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Effects of Polyethylene Terephthalate Fibers in The Water Resistance of Compressed Stabilized Earth Blocks.

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EFFECTS OF POLYETHYLENE TEREPHTHALATE FIBERS IN THE WATER RESISTANCE OF COMPRESSED STABILIZED EARTH BLOCKS.

by

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EFFECTS OF POLYETHYLENE TEREPHTHALATE FIBERS IN THE WATER RESISTANCE OF COMPRESSED STABILIZED EARTH BLOCKS.

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This research project focuses on investigating the effects of synthetic fibers (PET) and amount of cement stabilization on the water absorption, water surface erosion, and wet compressive strength of the compressed stabilized earth blocks (CSEB). The use of locally available soils blended with fibers and cement was investigated to obtain a design mix for compressed stabilized earth blocks capable of staying intact in wet and humid regions in the world (i.e. regions with annual rainfall of over 50 in). Blocks with varying cement percentages of 5, 8, 10, and 15% by weight were produced with 3 specimens each, with and without fiber at 0.25% by weight of the dry material (17 lb).

The findings of the research indicate that PET fibers increase the water absorption rate of CSEBs. The absorption rate of fiber reinforced blocks with 5 and 8% cement content was 2% more than the unreinforced blocks. An increase in cement content increases the resistance to water surface erosion, where 8, 10, and 15% cement content had zero surface erosion for both sets of blocks. According to the results of this research, the inclusion of fibers together with the increase in cement content improves the compressive strength of CSEBs. Ten percent stabilized CSEB with 0.25% PET fibers recorded a wet compressive strength of 1082 psi, which is almost double the corresponding 10% stabilized blocks without fibers at 547 psi. However, this finding is different than

common observation of fiber reinforced cementitious mixtures with respect to compressive tests. Future research is necessary to identify the causes and consistency of the strength increased observed. Based on the findings of this research, it can be concluded that 10% cement stabilized CSEB without fibers can be a viable option for water prone areas.

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LIST OF SYMBOLS

English

lb = Pound

Psi = Pound per square inch

m = Meter

% = Percent

mm = Millimeter

cm = Centimeter

ºF = Degree Fahrenheit

ºC = Degree Celsius

km = Kilometer

hr = Hour

min = Mins

ml = Milliliter

Chapter 1

Introduction

The goal of this research was to determine the effects of PET fibers and cement stabilization percentage in compressed stabilized earth blocks (CSEB), to increase their durability in wet climates. The research mainly focused on establishing a design mix to counter the effects of water surface erosion and water absorption caused by heavy rainfall, without compromising the structural integrity of the blocks.

1.1: Background and Motivation

Even though the world's population growth rate has declined over the years from 2.1% to about 1.2% per year, there still has been an increase in the total population globally. Population analysts predict that if this trend continues, there will be an increment of about 83 million increase to the overall population annually. Statistics show that within the next 35 years, there will be an addition of 2.5 billion people to the world's population with about 90% of this growth to be in the developing countries (Haub, 2011). Based on these figures, providing sufficient housing for all is a challenging and currently unaccomplished-task. According to *United Nations Organization in charge of Human Settlement* (UN-HABITAT), about 3 billion people lack satisfactory housing. This problem is largely attributed to lack of availability of building materials to meet the demand and the high cost of obtaining them.

Addressing this problem requires continued innovation and emphasis on sustainability. As dependency on non-renewable materials has been the norm, there is urgent need to research new materials that are affordable and sustainable to help solve the housing shortage problem in the world, especially in developing countries. Earth construction has proven to be a viable option in providing low cost and sustainable housing, and have been used for many centuries before the advent of present day building materials. However, thus far, earth construction has taken a back seat when compared to concrete blocks, steel, and timber in the building industry. It is now recognized that it may possess great economic and environmental benefits over the modern materials.

Past research has shown that, earth blocks are prone to water absorption and surface erosion as a result of rainfall, limiting their long term durability. Two target areas were selected for project parameters; the state of Florida in the U.S.A. and the West African country of The Gambia. Both of these regions are suspect to heavy rainfall, yet provide plausible locations for successful implementation of CSEBs for various reasons: soil appropriateness (Florida) and tradition of earth construction (The Gambia).

1.2: Research Significance

Compressed stabilized earth blocks (CSEB) have gained increased attention as an alternative building material in many parts of the world and have improved in terms of both strength and production (Obonyo, 2010). Over the years, a considerable amount of research has been carried out on CSEBs. Stabilizers, such as cement and lime, and the inclusion of plastic or natural fibers, have been investigated to increase ductility and toughness.

Currently, a research team from the University of Nebraska-Lincoln's Architectural Engineering program is studying the structural performance of engineered earthen masonry as part of a project funded by the National Science Foundation (NSF, award #1131509, PI: Erdogmus). Recent findings of this experimental program suggest that the block composition with soils containing 9% clay and stabilized with 10% cement produces compressive strengths of about 500psi. The addition of the synthetic fibers such as Polyethylene Terephthalate (PET) contributes little to the compressive strength but increases flexural capacity and local toughness (Erdogmus, Garcia, & Wagner, 2013). However, the scope of the NSF project does not include the blocks' resistance to water penetration and surface erosion, *i.e.* durability in wet climates.

1.3: Goals and Objectives

The ultimate goal of this research project is to study the effects of water on CSEBs, and to increase their durability in wet climates. Other studies were conducted on the resistance of earth blocks to water penetration; however these studies dealt mostly with the application of surface coatings such as engine oil and enviroseal (Chew, 2012). The objectives of this research are to investigate the effects of cement stabilization and fiber inclusion on:

1) Water absorption through the block, which is critical for use in rain-prone areas like Florida and The Gambia,
2) Resistance to surface erosion of CSEBs when subjected to the action of heavy rainfall with wind, and

3) Wet compressive strength of the blocks to get a better understanding of the structural performance of the blocks after they are exposed to significant amount of water.

1.4: Scope

For this project cement stabilization ranging from 5,8,10 and 15% by weight, and synthetic PET fibers 0.25% by weight are considered during block production. Only individual units were used during the experiments, therefore water absorption through the mortar joints in a wall setup were not considered.

The standard soil testing such as sieve analysis, Atterberg limits hydrometer tests, determination of moisture content are needed for the characterization of the soil. In order to better understand the behavior of the blocks when subjected to a considerable amount of moisture, following tests were employed:

1) Absorption: This test is conducted in accordance with ASTM C67-11. It is vital in determining the durability of the blocks when exposed to flooding. The rate of absorption of moisture has a direct relation to the physical deterioration of the blocks.
2) Surface Erosion test: In order to design blocks capable of withstanding heavy rainfall with high winds, we need to understand the behavior of blocks when subjected to pressurized water. Modified spray test (Obonyo, 2010) was used to create a rainfall scenario, and to measure the rate of erosion.

3) Wet Compressive test: The strength of the blocks is determined by conducting a compression test according to C67-11.

1.5: Thesis Overview

This thesis comprises of five chapters. A breakdown of the subsequent chapters is listed below.

