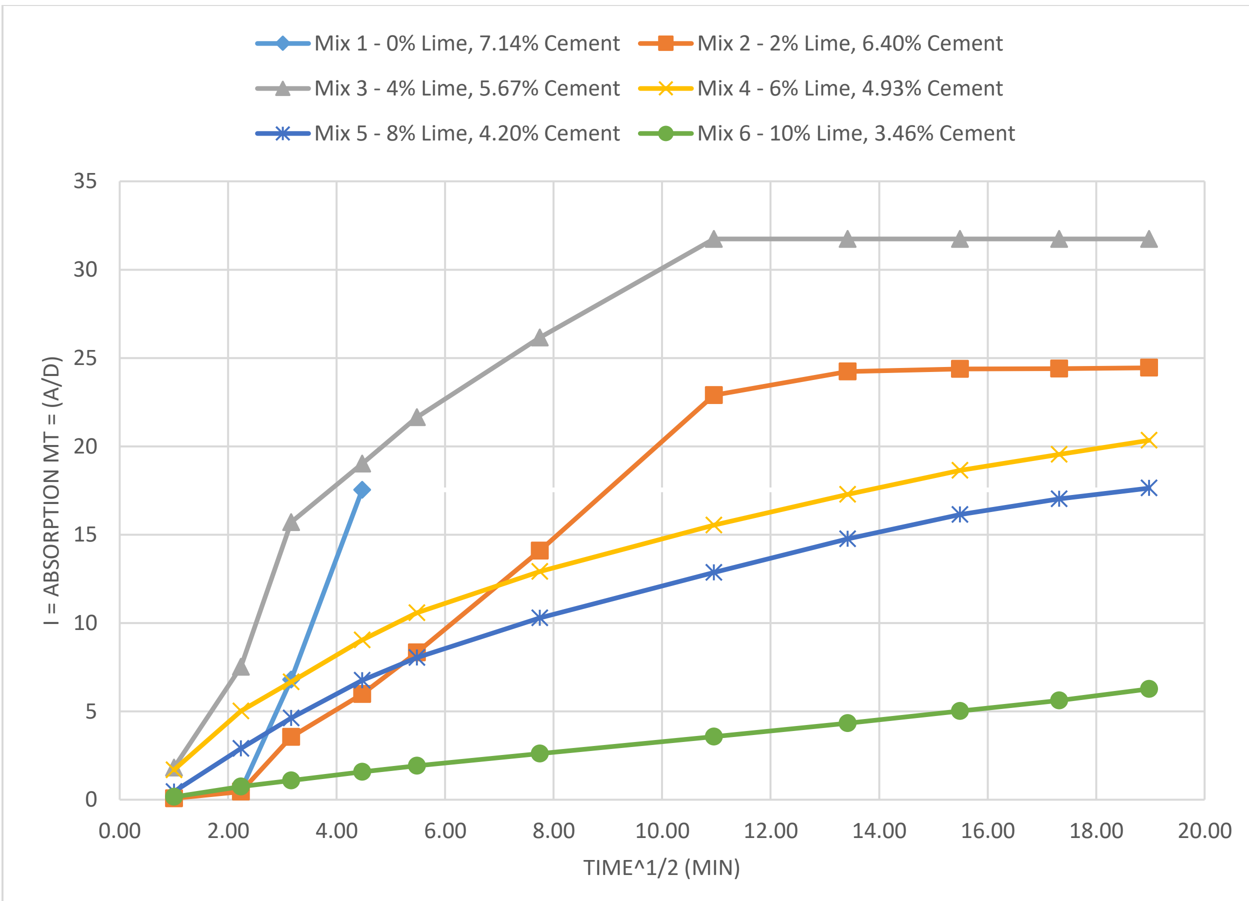


Figure 47: Capillary Absorption

Mix 1 which was the control sample failed after about 20 minutes after absorbing 10% mass of water. The plots show the absorption coefficient which was plotted against the square root of the time elapsed. The graph shows the rate and the amount of water absorption. From the plots of the absorption coefficient curves, as can be seen the lime content in the mix lowers, the more water absorption was for that sample. Mix 6 with the highest lime content had the lowest water absorption coefficient. Mix 3 had the highest absorption coefficient of all the samples followed by Mix 2; and although Mix 1 sample broke it can be deduced from the trajectory of the curve that it would have had a higher absorption rate. Mix 3, sample broke after 2 hours of testing at which time the cylinder hard already absorbed a lot of water. Another way of looking at the results would be to calculate the absorption mass percentage which is shown in

Figure 48: Absorption *Mass* (%) - Phase 1

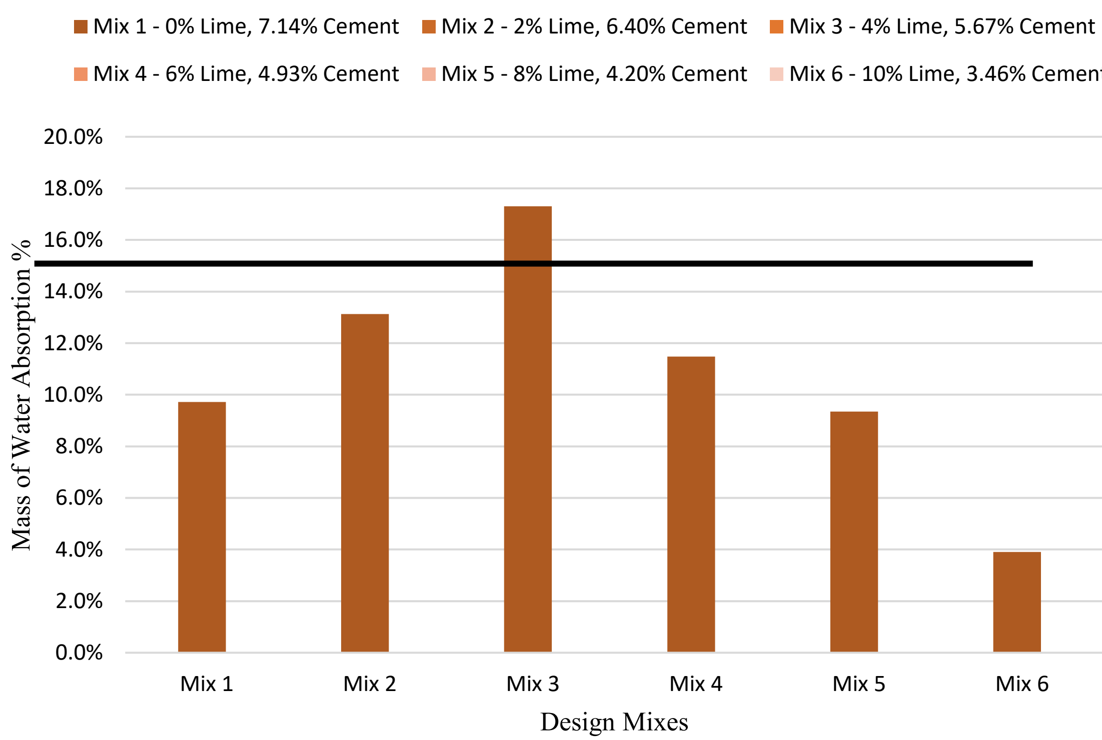


Figure 48: Absorption Mass (%) - Phase 1

Mix 3 had an absorption mass percentage of above 15% which is the value recommended for capillary absorption test (Guillaud, Houben H. ;CRATerre, 1984). All the other results show the samples had lower mass absorptions of less than the recommended value of 15%.

The quantity of lime in the mixes reduced the void volumes in the respective mixes, and the more the cement in the mix served to enhance the bonds and the formation of cement hydration products like calcium silicate hydrate (CSH) and calcium hydroxide. These products fill the voids and prevent the cylinders from absorbing a lot of water. Since the amount absorbed by the clay was constant, the clay content played a huge role in decreasing the voids in the volumes of the mixes. Mix 6 had the highest lime content and therefore had the lowest absorption of the all the samples.

Phase 2, testing absorption coefficients results are shown in Figure 49: Capillary Absorption - Phase 2. The cylinder sample for Mix 8 broke after 30 minutes of testing at which point it had absorbed 11% of water.

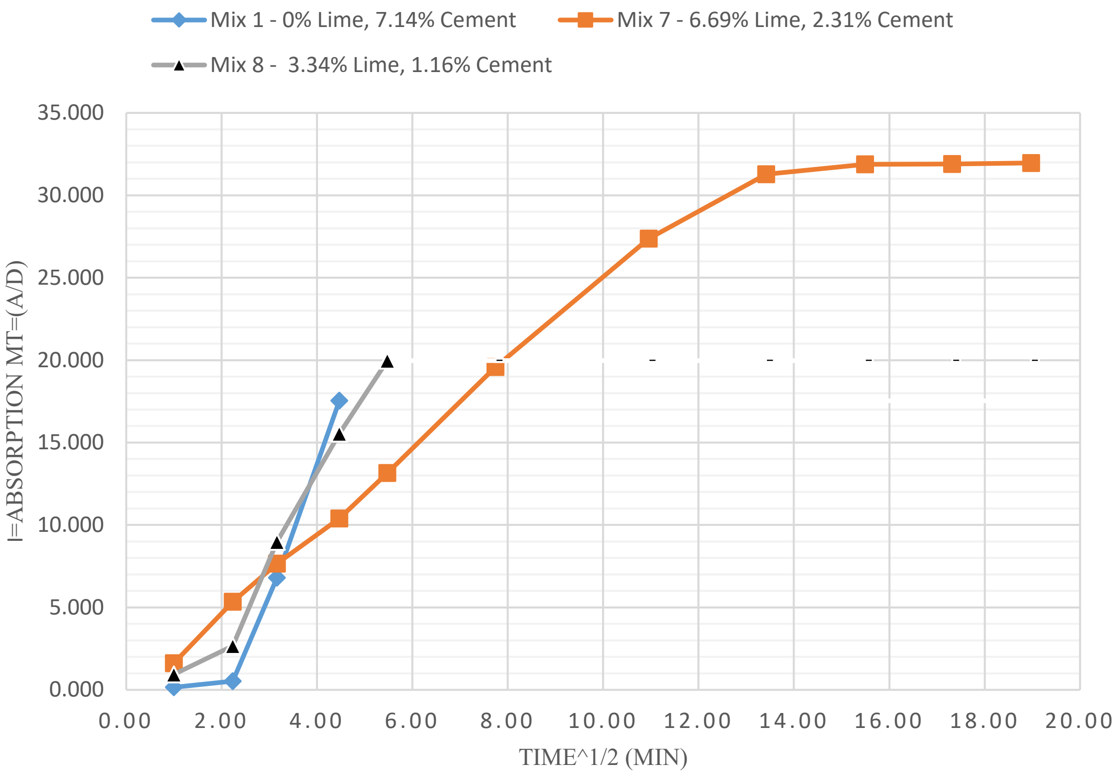


Figure 49: Capillary Absorption - Phase 2

As stated earlier, Mix 1 would have had a high absorption coefficient; Mix 8 would also have experienced a high absorption coefficient due to the low percentage of cementitious material in the mix. Mix 7 performed better than the control Mix 1 and Mix 8, the quantity of lime in the mix helped to break down the clay in the mix, and therefore enable the void volumes to be reduced during compaction. In Figure 50: Absorption Mass (%) - Phase 2, it shows the mass of water absorbed as a percentage and Mix 7 is well below the recommended range of 15% (Guillaud, Houben H. ;CRATerre, 1984).

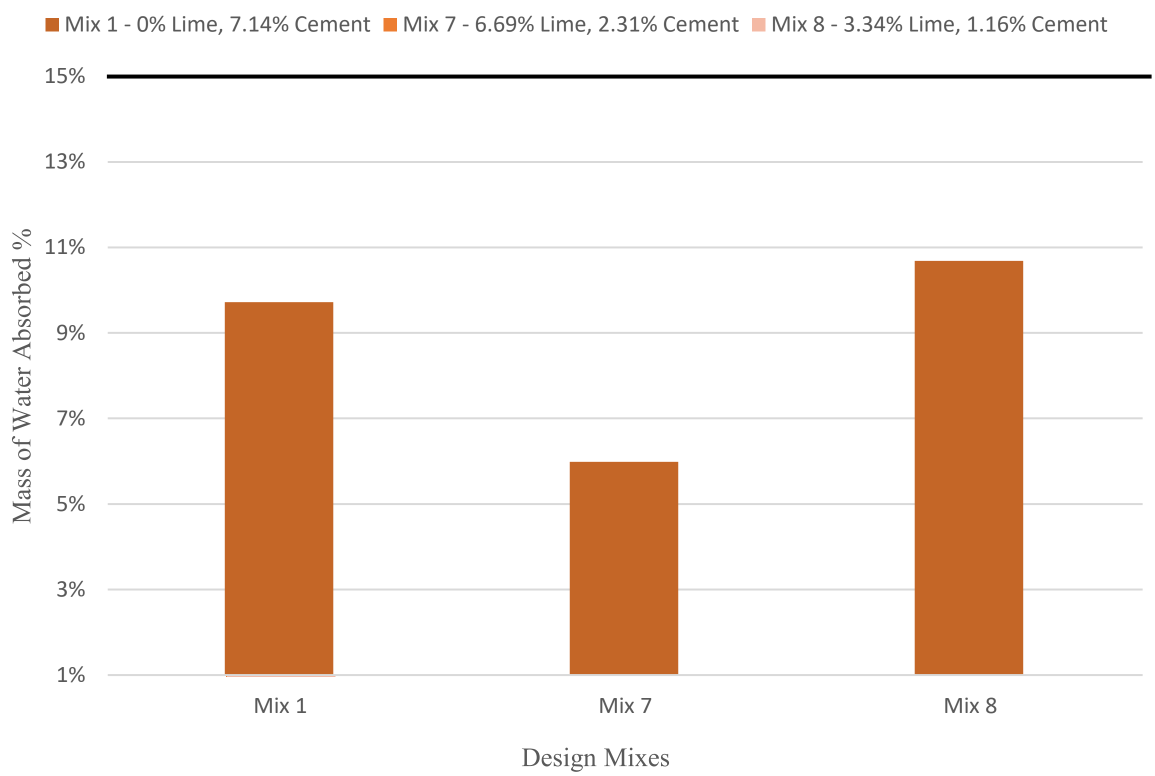


Figure 50: Absorption Mass (%) - Phase 2

The results of Mix 1 and 8 were only for 20 and 30 minutes before the cylinders broke, but they were absorbing water at high rates. Mix 1 had absorbed 10%, Mix 8 about 11% and Mix 7 meets the standards necessary to be used in construction dwellings or walls.

Abrasive Strength

After all the cylinder specimens were tested, the abrasion data was plotted as a histogram as shown in Figure 51: Abrasion Strength Test - Phase 1.The abrasion coefficient is defined as the ratio of the brushed surface to the mass of the material removed by brushing. From Figure 51: Abrasion Strength Test - Phase 1, Mix 1 had the lowest abrasion coefficient followed by Mix 2. Mix 3 had the highest abrasion coefficient and Mix 4,5 & 6 progressively had lower abrasion coefficients. The higher the quantity of lime the better the abrasion coefficient. The lime served to fill the voids in the mix and the quantity of cement aided in providing the structural strength for the Mixes 3,4,5 & 6. Mix 1 & 2 had no and lime, therefore the mixes could have a lot of voids even after compaction which made it easier to dislodge material from the surfaces. The results of abrasion strength coefficient are shown in Figure 51: Abrasion Strength Test - Phase 1.