Chapter 2-Literature Review: This chapter gives an in-depth look at the literature review. It presents a brief history on the evolution of CSEB and its application in the building industry. The mode of block deterioration by the absorption of water and surface erosion is also discussed. Furthermore, the benefits of cement stabilization and the inclusion of fibers in the design mix to improve the durability and compressive strength of blocks was reviewed. It also describes the climatic and environmental conditions in The Gambia and the State of Florida.

Chapter 3- Research Methodology: The methodology describes the experimental approach and procedures. All ASTM standard tests used in this study and any modifications to them are explained in this chapter.

Chapter 4 – Results: After successfully completing the experimental program described in chapter 3 the relevant data and results are presented in this chapter. The results for the water absorption test, water surface erosion, and the wet compression test are discussed. The significance and meaning of the results are explained in detail in this chapter. Also, if there are any discrepancies in the results the cause/reasons were discussed.

Chapter 5- Conclusion and Recommendations for future work: In this chapter the results obtained are compared to the original goals and objectives of the project. It also elaborates on future research projects that are beneficial to the subject matter.

Appendix A: Relevant equations, spreadsheets, and extra documentation involved in the geotechnical testing are given in this section.

Appendix B: Graphical representation of experimental test results, and submersion test calculations, spray test calculations, and determination of maximum wet compressive strength data.

Chapter 2

Literature Review

Earth block construction has changed considerably since pre-historic times. The performance and development of compressed stabilized earth blocks (CSEB) in recent years, contributed greatly in its application as a viable building material. This chapter intends to give a detailed review of the relevant literature on the subject matter in the following specific topics:

1) Evolution of CSEB and Soil Characteristics.
2) The practical application of CSEB as a building material
3) Water resistance and deterioration of CSEB
4) Climatic conditions for Florida, USA and The Gambia in West Africa.

Following the detailed literature review is a brief summary of the pertinent knowledge discussed therein. The chapter concludes with the establishment of relationships between potential research gaps and the project goals.

2.1: Evolution of Compressed Stabilized Earth Blocks

Centuries ago, earth architecture played a vital role in providing shelter to many. Builders over the years have developed both simple and complicated forms for casting earth blocks depending on the available resources. It is estimated that 1.7 billion people of the world's population live in earth houses (Roy, Sangeeta, & Swaptik, 2013). Earth has been in use in ancient cities in Egypt, the Roman Empire, and many European and Middle Eastern States. Some of these structures still remain standing, such as the great mosque of Timbuktu in Mali, as shown in Figure 2.1.

Figure 2.1: The great Mosques of Timbuktu, Mali

Source: Google Image, 2011

Earth has transcended the purpose of providing shelter for the rural communities in the past with some landmark structures such as monuments, pyramids, churches, and mosques (Rael, 2010). Years ago in dry climate regions where timber is scarce, new roofing strategies were developed. The roofs were covered with mud bricks without formworks during construction as shown in Figure 2.2 (Minke, 2006). Earth construction techniques vary according to geographical regions, and historical period. One of the techniques called *Torchis,* involves using branches of shrubs to create the frame of the house, and mud is then used to filled the spaces (Molla, 2012). Other techniques such as *pise,* involves compacting the soil into wooden forms (Molla, 2012). *Adobe* is also another technique in earth construction, was introduced in the Mediterranean area in ancient times. Actually this technology marks the beginning of CEB, involving the use of molded sun-dried earth blocks. (Molla, 2012)

Figure 2.2: Bazaar Quarter of Sidjan in Persia
Source: (Minke, 2006)

With the increased quest for sustainability in the late twentieth century, earthen construction have witnessed a renewed attention, which resulted in substantial research. Earth which is a heavy, dark and formless material, has been transformed into a workable building material to provide shelter (Roy, Sangeeta, & Swaptik, 2013).

In comparison with other building materials such as steel, timber, and reinforced concrete; CSEB offers a different option to the building industry. According to (Mujahid, 2010) earth blocks have series of advantages such as:

1) It encourages the use of local materials and also promotes in-situ productions which help reduce transportation cost.
2) It requires less energy during production, and the release of carbon emission to the environment is minimal, unlike CMUs which requires heavy machinery during production.
3) Its ability to absorb atmospheric moisture helps maintain a conducive indoor quality for the occupants.
4) It possesses the ability to resist fire and promotes noise control.

Despite its numerous benefits, there are some disadvantages as well (Adam & Agib, 2001):

1) When compared to conventional materials such as concrete blocks, steel and timber earth is less resilient.
2) Low tensile strength and low resistance bending moments.
3) Without proper reinforcement and protection they can have low resistance to abrasion.

2.1.2: Soil Composition

Soil is composed of substances which can be divided into four groups:

1) Gases: These are the atmospheric gases (oxygen, carbon dioxide, nitrogen) from the environment.
2) Liquids: Typically, water from rainfall and other substances provides the liquid component in the soil. Other atmospheric conditions such as mist and humidity are also sources of water for the soil.

3) Organic matter: Organic matter is typically found in the top layer of the earth and is part of the solid ingredients of the soil. It should be noted here that, it is not a good practice to include the organic content of the soil for earth construction (Adam & Agib, 2001).

4) Minerals: Minerals are also part of the solid components and are sub-divided into inert minerals and active particles. The inert minerals are the coarse grains in the soil and are non-cohesive. They consist of gravel, coarse sand, and fine sand (Schildkamp, 2009). The active particles are silt and clay and are often referred to as fines and are cohesive. Their presence in the soil composition is vital as they provide the binding capability needed for earth blocks. However, they are not as stable as gravel and sand, since they swell up and shrink when water is added or taken out (Schildkamp, 2009).

    a) Gravel (Figure 2.3): These are the most stable soil components, as they show little or no effects when exposed to moisture. They are made up of small grains, which are a result of the disintegration of the solid rock. The particles are varying sizes from 2 to 20mm.

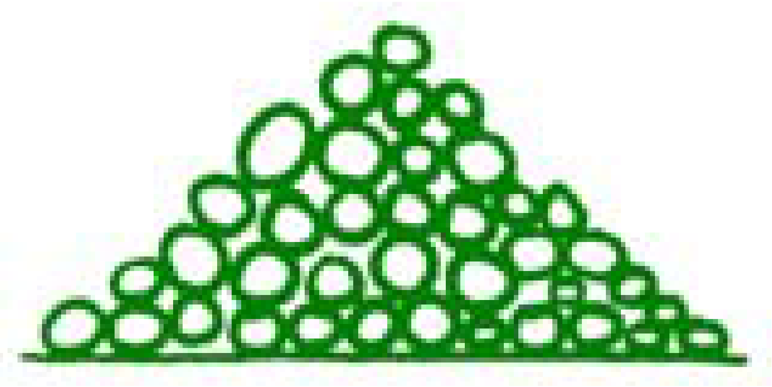

Figure 2.3: gravel particles. Source (Schildkamp, 2009)

b) Sands (Figure 2.4): These are composed of mineral particles of silica and quartz with an open permeable structure. The grain sizes vary between 0.06 and 2mm. Although a very stable soil components, it lacks the cohesive force to keep the particles together when dry.

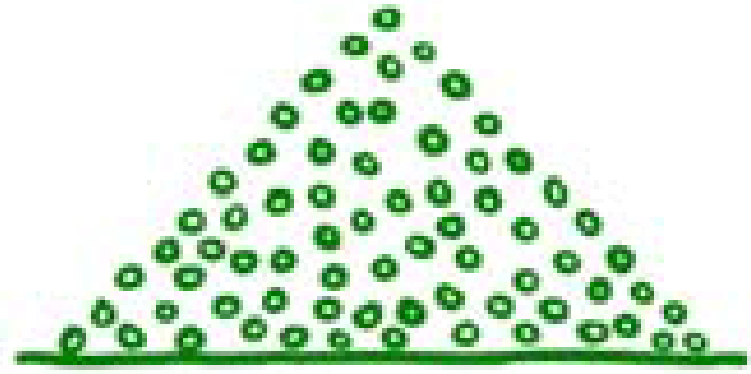

Figure 2.4: Sandy particles, Source (Schildkamp, 2009)

c) Silts (Figure 2.5): With respect to the physical and chemical properties, silt and sand particles are quite similar. Silt has a particle size between 0.002 and 0.006mm, and lacks cohesion when dry. It has the ability to swell and shrink when exposed to different levels of humidity. They provide the soil with some stability by increasing its internal friction and filling the voids in the grains.

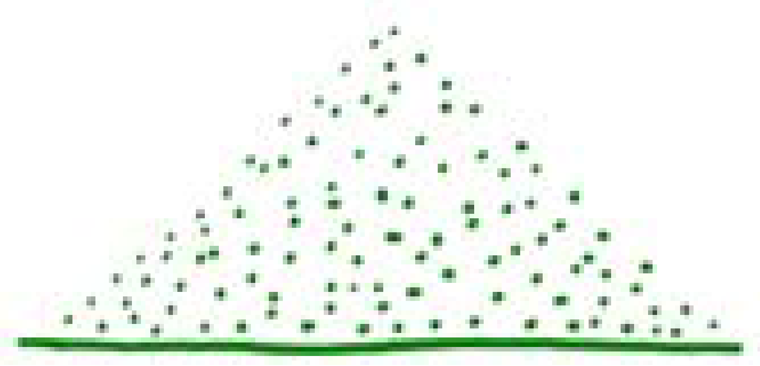

Figure 2.5: Silty Soil, Source (Schildkamp, 2009)

d) Clay (Figure 2.6): These are the finest particles in soils with size of less than 0.002mm. Clay also has unique characteristics, such as inclusion of microscopic mineral particles such as kaolinites, illites, and montmorillonites. They are very different from other particles, both physically and chemically, their plate-like shape molecules are electrically charged, which attracts water easily.

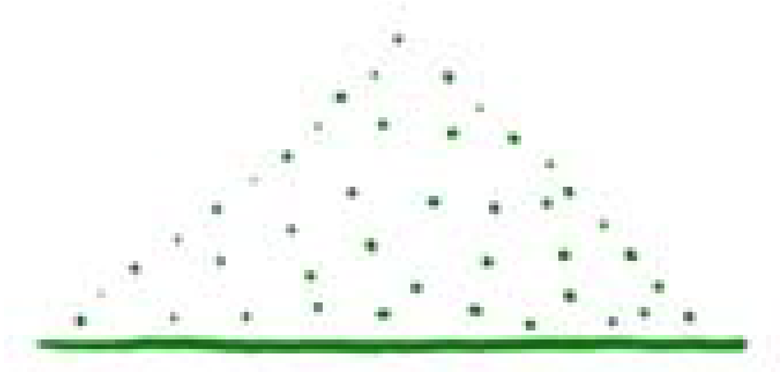

Figure 2.6: Clay Particles, source (Schildkamp, 2009)

2.1.3: Dispersive Clay Soils

Dispersive clay soils have unique properties which under certain conditions deflocculate, and are rapidly eroded by flowing water (Knodel, 1991) . Some naturally occurring clay soils disperse in the presence of water, which renders them susceptible to erosion. The ability for dispersive erosion mainly depends on the mineral content and the chemistry of the clay (Knodel, 1991). These soils are eroded with ease by slow moving water when compared to fine sands and silts.

When dispersive clay soils are completely submerged in water, the clay fraction tends to behave like a single particle. As a result of this, the clay particles lose their electrochemical attraction with other soil particles. Knodel also states that dispersive clays will erode in the presence of flowing water when the individual clay platelets are divided and carried away by the flowing water. The main difference between dispersive clays and ordinary clays is the type of ions in the pore water of the clay. Dispersive clays possess excess sodium cations whilst ordinary clays have calcium, potassium, and magnesium cations in excess.

2.1.3.1: Properties of Dispersive Clays

1) Dispersive clays are low to medium plasticity and generally classified as CL in the United Soil Classification System (USGS). Other classifications that may contain dispersive clays are ML, CH and CL-ML. Soils classified as MH rarely contain dispersive clays (Knodel, 1991).
2) There is a difference in the electrochemical attractive force in a dispersive clay soil. As a result of this, the soil particles in dispersive clays are repelled rather than attracted to each other. Consequently, for dispersive clays the particles react as single grained particles instead of an aggregate mass.
3) Dispersive clays are highly erosive because they contain higher percentage of sodium cations in the pore water. The sodium increases the thickness of the double water layer surrounding the clay particles. This makes the repulsive force greater than the attractive force, thus the particles go into suspension in the presence of water (Knodel, 1991).

2.1.3.2: Location of Dispersive Clays

Dispersive clays have not been definitely associated with any specific geologic origin, but most of known dispersive clay sources are found as alluvial deposits in the form of slope wash, lake bed deposits and flood plain deposits. There is no distinct color associated with these soils; they can be red, brown, yellow or a combination of colors (Knodel, 1991). Previous studies showed that dispersive clays were associated with soils formed in arid or semiarid regions. However, recent literature (Heinzen & Arulanandan, 1976) states that similar soils and erosion patterns were also observed in humid climates in various locations such as the America's, Ghana, and Brazil. Dispersive clays can also be found in Nebraska, most commonly around Winnebago. The properties of dispersive clays are relevant for the purpose of this research, because the soil needed for block production was obtained from Winnebago.

2.1.3.3: Rainfall Erosion of Dispersive Clays

There is a significant difference in the erosion potential of dispersive and non dispersive soils due to rainfall and runoff on exposed surfaces. Erosion occurs as a result of induced fluid flow, when the shearing stress on a surface gets large enough to cause the removal of particles from the surface. According to recent literature by (Heinzen & Arulanandan, 1976), soil erosion is basically a complicated phenomenon, involving the structure of the soil and the nature of interaction between the pore and the eroding fluids such as run-off water at the surface. It was also observed that the stress required to initiate erosion is affected by the amount and type of clay, pH levels, temperature, presence of organic matter, water content, concentration of ions in the pore fluid (Heinzen & Arulanandan, 1976).