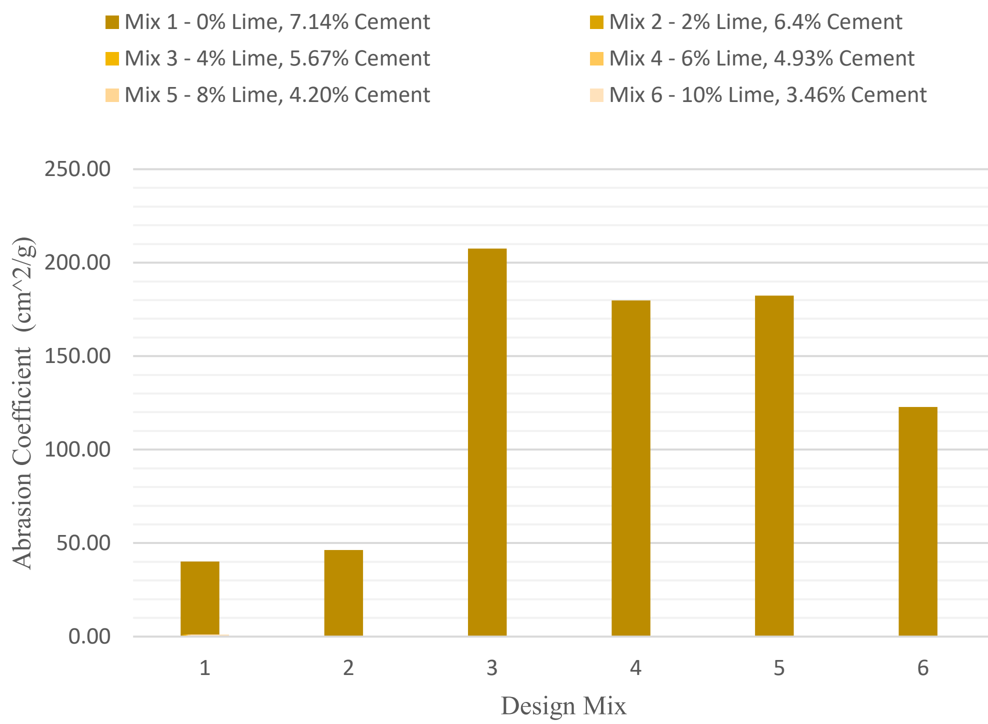


Figure 51: Abrasion Strength Test - Phase 1

Another parameter used to evaluate abrasive strength is the mass loss through abrasion by using a steel brush. Fitzmaurice (1958) recommends limits for maximum weight loss as 5% for permanent building and 10% for rural buildings in any type of climate. The abrasion mass loss data is shown in Figure 52: Abrasion Mass Loss (%) - Phase 1. From the data, the control sample Mix 1 had the highest mass loss followed by Mix 2 which was slightly below 5%. Mix 3, 4, 5 & 6 had mass loses of less than 2% which proved that they would be satisfactory for construction.

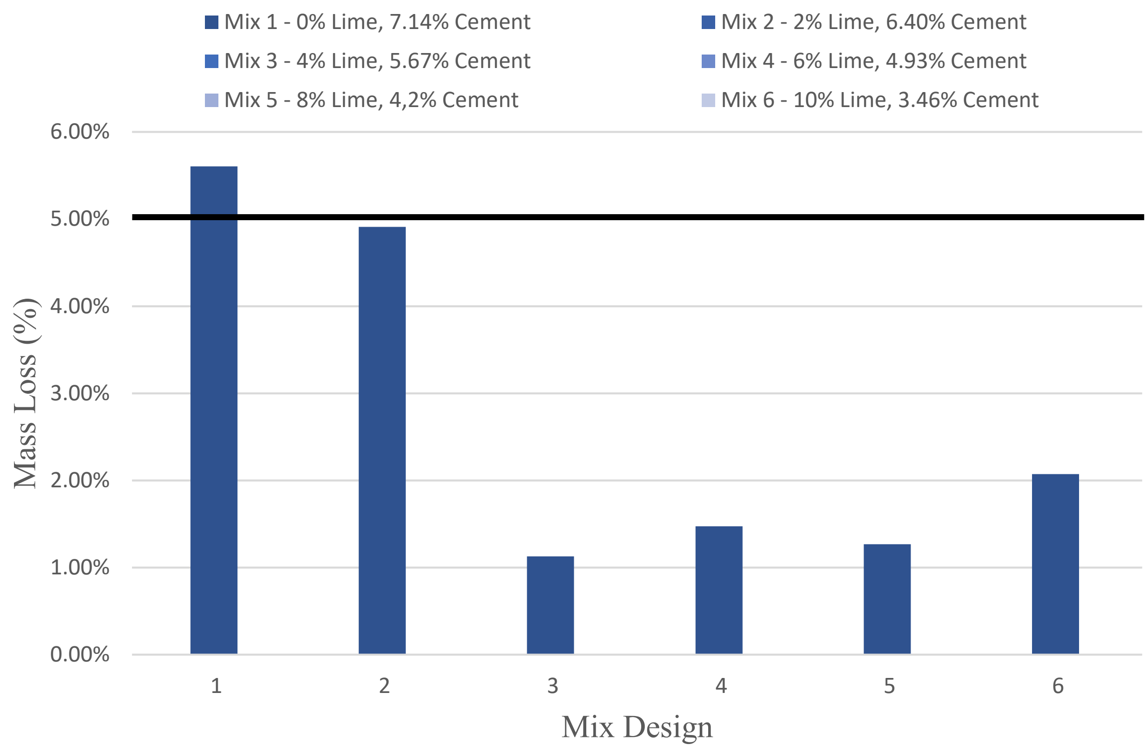


Figure 52: Abrasion Mass Loss (%) - Phase 1

Phase 2

The mode of testing for Phase 2 was like Phase 1 testing so that everything would be consistent to enable comparison of results. As discussed earlier the quantity of cementitious material was reduced to 9% (lime and cement) for Mix 7 and halved for Mix 8.

The results of the abrasion coefficient are shown in Figure 53: Abrasion Strength Test - Phase 2. As discussed earlier the higher the abrasion coefficient the better the sample would be able to resist any durability related issues.

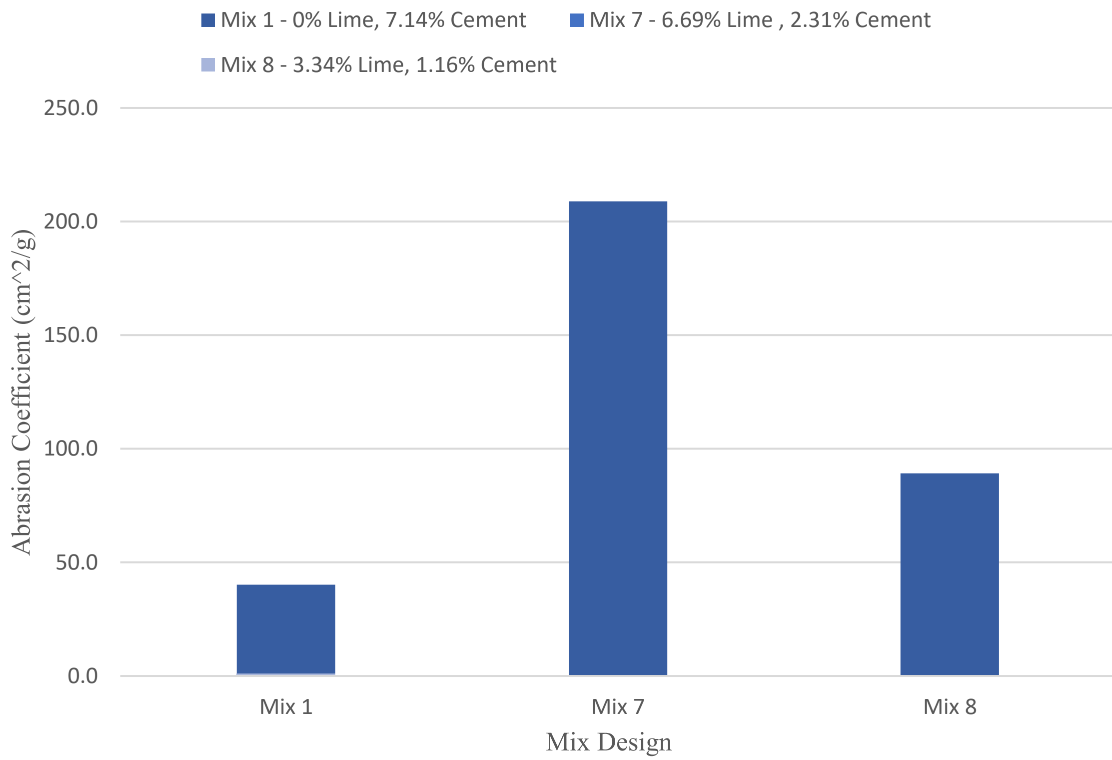


Figure 53: Abrasion Strength Test - Phase 2

As discussed earlier during phase 1 testing Abrasion Mass Loss was also calculated for Phase 2 testing. Figure 54: Abrasion Mass Loss - Phase 2 depicts the results of abrasion testing for Mix 7 and 8 which had lower mass losses than the control sample Mix 1. Both had mass losses lower than 5% as recommended by (Fitzmaurice, 1958). The presence of lime in the mix filled up the voids in the mix and enabled higher compaction to be achieved which relates to better durability of the samples being tested.