2.1.4: Principles of Stabilization

The strength of the soil used in producing blocks can be improved in many ways, simplest being compaction with a mechanical press. This increases the compressive strength and makes the block denser (Roy, Sangeeta, & Swaptik, 2013). To increase earth blocks strength and durability even further, stabilizing materials can be added to the soil. Currently, there are over 100 potential stabilizers capable of blending effectively with earth, but there is a very thin margin of distinction amongst them. The most commonly used stabilizers are cement and lime. Bitumen, chemicals, and other enzyme-based stabilizers have been used with the same objective as all other stabilizers (Heath & Walker, 2013). According to (Mohammad & Lee, 2003) there are three (3) basic stabilization processes:

1) Mechanical Stabilization: This is the compaction of the soil with the aid of a mechanical press to improve its strength, durability, and water resistance.
2) Physical stabilization: It involves the modification of the soil texture through heat and electrical treatment.
3) Chemical Stabilization: The process of adding chemicals to modify the properties of the soil or by creating a matrix for binding the grains together.

There are certain guidelines listed in the literature (Obonyo, Exelbirt, & Baskaran, 2010), that can be used as a benchmark for the selection of stabilizer. Appropriate stabilizer types for various soil types are listed in Table 2.1.

Table 2.1: Types of Stabilizers for different soil types
Source: (Obonyo, Exelbirt, & Baskaran, 2010)

Type of Soil/Condition	**Stabilizer**
For nearly all types of soils	Portland
Medium, moderate, fine and fine-grained soils	Hydrated Lime
Coarse grained soils with little if any fine grains	Fly Ash
Cold climate applications	Calcium Chloride
For increasing resistance to water and frost	Bitumen

As discussed in the previous section, silt and clay are unstable, especially when water is added. The clay particles tend to swell when wet and shrink when dry. This phenomenon can easily lead to cracking in earth blocks, which in return increases the possibility of surface erosion and compromises the structural integrity of the block (Adam & Agib, 2001). The adoption of right stabilizing method can improve the compressive strength by almost 400% and also increases the block's resistance to surface erosion (Adam & Agib, 2001).

2.1.4.1: Cement Stabilization

Portland cement is by far the most common stabilizing agent use in the production of earth blocks. When water is added to cement, it hydrates and as a result the reaction produces a cementitious gel, which is made up of calcium silicate hydrates, calcium aluminate hydrates, and hydrated lime. This process is known as hydration (Adam & Agib, 2001). This chemical reaction produces a matrix of interlocking filler which covers the aggregates, to form a strong binding force (Molla, 2012). The addition of cement in the soil mixture, improves the performance and resistance to water. Cement can be used with any soil type, but it is considered uneconomical when added to soils with a Plastic

Index greater than 15% (Riza, Rahman, & Zaidi, 2006). Generally, cement content varies between 3% to 18% by weight depending on the soil type (Adam & Agib, 2001).

2.1.4.2: Physical properties of Portland cement

Portland cement is an important constituent in CSEBs, which differentiates it from CEBs. Two of the most important physical properties of cement are specific surface area and particle size distribution. These properties are important for CSEBs, as they dictate how the binder stabilizes the soil (Kerali, 2001):

1) Specific Surface Area: Since the hydration process during stabilization starts at the surface of the soil particle and proceeds inwards. It is important to increase the surface area, so that the rate of reaction will be faster (Kerali, 2001).
2) Particle Size Distribution: Particle size of cement affects hydration and rate of strength gain. The average size of cement grains is about 10µm, which can be compared to the finer particles in a clay soil with an average size of less than 2µm. Small particle sizes provide greater surface area to volume ratio, which gives more area for water-cement reaction (Kerali, 2001).

2.1.4.3: Lime Stabilization

In the process of lime stabilization, 4 chemical reactions take place, namely; cation exchange, flocculation and agglomeration, carbonation and pozzolanic reactions. The last stage is the most crucial and occurs between the lime and clay particles, which form a cementitious compound binding the particles together (Adam & Agib, 2001). Generally, soils with a Plastic Index greater than 15 are best stabilized with lime (Riza, Rahman, &

Zaidi, 2006). The calcium ions in lime are exchanged with the metallic ions of the clay thus stronger fine particles are formed. It reduces the absorption rate of the clayey soil making it more resistant to moisture penetration (Adam & Agib, 2001).

In a rural setting, lime is more commonly used as a stabilizer as compared to cement because it is cheaper, and can be produced locally in a traditional kiln. Some other advantages of lime over cement is that, it requires less fuel during production thus releases less carbon in the atmosphere (Adam & Agib, 2001)

2.2: Practical Applications of CSEB as a Building Material

Building with earth blocks is an ancient practice dating far back as 8000 to 6000 BC in different parts of the world most notably in Turkestan, Assyria, which was built in 4000 BC (Minke, 2006). Compressed stabilized earth blocks are made from naturally occurring soil with the addition of synthetic or organic fibers to improve its strength and durability. Earthen blocks are considered as a sustainable material because its energy requirement during production is 70% lower as compared to fired clay brick. They are also roughly 20-40% cheaper than fired brick (Victor & Leveille, 2005). Building material is a factor in the construction industry that requires serious attention since the material cost constitutes about 50% of the construction cost. In developing countries, the over-dependence of foreign imported products is the main cause of high construction costs (Minke, 2006).

Today 30% of the world’s population lives in earthen houses. This figure represents a great benefit to the global struggle in reducing green house gases to our environment. With the use of modern materials such as steel, concrete, and plastic as our only means of building material, we tend to drive towards ecological breakdown (Minke, 2006). Earth provides an alternative building material and a cheaper means of providing shelter.

Earth construction can be a viable option for tornado-proof structures, which are capable of surviving decades. They are relatively comfortable, renewable and noise proof, these characteristics amongst others make them durable. Earth blocks capability to resist tornados are based on the lump mass in the block, which will be so hard to crush or carried away (Victor & Leveille, 2005) .

2.3: Water Resistance of CSEB

Earth materials, when exposed to harsh climatic conditions such as rainfall and other water prone calamities undergo some form of deterioration over time. The continuous wetting and drying of the compressed stabilized earth blocks allows them to withhold an amount of moisture within its cells thus weakening its chemical bonding properties (Kerali, 2001). For good construction practice, durability of earth blocks against erosion or leakage issues due to rain, wind and dampness must be considered.

Some of the ways to improve erosion resistance of building façade includes the following:

1) The addition of a stabilizing agent such as cement and lime, which acts a binder between the soil particles.
2) Increasing the density of the soil.
3) The inclusion of a water proofing agent in the design mix.
4) Applying layer of plaster on the external walls.

The process and rate of block deterioration has been a major concern to many researchers. The initial time before deterioration begins is known as the initiation stage. This is later followed by the propagation stages which signal the beginning of deterioration (Adam & Agib, 2001). In relatively moderate climates the propagation phase is shorter than the initiation stage, which leads to the erosion or loss of materials. The rate of erosion depends on factors such as the type of stabilizer, level of exposure of the block surface, and the block resistance level. However CSEB are required to resist the effects of exposure conditions such as rainfall, throughout the duration of its life span. Therefore blocks in humid regions are more vulnerable to deterioration than those in dry regions (Kerali, 2001)

2.3.1: Water Absorption test

The main objective of this test is to determine the water absorption capacity of the blocks. This test is conducted in accordance with the ASTM C67-11, for water absorption. One study was conducted to determine the rate of absorption of 12 CSEBs blocks by varying cement content 5, 7.5 and 10% by weight, and also tested 3 samples with 5% cement blended with 0.5% jute fiber (Kabiraj & Mandal, 2012).