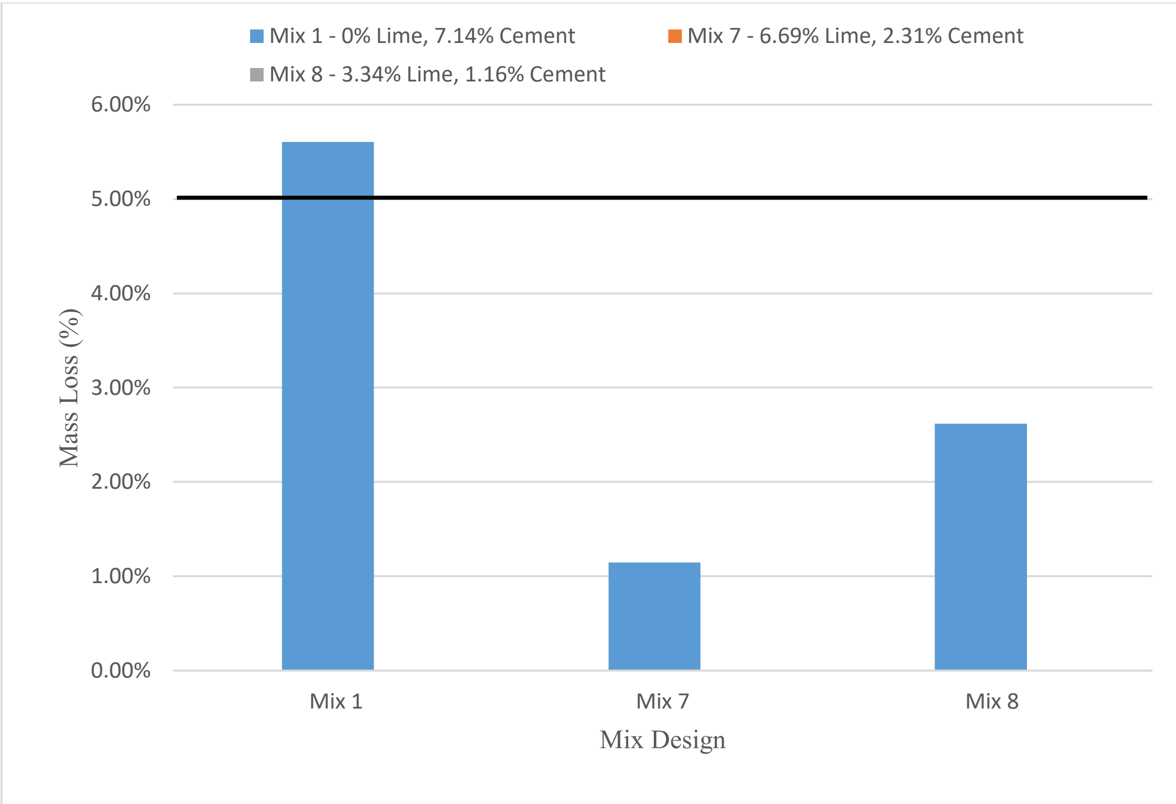


Figure 54: Abrasion Mass Loss - Phase 2

Scanning Electron Microscope Images (SEMs)

To better understand the surface topography and the morphology of the samples a scanning electron microscope equipment was used to look at the cured samples under different magnifications (SEM). The SEM uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from the electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample. In most applications, data are collected over a selected area of surface of the sample, and a 2-dimensional image is generated that displays the spatial variations in these properties (SERC Carleton College, 2017).

Microstructural analyses of the cylinder samples for phase 1 and 2 were determined using an SEM at the University of Missouri Kansas City (UMKC). The samples analyzed were for phase 1; the original soil, Mix 1, 2, 3, 4, 5, 6 and for Phase 2 Mix 7 & 8. The soils were analyzed under 50 to 200 times magnification. The samples analyzed were from broken dry compressive strength testing after 28 days of curing.

The samples were analyzed at 200, 100 and 50 microns. Figure 57: Phase 1 Testing SEMs - 200 um shows the samples having flat dense surfaces with few voids. The products of cementation of pozzolanic reactions between soil, lime and cement have caused the presence of the dense surface morphology. The dense surface consists of hydration products of calcium silicate hydrates (CSH gel) and don't exhibit any pores on the surface. Mix 6 had a high content of lime compared to cement, therefore there were less hydration products and as a result a flocculated structure was present. Figure 55: Phase 1 Testing SEMs – 50 um shows the various microstructural surfaces as discussed.

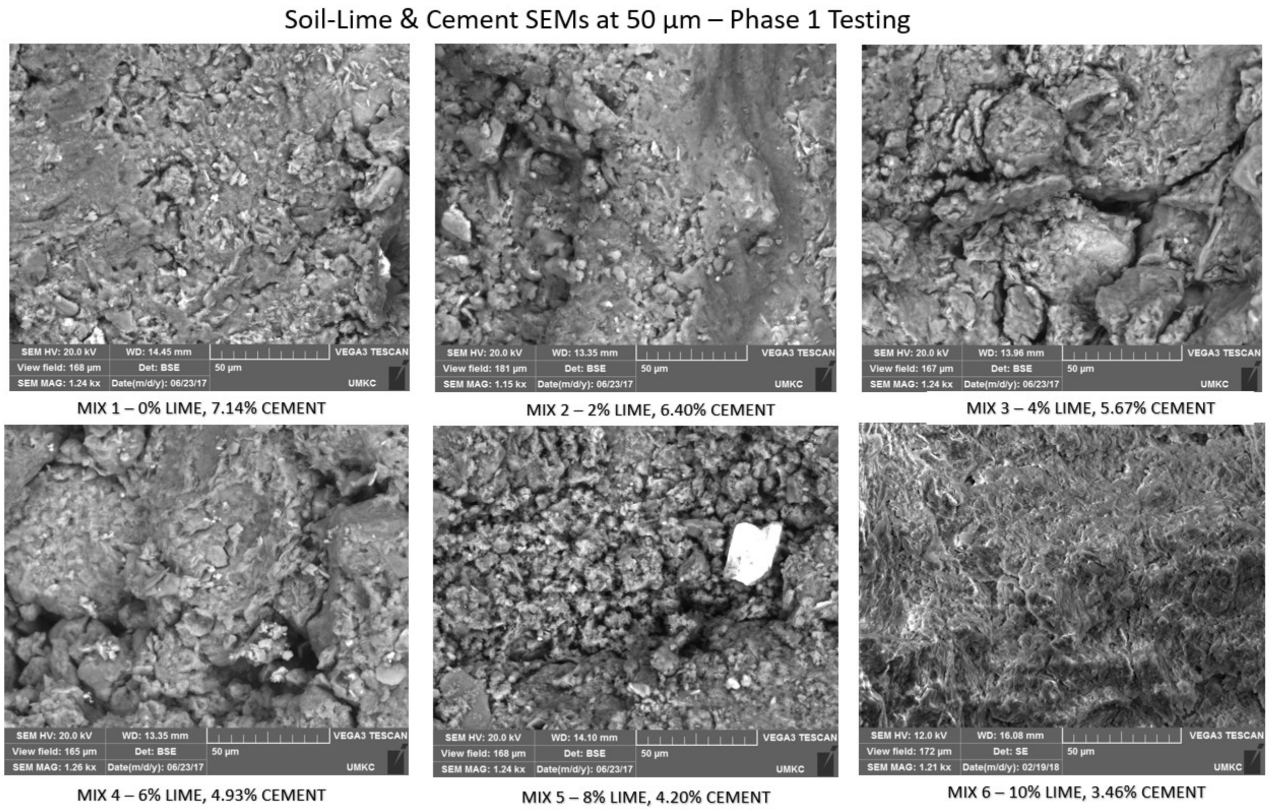


Figure 55: Phase 1 Testing SEMs – 50 um

For reference Phase 1 testing SEMs at 200 and 100 magnification are included to show the different microstructural images. It can be seen from Figure 56: Phase 1 Testing SEMs - 100 um and Figure 57: Phase 1 Testing SEMs - 200 um that the microstructural surfaces are not overly distinguishable at higher magnifications.

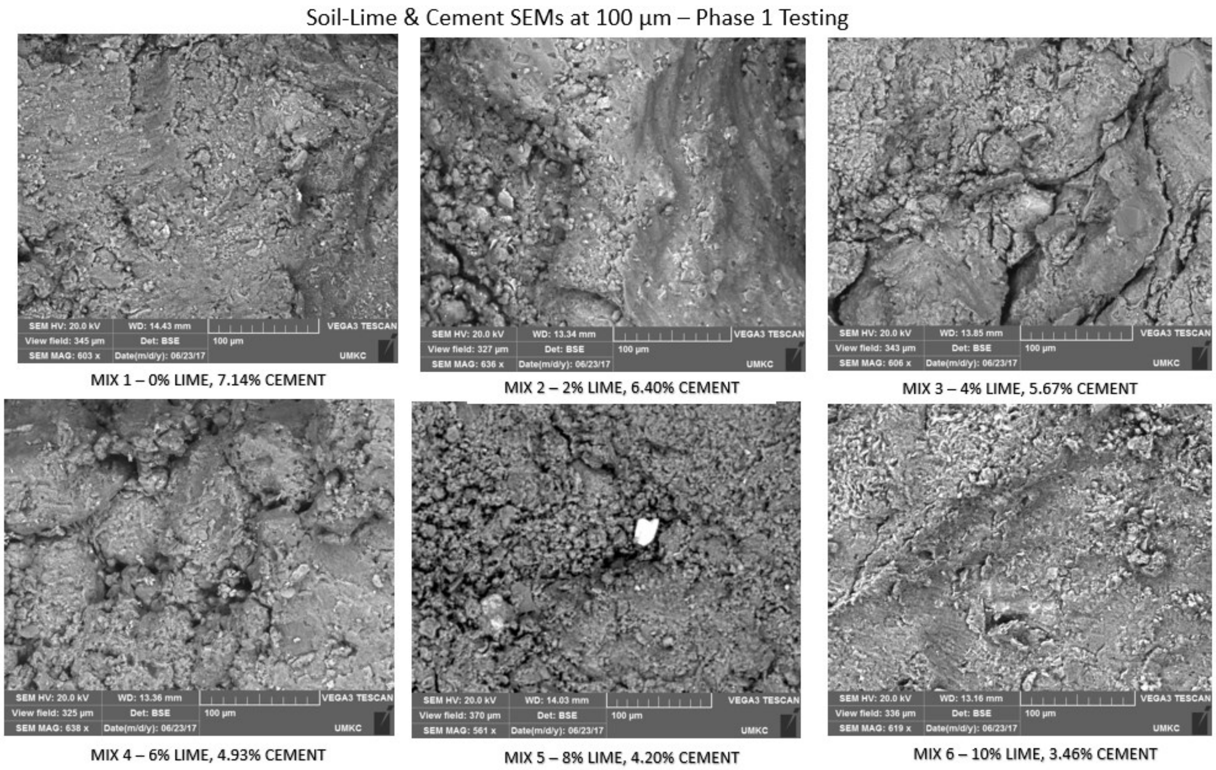


Figure 56: Phase 1 Testing SEMs - 100 um

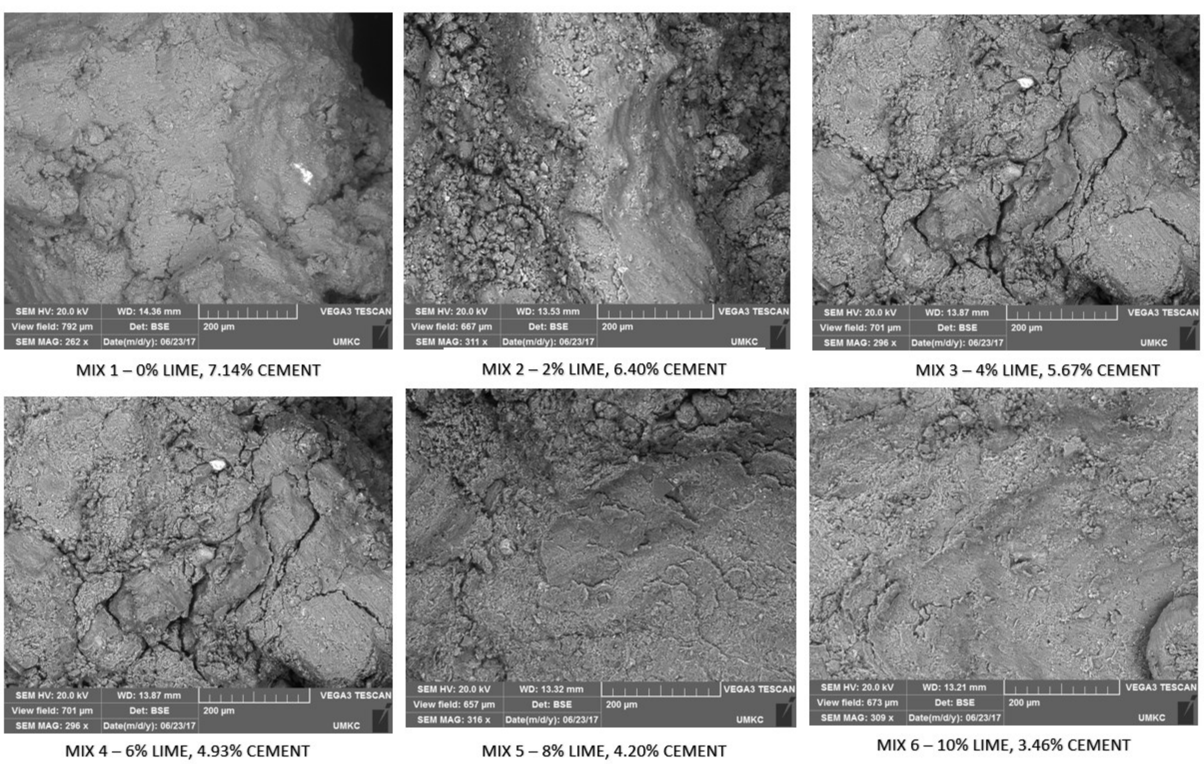


Figure 57: Phase 1 Testing SEMs - 200 um

Phase 2 testing samples were analyzed the same way as Phase 1 testing. They were analyzed at 50, 100, and 200 um. Phase 2 testing had two mix designs (Mix 7 & 8). Figure 58: Phase 2 Testing SEMs shows both the samples with the 3 magnification levels. It can be seen from the SEMs that the two mix designs are almost similar and contain high amounts of lime compared to the cement contents. The surfaces of the specimens have a porous texture, are wavy like crystalline structure showing that flocculation and aggregation has taken place. The small amount of cement has not produced a dense compact surface which was present in Phase 1 testing of the microstructural analysis of the SEMs.