From the results, as shown on Table 2.3, show that 5% stabilized soils recorded the highest percent water absorbed of 18.92%. The blocks stabilized with 10% cement recorded the least amount of absorption. The addition of jute fibers in the design mix did not have a positive effect on the water absorption, as it recorded the highest percent of 20.53% even greater than the 5% stabilized soil. This could be attributed to the fact that jute fibers are organic and as a result they tend to absorb more moisture. Blocks stabilized with 7.5% cement and no fiber prove to be a viable and economical option, since the absorption rate meets the BIS (IS- 1725) code recommendation of 15% or less absorption rate for earth blocks (Kabiraj & Mandal, 2012). There is also a minimum water absorption requirement according to the New Mexico Code of 4%. This minimum will allow the blocks to form a strong bond with the mortar in a wall setup.

Table 2.2: Water Absorption at 28 days maturity
Source: (Kabiraj & Mandal, 2012)

Mix	Proportion	Water absorption(%) at 28 days maturity	Average water absorption(%) at 28 days maturity
CM1	5% cement only	19.21 19.05 18.50	18.92
CM2	7.5% cement only	14.27 13.86 13.45	13.86
CM3	10% cement only	10.51 10.02 10.83	10.45
CM5	Cement 5% + 0.5% jute fiber of 2.5cm	21.41 19.89 20.30	20.53

The absorption rate of earth blocks can be calculated with the aid of simple apparatus such as an electronic weighing machine. The blocks were weighed then submerged in water, and readings at 24hr period are recorded. The percentage absorbed rate can be calculated by the formula (Kabiraj & Mandal, 2012):

$$M_c = \frac{W_w - W_d}{W_d} \times 100 \qquad (2.5)$$

M_c = percentage moisture absorption (%)

W_w = mass of wetted sample (g)

W_d = mass of dry sample (g)

2.3.2: Compressive Strength of CSEB

The compressive strength of compressed stabilized earth blocks is the ability of the blocks to withstand applied loads. The amount of stabilization such as cement and lime in CSEBs affects the compressive strength. An increase in stabilization generally increases the strength (Heath & Walker, 2013). The water content in a mix design also affects the strength of the blocks. The strength of the blocks increases when small quantity of water is added to the mix during production (Victor & Leveille, 2005). From Figure 2.7, water content of less than 1% recorded the highest average compressive strength of about 6N/mm^2. Increase in water lowers the strength, at 3% water content, the capacity was reduced by 1/3 (Heath & Walker, 2013)

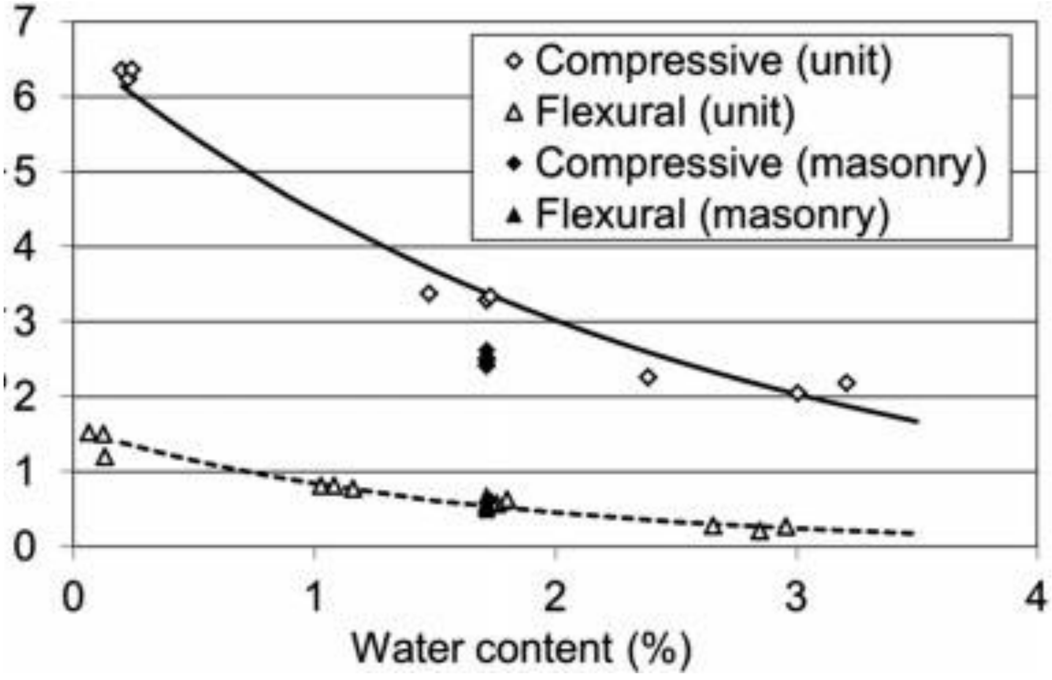

Figure 2.7: Decrease in strength in water content
Source: (Heath & Walker, 2013)

The effect of using natural fibers such as jute, for the improvement of compressive strength of CSEB was investigated by varying fiber 0.25, 0.5%, and 1% by weight. A total of 33 specimens were tested, with varying cement content from 5-10% (Kabiraj & Mandal, 2012). From the results obtained, it was observed that the inclusion of fiber increased strength. . For 5% cement content and jute content of 0.25%, 0.5% and 1.0% increased the compressive strength by 78.45%, 134.87% and 253.76% respectively. For 7.5% cement content and jute content of 0.25%, 0.5%, and 1.0% increased the compressive strength by 69.40 percent, 90.95 percent and 121.95 percent respectively. For 10% cement content and jute content of 0.25%, 0.5%, and 1.0% increased the compressive strength by 60.54%, 95.92%, and 115.30% respectively (Kabiraj & Mandal, 2012).

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2.3.3: Deterioration in Earth blocks

The external surface of building materials is among its most vital components. For CSEBs the quality of its surface is important in determining the durability (Hughes, 1983). The overall life cycle of a building material can be attributed to several factors, such as its resistance to deterioration over the life span of the building. The performance of the block surface largely depends on properties such as resistance to surface wetting, absorption, adhesion and abrasion (Young, 1998). CSEBs have a longer life span than CEBs, but the exposed surfaces are vulnerable to environmental factors surface erosion. This is as a result of consistent rainfall and wind action on the material over a period of time. Defects such as cracks, shrinkage are typical signs of such effects (Spence & Cook, 1983). The main common mechanisms of deterioration in blocks are:

1) Water related deterioration: Water constitutes the most likely cause of deterioration in earth blocks, in most cases comes from driven rain and rising

damp condensation. In areas of seasonal weather, the continuous alternate wetting and drying, allow the block to retain some amount of moisture. This process leads to the softening and abrasive action erodes the external surfaces (Kerali, 2001).

2) Temperature related deterioration: In regions of high temperatures, the building envelop is subjected to dimensional changes. Depending on the location of the building, the difference between the nocturnal and diurnal temperatures will have an adverse effect on the blocks which may cause cracks and splitting (Kerali, 2001).
3) Physical Action: this is mostly as a result of adhesive and abrasive action on the block surfaces. When two surfaces under high pressure slide against each other, adhesive action occurs. Whilst when a material is removed from the surface of the block, by cutting action of other particles causes abrasion (Kerali, 2001).

2.3.4: Fiber Reinforcement in Compressed Stabilized Earth Blocks

Earthen materials in general are quite weak and brittle, and thus in order to improve its compressive strength stabilizers are added, and for tensile strength fibers either organic or synthetic are required to help reduce cracking (Rigassi, 1995). At peak loading conditions fiber reinforcement reduces the effects of cracking, by keeping the particles closer together thereby acting as tensile reinforcements. Fibers also increase local toughness of the blocks. For low cost housing organic (plant) fibers are preferred as they are readily available, renewable and cheaper than synthetic fibers, but they offer variable properties to compressed stabilized earth blocks (Donkor, 2013). The fibers either increase or reduce compressive strength; this inconsistency can be attributed to the adhesion between the fibers and the soil, the hydrophilic characters of the fibers, and the distribution of the fibers within the design mix (Donkor, 2013).

The use of organic fibers in the production of compressed stabilized earth blocks was studied (Okoye & Mama, 2013), Palm kernel fibers were used and the cement content was kept constant whilst varying the fiber content. The water absorption rates of the blocks ranging from 5-12% were recorded, as shown in the Figure 2.8. The lower values were recorded at 1% fiber content and the highest at 5%. This research also showed that water absorption increases with increase in fiber content; therefore natural fibers are not a good option for water resistant earth blocks (Okoye & Mama, 2013). This is as a result of the water absorbed by the cellulose fibers, which is influenced by the volume of the voids and how much fiber is present in the mix (Okoye & Mama, 2013). These results further solidify the notion that fibers absorb moisture and expand during mixing and drying of the blocks. Consequently they swell and push away the soil, at the end of the drying stage, water is lost from the fibers and they shrink back to its original size. This process introduces fine voids to the overall block.

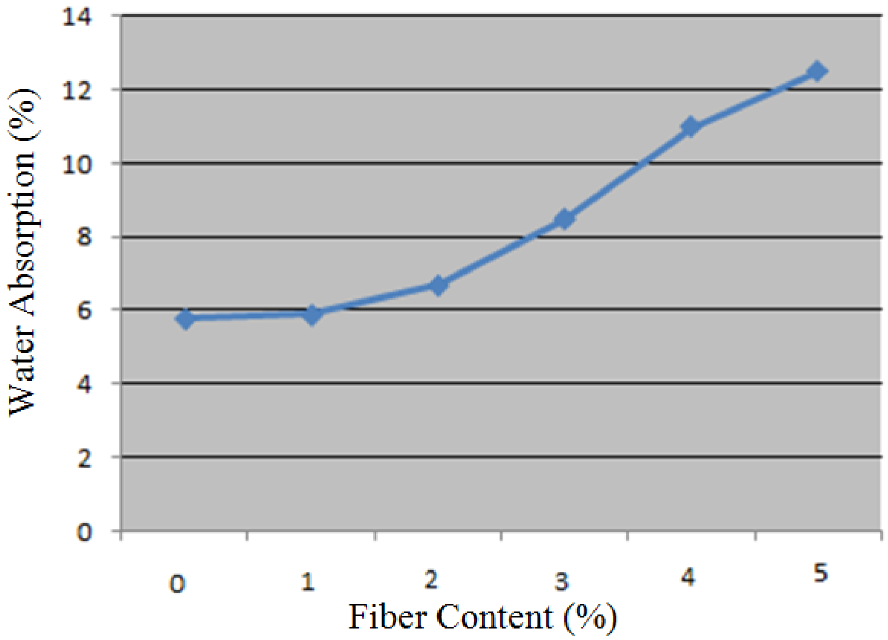

Figure 2.8: Relationship between fiber content and water absorption
Source: (Okoye & Mama, 2013)

According to (Donkor, 2013) positive results were obtained when synthetic fibers were used especially when the matrices is weak, brittle and low modulus. Polypropylene fibers have been successful in providing secondary reinforcement for masonry and concrete industry.

Figure 2.9: Polypropylene Fibers
Source: (Donkor, 2013)

Fiber content of between 0.1% and 2% polypropylene have no effect on the compressive strength of concrete but they tend to dictate the mode of failure of the concrete cylinders by making them more ductile (Donkor, 2013). There is little information available in the use of polypropylene fibers in earth blocks but its material properties is influenced by fiber volume and geometry, surface conditions and method of production. From Figure 2.10 it can be deduced that compressive strength gradually increases with fiber content up to about 0.4% weight which acts as the upper limit. From there any addition in fiber content is insignificant to the strength because, there is reduction in strength (Donkor, 2013).

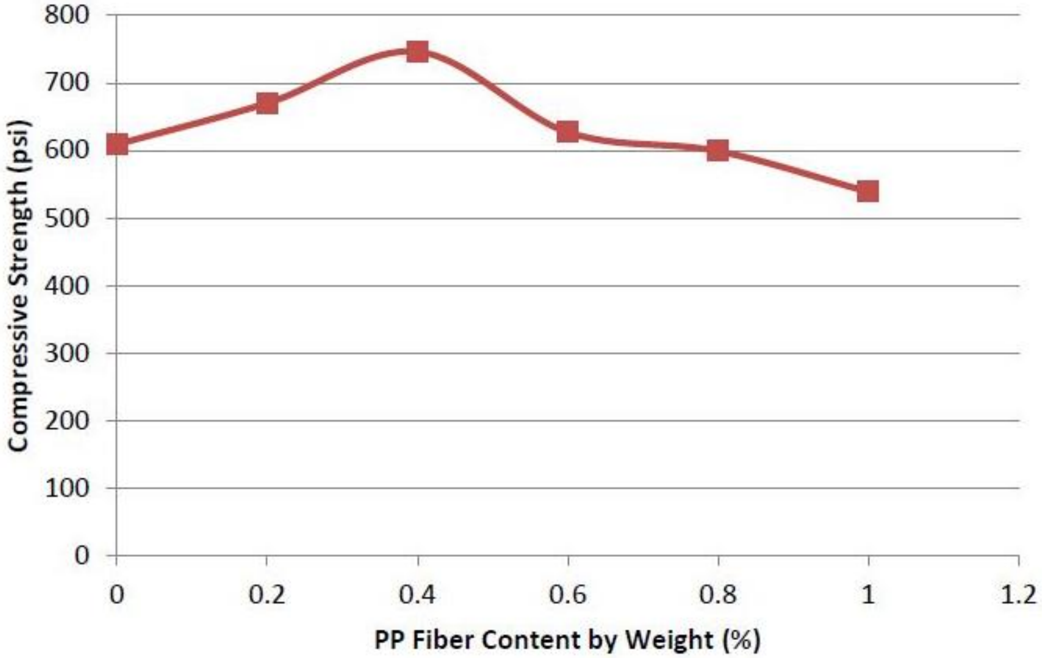

Figure 2.10: Relationship between fiber content and compressive strength
Source: (Donkor, 2013)

2.4: Geographic and Climatic Conditions

As previously mentioned, Florida, USA and The Gambia are the geographical areas that will constitute the subjects of this study. For this reason their geographic and climate conditions will be utilized to study the effects of heavy rainfall on CSEB blocks with and without fibers.