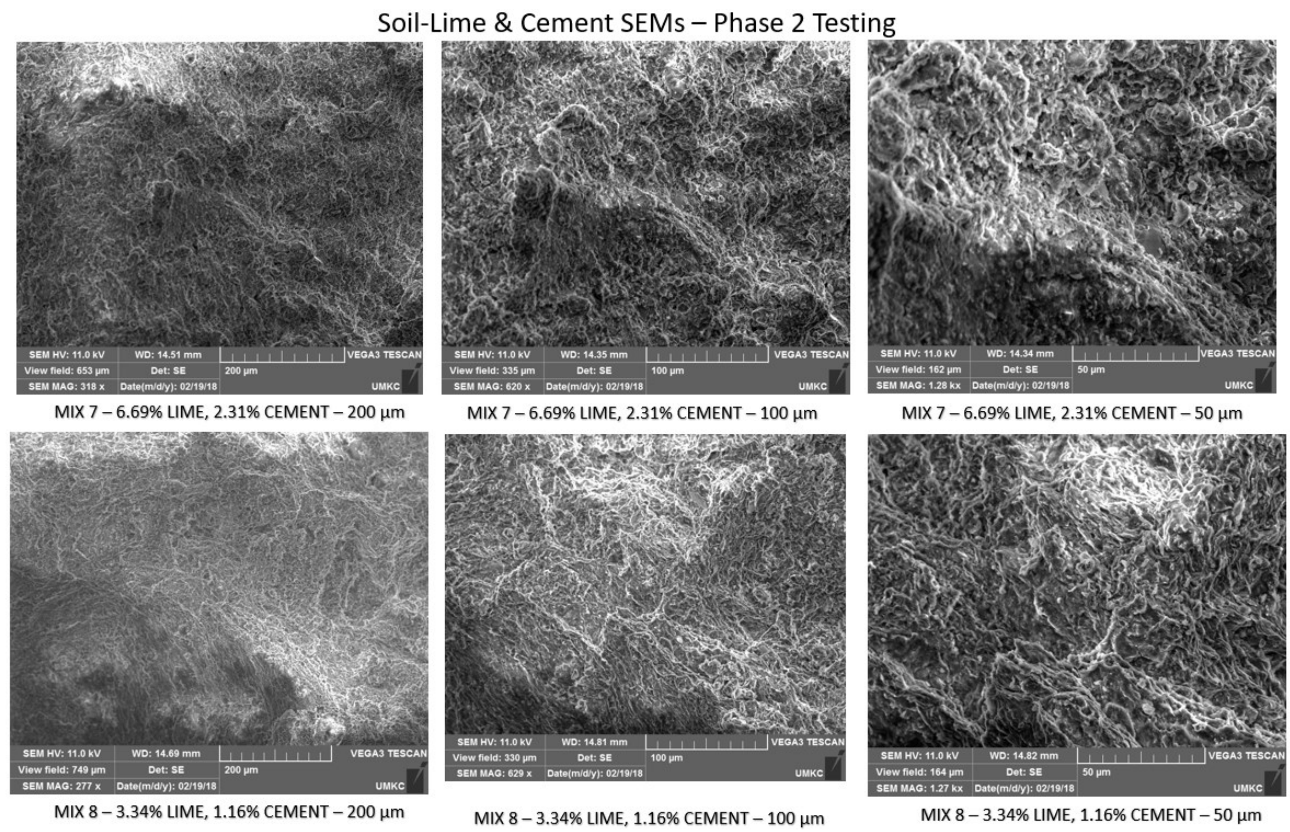


Figure 58: Phase 2 Testing SEMs

CHAPTER 5. CONCLUSIONS

The environmental benefits of using earth for construction are vast and include ease of availability, plentiful, cost efficient, fire resistant and low energy embodiment. The bricks can either be unfired and not stabilized (sun dried) and CSEBs, whereby any type of stabilizer available can be used for example lime, cement, asphalt emulsion or pozzolans. The current practice of block production involves using only cement as the stabilizer and if the soil has a higher clay content more cement is added which increases the cost of the blocks. Rarely is lime used as the lone stabilizer due to the time it takes to achieve the required strength and lack of the required knowledge of its usage to produce high quality blocks. Another practice is to use quarried stone which is "machine cut" from the quarry to the required standard building blocks. This are expensive to produce and leave an eye sore in terms of deep quarries which become hazards for the residents in the community by promoting breeding grounds for malaria.

The stabilizers can be used by themselves or mixed together to achieve certain characteristics or for certain types of soils. This research project developed a two-stage process for CSEBs production by using lime for the initial mixing, mellowing (24hrs) and then adding cement. Cylindrical specimens were molded and tested for various durability and compressive strength parameters to determine their effectiveness in construction. The research was carried out in two phases; phase 1 was a mix design with a combination of various lime and cement contents and phase 2 was a reduction of the cementitious material used for the mix designs with the best performance characteristics.

Phase 1 and 2 results showed that the design mixes meet and exceed the industry standards for CSEBs to be used in housing construction when tested for strength, durability and moisture susceptibility. The physical characteristics of the cylinders during molding were monitored for consistency. This included dimensional and geometrical and appearance. The metrics measured from these characteristics were consistent for any samples and met the tolerance limits for length, diameter and height. This indicated that the mix designs could be produced consistently without wide variations by adhering to the production standards. It was observed that when these standards are maintained the quality and material characteristics were easily controlled.

Summary of Results

Phase 1 dry densities of the mix designs were computed and compared to the control sample. All the densities were in the acceptable range of 1,700-2,200 kg/m^3 (Adam & Agib, 2001). Pulverization of the soil helped to create a homogenous mix with the soil-lime and cement. Higher quantities of lime (5-10%) alter the gradation of the soil and lower the unit weight of the soil due to the low specific gravity of lime (2.2) particles compared to those of soil (2.6) and cement (3.0). The phase 2 results consisted of mix 7 and 8 which had reduced cementitious materials, mix 7 had 9% cementitious material (lime and cement) and Mix 8 had half of that. The dry densities were within the acceptable standards mentioned earlier at 1,827.58 kg/m^3 and 1,838.05 kg/m^3 for mix 7 and 8.

Phase 1, dry and wet compressive strengths were above the minimums required to construct a one- or two-story house except for Mix 8 wet compressive strength which was not determined. All the other mix designs proved the efficacy of the mix designs were acceptable. The highest compressive strength was Mix 5 followed by Mix 3 which was about 0.4% lower. Mix 1 and 2 samples broke after being submerged in water for wet compressive strength testing. The samples which were successfully tested met the industry standard of more than 1-40 MN/m^2 (Adam & Agib, 2001). Mix 2 had the lowest and Mix 6 had the highest wet compressive strengths. The higher lime contents were able to react with the silica and alumina in the clay and contributed to higher strengths due to the formation of calcium-silicate-hydrates (CSH) and calcium aluminate hydrate (CAH) from the reaction between lime and soil. The addition of cement further enhanced the formation of these hydration products to the mix which made it denser and more impermeable. The dry compressive strengths were also high and comparable to Phase 1 testing results with Mix 7 at 8.78 MPa and Mix 8 at 7.71 MPa. This shows that with further mix design optimization for phase 1 acceptable standards can still be attained with reduced cementitious products, which translates to lower production costs for the blocks.

The abrasive strength testing was done under Phase 1 and Phase 2. Phase 1 testing indicated that the abrasion coefficients for all the mixes were higher than the control sample mix 1. Mix 3 had the highest abrasion coefficient (80% higher than the Mix 1) and as the lime content continued to increase with corresponding low cement amounts the abrasion coefficients trended lower. Another metric used to quantify the abrasive strength was abrasion mass loss. Mix 1 had the highest abrasion mass loss at about 5.6% and Mix 3 had the lowest abrasion mass loss of about 1.13%. Mix 1 had a slightly higher abrasion mass loss than the standard recommended which is about 5% maximum for permanent construction but would be ideal for rural housing. The inclusion of lime in the mix design, helps it to be acceptable for construction and provides an added factor of safety. The inclusion of lime increased the quantity of hydration productions CSH and CAH which also form when cement is added to the mix. This created a denser soil-lime and cement mix matrix with very little void spaces, thus very little material to dislodge when the sample is subjected to any kind of abrasion. Phase 2 testing consisted of testing mix 7 and 8 and comparing them to the control sample. As mentioned earlier mix 1 had a low abrasion coefficient than Mix 7 and 8. Mix 7 performed better than Mix 8. The abrasion mass loss percentages mirrored the abrasion coefficient numbers. All the mixes satisfactorily met the abrasion standard parameter to be used in a building.