2.4.1: Florida, USA:

As seen in Figure 2.11 the majority of the state lies within the southern portion of the northern hemisphere's humid subtropical climate zone. It is well known for its long, hot, and humid summers, followed by mild and temperate winters. According to the National Climatic Data Center mean temperatures during Florida's coldest month range from 50 ^{o}F in the north and around 60 ^{o}F in the south. In the hottest month (July) the range is between 90^{o}F (32^{o}C) to a maximum of 109^{o}F (43^{o}C). The data center also stated that Louisiana is the only state that receives more rainfall on average than Florida, where, on average about 54 inches of rainfall is recorded annually for Florida.

Figure 2.11: Map of Florida (Source: Google Images, October 2013)

2.4.2: The Gambia

The Gambia, situated on the western coast of Africa, resembles a thin ribbon of land. The maximum width of the country does not exceed 50km (30 miles) from east to west. The river separates the country in two halves as seen in Figure 2.11 and has a width of about 15km (9 miles). The Gambia is bounded on 3 sides by Senegal and the forth by the Atlantic Ocean (Republic of The Gambia, Country Profile, 2011).

The country lies in a region that has arguably the most agreeable climate in West Africa; the weather is subtropical, with distinct dry and rainy seasons. From mid November to early June, coastal areas are usually dry, while the rainy season lasts from late June to October. Inland, the cool season is shorter, and daytime temperatures are very high between March and June. Sunny periods occur on most days, even during the rainy season. Hot, humid weather dominates the rest of the year, with a rainy season from June to October; during this period, temperatures may rise as high as 43° C (109° F) but are usually lower near the sea. These figures are very comparable to the average temperatures recorded in Florida. Mean temperatures range from 23° C (73° F) in January to 27° C (81° F) in June along the coast and from 24° C (75° F) in January to 32° C (90° F) in May inland. The average annual rainfall ranges from 92 cm (36 in) in the interior to 145 cm (57 in) along the coast (Republic of The Gambia, Country Profile, 2011).

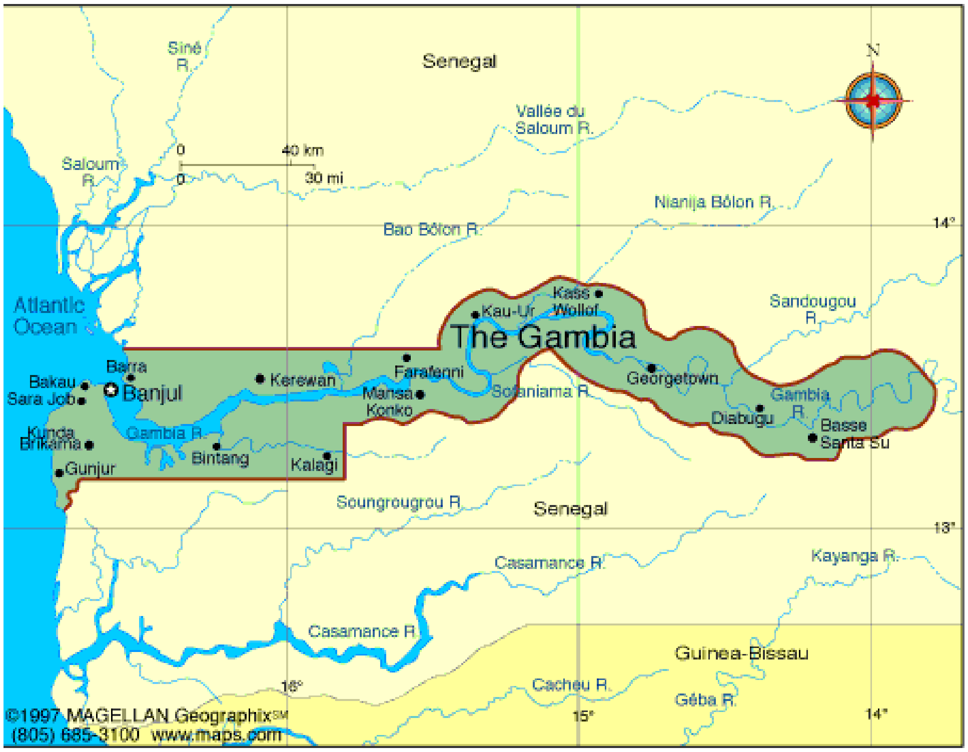

Figure 2.12: Map of The Gambia (Republic of The Gambia, Country Profile, 2011)

2.4.3: Use of Earthen Construction in The Gambia

Earthen structures are a common building material in rural Gambia. However its use is rarely attributed to a conscious regard for sustainability, but necessitated by the poorer rural population. The lack of proper technique and adequate machinery leads to the production of lower quality blocks (Figure 2.13). As previously mentioned, The Gambia is subject to a yearly wet season with heavy rains often resulting in disastrous flooding. The low strength blocks used in residential construction when exposed to heavy rainfall absorb moisture which weakens the molecular bonds holding the particles together. This will make the blocks lose its structural integrity and in most cases resulting in collapse.

Figure 2.13: Gambian Earth Blocks**:** Newly cast earth blocks curing in open air in a construction site in The Gambia

Nearly all the earth blocks made in the Gambia are unstabilized and produced without the proper machinery thus their structural integrity and durability is compromised. In order to address this problem, an effective design to produce high quality blocks that are durable and water resistant is needed.

Figure 2.14: Typical Gambian Earthen Wall**.** The photo above illustrates the erosion of poorly made earth blocks when exposed to the Gambian wet season, Source (Author).

Figure 2.14 shows a typical example of blocks that are under constant threat of erosion. Without surface rendering, water exposure causes a loss of bonding capabilities. This in turn severely affects the durability of the blocks.

2.5: Summary

The use of compressed stabilized earth blocks as a building material has proven to be a success in many countries, with the aid of ongoing research some of the problems faced by builders are gradually been resolved. From literature (Kerali, 2001), clay type, water content, choice of stabilizer and fiber, climatic conditions amongst a few plays a vital role in the overall performance of the earth block. Deterioration of the blocks also has been a stumbling block in the life span earth buildings. There is a research gap in the use of synthetic fibers such as PET in the area of water penetration and surface erosion. Although the use of organic fibers in the design mix has been studied, results show that they have a great ability to absorb water. Thus this prompted the need to investigate the effects of synthetic fibers which happens to be the main goal of this research.

Chapter 3

Research Methodology

Building with earth materials in water prone areas requires special consideration for the quality of the blocks. The performance of Compressed Stabilized Earth Blocks (CSEB) under severe moisture attack can be better understood by performing specific laboratory tests. This chapter describes the experimental approach and procedures. All ASTM standard tests used in this study and any modifications to them, if applicable, are explained in this chapter.

3.1: Geotechnical Analysis

The soil used in this research was obtained from Winnebago, Nebraska (Figure 3.1) due to availability. During the excavation process, the top soil was scraped off to eliminate the inclusion of organic material in the blocks (Adam & Agib, 2001). The excavated soil was then sieved to remove any unwanted material buried in the soil strata. This is important in order not to compromise the quality of the blocks produced. In the process of classifying the soil the following tests were conducted as recommended by the American Standard of Testing Methods (ASTM).