The cylinder samples were also tested for capillary absorption, and one of the standard classifications used to measure absorption was the coefficient of absorption. During phase 1 testing, Mix 1 broke during testing after 20 minutes of being in the water. It can be inferred from the trajectory of the capillary absorption curve that it would have been higher than Mix 3. Mix 3 had the highest absorption coefficient followed by Mix 2 and then a trend emerged where the absorption coefficient decreased with lower amounts of cement in the mix which corresponded to higher lime content. Phase 2 capillary absorption testing consisted of testing Mix 7 and 8. Mix 8 sample broke after thirty minutes in, from the trajectory of the capillary absorption curve it can be inferred that the absorption coefficient would have been higher than the capillary absorption curve for mix 7. As discussed, Mix 1 sample broke at around 20 minutes and when compared to Mix 8 and 7 it would have been the highest judging from the trajectory of the capillary absorption curve. Another metric used was the calculation of the absorption mass. Mix 7 had about 6% by weight of mass absorbed and by the time Mix 8 broke it had already absorbed approximately 10% mass of water. Mix 7 had 6.69% of lime which filled up the void spaces in the mix and prevented absorption of an appreciable amount of water. This can be attributed to the formation of the hydration products of CSH and CAH. The little amount of cement in the mix also contributed to the formation of the hydration products. Mix 8 had half (4.5%) the cementitious content of mix 7 and therefore was not expected to last the full duration of the capillary absorption testing of 360 minutes.

Comparison of Mix 1 to Mix 3 & 4

The best mixes in the research were Mix 3 and 4, the properties of these mixes were superior than the control sample (Mix 1) in all facets (strength, durability and absorption testing). For the same cost of producing the control Mix 1 you can incorporate lime and get far superior blocks with better performance. Since you will be replacing a portion of the cement with a product which is lower in cost by 40-60% depending on whether you are in an urban or rural setting. The total savings cost per square meter is approximately 40-50%. If you can source construction grade lime produced in ground kilns, then the cost drops even further since the calcination of the limestone can be done in the villages or the project site, thereby mitigating the transportation costs which can be prohibitive.

Phase 1 mix designs produced blocks with the same cost and better performance than the control sample Mix 1. The best mixes were 3 & 4 after looking at the test results. Mixes 3 & 4 exceed the performance characteristics of the control sample Mix 1. The comparison of results for Mix 1 and Mix 3 & 4 are shown in Table 11: Performance Results for Mix 1 & Mix 3 & 4.

Table 11: Performance Results for Mix 1 & Mix 3 & 4

Mixes	Test	Results
3 & 4	Dry Density	1,806.97 & 1,768.54 kg/m^3
1		1,793.79 kg/m^3
3 & 4	Dry Compressive	9.49 & 8.59 MPa
1		7.95 MPa
3 & 4	Wet Compressive	1.28 & 2.32 MPa
1		Sample Broke
3 & 4	Capillary Absorption	17.3 % & 11.5% - Mass of Water
1		9.7 % (Sample broke after 20 min) - Mass of Water
3 & 4	Abrasive Strength	1.13 & 1.47% - Mass Loss
1		5.6% - Mass Loss

From the results above it is can be seen that Mix 3 & 4 have better results than the control sample Mix 1 and would perform better in construction. This proves that Mix 3 & 4 bricks can be used for the same cost with better performance in compressive strength and durability. Therefore, the introduction of lime is a feasible and viable alternative for mix design development for CSEBs.

Comparison of Mix 1 to Mix 8

The production of CSEBs using lime and cement in a two-stage process would extend the use of cement. For example, when using a soil with a PI of 35 you need to use approximately 7.14% of cement by weight to stabilize the soil (Mix 1). Mix 8 had 3.34% of lime and 1.16% of cement by weight, this was 36.97% less of cementitious material than Mix 1. A comparison of Mix 1 and 8 shows some favorable characteristics obtained from both mixes. The dry densities of both mixes were about the same, with Mix 1 having a dry density of 1793.79 kg/m^3 and Mix 8 having a dry density of 1,838.05 kg/m^3 which is a difference of 2.41%. The dry compressive strengths were also almost the same with Mix 1 having a dry compressive strength of 7.95 MPa and Mix 8, with 7.71 MPa. These was a difference of 3.01% in the dry compressive strengths. The wet compressive strengths for both mixes were unable to be obtained because the samples broke during the soaking part of the testing.

During the testing for the capillary absorption, Mix 1 broke after 20 minutes and Mix 8 after 30 minutes. After 20 minutes, Mix 8 had absorbed about 76 grams more of water than Mix 1, this can probably be attributed to the lower content of cementitious material in Mix 8. The abrasion coefficient of Mix 1 was 40.19 cm^2/g and for Mix 8 was 89.24 cm^2/g and comparing the abrasion mass loss Mix 1 had 5.60% mass loss and Mix 8 had a 2.62% mass loss. This can be attributed to the presence of lime in Mix 8 which helped to produce a denser soil-lime and cement matrix when subjected to the abrasion test. All the metrics measured were acceptable for the mixes to be used in construction.

Mix 1, is costlier to produce than Mix 8 because of the higher cement content, though the performance characteristics were almost the same and differed only marginally. Mix 8 could therefore be used instead of Mix 1 in construction of areas where the blocks will not be exposed to severe weather elements. An example of this would be to construct partition walls in a house or in a semi-arid, arid areas of the country.

Lower Cost with Same Performance

Phase 2 mix design and testing provided an opportunity to further optimize the mixes due to the large performance gap from the control sample Mix 1 to the other five mixes. The design of Mix 7 and 8 with less cementitious materials in them provided the opportunity to lower cost of production and still maintain acceptable performance standards. Mix 7 had 9% cementitious material and Mix 8 had 4.5% of the same. By incorporating lime you can reduce the cement usage by less than half or half and use approximately 4.5 % lime or more.

One bag of cement in Kenya cost's $8-9 depending on where you are buying it and that does not include the cost of transportation. High grade lime costs about half or a little more than the cost of cement, while construction grade lime has about 50-70 purity depending on the calcination process and is also cheaper than the conventional lime produced in factories. Incorporating construction grade lime lowers the energy embodiment of the construction materials being used, therefore less the emission of carbon dioxide to the atmosphere. The benefit of all this is the quality of the blocks is vastly superior than using cement just by itself which helps alleviate the prevailing stigma of CSEBs as low-quality building material. Phase 2 testing proved that Mix 7 is a viable mix lower in cost that can be used in construction of low to medium-cost housing with the same performance characteristics of Phase 1 mixes. Cement manufacturing is highly energy and emission-intensive because of the extreme heat required to produce it. Producing a ton of cement requires 4.7 million BTU of energy, equivalent to about 400 pounds of coal, and generates nearly a ton of CO_2. Given its high emission and critical importance to society, cement is an obvious place to look to reduce greenhouse gas emission. (Rubenstein, 2012).

The less use of high energy embodied materials like cement, the better it is for the environment since the production of cement requires the use of mined virgin aggregates which are becoming harder to source as the years go by. Soil requires low energy input in processing and handling soil; only about 1% of the energy required to manufacture and process the same volume of cement concrete. This aspect was investigated by the Desert Architecture Unit which was discovered that the energy needed to manufacture and process one cubic meter of soil is about 36 MJ (10kwh), while that required for the manufacture of the same volume of concrete is about 3,00 MJ (833 kwh). Similar findings were also reported by Habitat (UNCHS), Technical Note. 12 comparing adobe with fired clay bricks. (Adam & Agib, 2001).

This technology is be sustainable and appropriate for the communities in urban areas where there is constant inflow of migrants from the rural areas. There is also a big challenge in the rural areas in terms of sourcing sustainable and appropriate building materials.

Future Research

Future research that would improve the production of CSEBs would be to investigate to what the effect of adding lime to soil-cement mixtures and see whether any cost savings and improvement of strength and durability can be achieved. Another area would the effect of soil pulverization, currently 20mm particles are restricted, finely ground soils produces a homogeneous mix of soil-lime and or soil-cement. What would be the ideal particle size and whether this has effect on the amount of stabilizers used.

Research on an alternative use of lime with lower energy embodiment material, although construction grade lime is produced by mostly burning tires to achieve the high temperature necessary for calcination of the calcium carbonate. The use of magnesium oxide and hydroxide has shown promising results and requires less energy to process.

The use of bio-enzymes, there performance criteria in developing the strength and durability properties and their economic feasibility. The effect of adding pozzolans, for example lithic or volcanic soils which have silica and alumina contents to enhance the use of excess lime in the mixture by forming the cementitious products of CAH and CSH which improve the quality of the CSEBs.

The effect of soil blending and using lime and cement in a two-stage process could further be investigated with the intent of mitigating the use of lime and cement in the design mixes. Most of the soils are found lacking in the clay, silt, sand or gravel content. Therefore, if a soil is found to not have enough clay and sand, this can be added to produce an ideal soil which would also ensure its not be gap-graded. This blending would minimize the cost of CSEBs by mitigating the use of stabilizers.

The use of renders/plasters with soil-lime and cement; this can be used to further seal the walls of CSEBs which might have a higher absorption capacity than recommended or provide a protective coating where the blocks might be susceptible to durability or strength issues. One layer of render could be for providing flexibility while another one could be for providing strength, this could be used to supplement CSEBs made with only lime and incorporating cement in the renders. The current practice is to provide sand and cement renders for walls which is usually cost prohibitive.

REFERENCES

Adam, D., & Agib, P. (2001). *Compressed stabilised earth block manufacture in Sudan.* Paris: United Nations Educational, Scientific and Cultural Organization.

Appro-Techno SPRL. (2017). *Appro-Techno*. Retrieved from Terstamatic Press : http://www.appro-techno.be/fr/page_presse-terstamatique_66.aspx

Ashish Sharma, M. I. (2011). Role of nanotechnology for development of sustainable concrete. *Proceedings of the International Joint Journal Conference on Engineering and Technology (IJJCET 2011). Volume 2. No 1.* gopalas Publications & TCET.

ASTM - D559. (2015). ASTM D559/D559M-15, Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. *ASTM D559/D559M-15, Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures*. West Conshohocken, Pennsylvania, USA: ASTM International.

Aureka - Machinery for Sustainable Construction. (2014). *Earth Construction Equipment*. Retrieved from Aureka.com: http://www.aureka.com/earth-construction-equipment/auram-press-3000

Auroville Earth Institute. (n.d.). *Auroville Earth Institute*. Retrieved from AVEI Technologies: http://earth-auroville.com/sitemap_en.php

Blumer, M. (1977). *Soil stabilization using bitumen emulsions.* Hanover, NH: Corps of Engineers U.S. Army - Cold Regions Research and Engineering Laboratory.

Chen, G. Y. (2009). *Analysis of stabilized Adobe in Rural East Africa.* San Luis Obispo: California Polytechnic State University.

Davidovitts, J. (1988). Geopolymeric cross-linking (LTGS) and building materials. *Geopolymer. Vol. 1*, pp. 79-88. Compiegne, France: Geopolymer Institute.

Fitzmaurice, R. (1958). *Manual on stabilized soil construction for housing.* New York: United Nations Publication.

GATE. (1994). *Stabilizers and Mortars.* Eschbom: Deutsches Zentrum Entwicklungstechnologien.

Geotechdata.info. (2016, October 4). *Proctor Compaction Test*. Retrieved from Geotechdata.info: http://www.geotechdata.info/geotest/proctor-compaction-test.html

Guillard, H., & Houben, H. (1994). *Earth construction: A comprehensive guide.* London: ITDG Publishing.

Guillaud, Houben H. ;CRATerre. (1984). Primer on Earth construction. *CRATerre.* Brussels: CRATerre/PGC/CRA/UNCHS/AGCD.

Habitat Verde. (2014). *Projects & case studies*. Retrieved from Habitat-Verde.com: www.habitat-verde.com/global.html

Harichane, K., Ghrici, M., & Kenai, S. (2012). Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: A preliminary study. *Environmental Earth Sciences*, 66:2197-2205.

Hosokawa Micron Powder Systems. (2018). *Mineral - Kaolin*. Retrieved from Hosokway Micron Powder Systems: https://www.hmicronpowder.com

Houben, H. V. (n.d.). *Compressed earth block technology and small contractor development in Africa.* Grenoble: International Center for Earth Construction - School of Architecture of Grenoble.

Houben, H., & Rigassi, V. (1999). Compressed Earth Block Technology and Small Contractor Development in Africa. *CIB REPORT*, 34-43.

International Labour Office and the United Industrial Developement Organization. (1984). *Small-scale brickmaking.* Geneva, Switzerland: ILO Publications.

Ipinge, I. L. (2012). *Durability of compressed stabilised earth blocks (Master of Science Dissertation).* Johannesburg: School of Civil and Environmental Engineering, University of Witwatersrand.

Kerali, A., & Thomas, T. (2002). Effect of mix retention and curing on low-cement walling blocks. *Building Research & Information, Vol. 30, Number 5*, 362-366.

Kuchena, C. J., & Usiri, P. (2009). Low cost construction technologies and materials case study Mozambique. Bath: 11th International Conference on Non-Conventional Materials and Technologies (NOCMAT 2009).

Kumar, R., Mathur, R., & Kumar, A. (2011, August). *NBM Media - construction information*. Retrieved from NBMCW: http://www.nbmcw.com/articles/miscellaneous/others/25054-use-of-nanotechnology-in-cement-based-materials.html

Latha, M., & Venkatarama, R. B. (2014). Influence of soil grading on the characteristics of cement stabilized soil compacts. *Materials and Structuress*, Vol 47: pages 1633-1645.

Linyi Fulang Trading Co. Ltd. (2018, May 5). *Product catergories*. Retrieved from Interlocking Block Machine: https://brickmachines.en.alibaba.com/company_profile.html

National Lime Association. (2004). *Lime-treated soil construction manual - lime stabilization & lime modification.* Arlington, VA: National Lime Association. Retrieved from https://www.lime.org/

Peace Corps. (1981). *Handbook for Building Homes of Earth.* Washington, DC: Peace Corps' Information & Exchange (ICE). Retrieved from https://pdf.usaid.gov/pdf_docs/PNAAE689.pdf

Proto, C. G., Sanchez, D. W., Rowley, K. S., Thompson, R. S., & Moss, D. R. (2010). *Interlocking compressed earth block (ICEB) : Design and construction manual.* San Luis Obispo: California Polytechnic State University.

Rai, D. A. (n.d.). *Mud stabilized-blocks: Production and use technical manual.* Vienna: United Nations Industrial Development Organization.

Reddy, B., & Gupta, A. (2005). Characteristics of soil-cement blocks using highly sandy soils. *Materials and Structures 38*, 651-658.

Reddy, K. R. (2002, August). Engineering properties of soils based on laboratory testing. Chicago, University of Illinois.

Rigassi, CRATerre-EAG, V. (1985). *Compressed earth blocks: Manual of production.* Eschborn: GATE.

Rubenstein, M. (2012, May 12). *Emissions from the Cement Industry.* Retrieved from State of the Planet - Earth Institute Columbia University: https://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/

Schildkamp, M. (2009). *Suitability of local soil for cost saving construction techniques.* South Holland, Nertherlands: Smart Shelter Foundation. Retrieved from https://www.smartshelterfoundation.org/wp-content/uploads/2014/07/SSF-soil-testing-manual.pdf

SERC Carleton College. (2017, October 5). *Geochemical instrumentation analysis*. Retrieved from SERC.Carleton.edu: https://serc.carleton.edu/research_education/geochemsheets/techniques/SEM.html

Sturm, T., Ramos, L., Lourenco, P., & Campos-Costa, A. (2014). Mechanical characterization of dry-stack interlocking compressed earth masonry. *International Masonry Conference.* Guimaraes: International Masonry Society.

Venkatarama, R., Lal, R., & Rao, K. (2007). Optimum soil grading for the soil-cement blocks. *Journal Material Civil Engineering (ASCE) 19 (2)*, 139-148.

Walker, P., & Stace, T. (1997). Properties of some cement stabilized compressed earth blocks and mortars. *Materials and Structures 30*, 545-551.

Wolfskill, Lyle A. ; Agency for International Development. (2005). *Handbook for building homes of earth.* Honolulu: University Press of the Pacific.

VITA

Kenneth Wachira was born on February 16^{th}, 1972 in Nairobi, Kenya. He attended Eastleigh High School in Nairobi, Kenya. He then studied for an associate diploma in Civil Engineering from Mombasa Polytechnic in Mombasa, Kenya. After a brief break to his educational career Kenneth moved to the United States in 1996 and completed a degree in Civil Engineering at Kansas State University. While in school Kenneth has worked as a Civil Engineer specializing in airport design and construction. He currently is working as an Airport Engineer with Burns & McDonnell.