1) Moisture Content test (ASTM 2216-05).
2) Atterberg limits test (ASTM 4318-10).
3) Dry sieve test (ASTM 422-07).
4) Hydrometer test (ASTM 422-07).

Figure 3.1: Map of Winnebago, Nebraska
Source: Google Map

3.1.1: Moisture Content Test

This test is performed to determine the water content of soils. The water content is the ratio, expressed as a percentage of the mass of water in a given mass of soil to the mass of dry soil. The test is performed in accordance with ASTM D2216-05 (ASTM, 2005). The process for moisture test starts by collecting about 30g sample of soil and divide it into 3 portions. Each portion is weighed and recorded before drying them in the oven for 16-24hrs at a temperature of 105^{o}C (221^{o}F). After the drying period, each portion is weighed again, and if there is no change in mass we conclude that the soil is dry. The average differences between the wet and dry samples give the amount of moisture in the soil. This water content is expressed as a percentage of the weight of the dry mixture giving by the formula below:

$$W=\frac{M_{cms}-M_{cds}}{M_{cds}-M_{c}}\ x\ 100 \qquad (3.1)$$

W = water content, %

M_{cms} = mass of container and moist content, g

M_{cds} = mass of container and oven dried specimen, g

M_{c} = mass of container, g.

3.1.2: Atterberg Limits Test

Soil can exist in three different states: solid, liquid, and gas. One way of determining the hydrous state of a soil is to conduct the Atterberg Limits Test. The Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) are among the properties that can be measured with Atterberg Limits test and were investigated for the purpose of this research as recommended by ASTM 4318-10 (ASTM, 2010). A Soil sample of approximately 400g was first oven dried and later passed through the #40 sieve. The passing portion of the sample was used for the determination of the Liquid and Plastic Limits tests.

3.1.2.1: Liquid Limit

The Liquid Limit (LL) is defined as the water content in percent of a soil at the boundary between semi-liquid and plastic states. It is determined by using the casagrande device shown in Figure 3.1. The procedure for the experiment is listed below:

1) Add water gradually to three-quarters of the sieved soil, until a stiff consistency is reached.
2) Put a portion of the wet soil in the bowl of the casagrande device shown in Figure 3.2. Use a grooving tool to divide the soil evenly into 2 parts, with the maximum thickness not more than 10mm. The grooving tool is always held perpendicular to the bowl.
3) Turn the handle of the device, in order to drop the bowl at a constant rate of 2 cycles per second; this process is continued until the gap closes.
4) The number of drops is recorded and a sample of about 5cm^3 is obtained from the center and the water content is determined.
5) The drop procedure is repeated 2 times and in each case stage (4) is repeated. The number of drops should reflect a range of 15-35 drops. When the gap closes at exactly at 25 drops, the liquid limit is equal to the water content.

Figure 3.2: Casagrande Device
Source: Author

3.1.2.2: Plastic Limit

The plastic limit (PL) is expressed as the percent water content at the boundary between plastic and semisolid states. In order to determine the plastic limit of the soil, the same mixture used in the liquid limit test is rolled by hand to form threads of 3mm diameter as shown in Figure 3.3. Once the threads are molded, they are then formed into balls and re-molded into threads again. Consistency in rolling techniques must be adhered to, so once the 3mm thread breaks apart, a portion of 5g is oven dried and the water content is calculated.

The process is repeated to obtain 2 more moisture content readings. The Plastic Limit is calculated by taking the average water content of the three samples that do not deviate by more than 2% from each other.

Figure 3.3: Soil molded into threads to determine the Plastic limit
Source: Author

3.1.2.3: Dry Sieve Test

A portion of the soil was air dried and later shifted through different sieves in accordance to ASTM D422-07. Sieve sizes #4, 10, 20, 30, 40,50,60,80, 100, and 200 as shown in Figure 3.4 were arranged in the standard sieve agitator in descending order with sieve # 200 at the bottom. The weights of the sieves, the collection pans, and the sieve lids were recorded.

The soil was placed in the uppermost sieve and the sieve agitator was turned on for 5 mins, allowing the soil to run through all the different sieve sizes depending on the particle size. The collection pan captured all the soil passing through the last sieve (#200) and the weight was recorded. The weights of the other sieves and soils were also recorded.

Figure 3.4: Different Sieve pans stack together
Source: Author

3.1.3: Hydrometer Test

The Standard Test method for particle Size Analysis of Soils ASTM D422-07(ASTM, 2007), elaborates the procedures in determining the clay content in a soil sample. A calibration solution using 40g of sodium hexametasulphate mixed with 1000ml of distilled water was prepared. To calibrate the hydrometer 875ml of distilled water was added to 125ml of the calibration solution in a graduated cylinder. The hydrometer (type 152H) was inserted into the solution and allowed to reach equilibrium with the temperature of the solution and the reading on the hydrometer was recorded. 50g of soil was dispersed with 125ml of the calibrated solution, using the mixing device specified by ASTM 422-07. The soil mixture was then placed in a second graduated cylinder, and distilled water was added to the cylinder until it reaches the 1000ml mark. The cylinder was sealed and shaken vigorously for one minute, and placed vertically upright. Hydrometer reading was then recorded for time intervals 2, 5, 15, 30, 60, 250, and 1440 mins. Before each reading was taken, the hydrometer was inserted into the cylinder 25 to 30 sec in advance to allow it to reach equilibrium with the solution.

3.2: Block Casting and Curing

Two sets of test matrices are created. Winnebago soil samples that were characterized using geotechnical tests for the production of the blocks. The design mix was divided into:

1) Unreinforced compressed earth blocks: unstabilized and stabilized.
2) Fiber reinforced compressed stabilized earth blocks

This conforms to the main goal of the project, which is to investigate the effects of stabilization and PET fibers in earth blocks to improve their durability.

3.2.1: Unreinforced compressed earth blocks: unstabilized and stabilized

For the production of compressed stabilized earth blocks without PET fibers, four mixtures each with 3 specimens were used. Cement content was varied from 5, 8, 10, and 15%. The water content of the soil before production was calculated at 22.8%. From literature it was stated that the amount of water added during block production is related to the block strength. The smaller the amount the stronger the blocks, therefore water to binder ratio of 25% was used to determine amount of water needed. Table 3.1 gives a detailed description of the design mix.

Table 3.1: Test Matrix for Unreinforced CSEB
Source: Author

		Stabilizer			
Block ID	**Soil (lb)**	**Percent by weight (%)**	**Weight (lb)**	**Water to binder ratio**	**Water content (lb)**
CEB-1	17	0	0	0.25	0.17
CEB-2					
CEB-3					
CSEB(5)-1	16.15	5	0.85	0.25	0.17
CSEB(5)-2					
CSEB(5)-3					
CSEB(8)-1	15.64	8	1.36	0.25	0.17
CSEB(8)-2					
CSEB(8)-3					
CSEB(10)-1	15.3	10	1.7	0.25	0.17
CSEB(10)-2					
CSEB(10)-3					
CSEB(15)-1	14.45	15	2.55	0.25	0.17
CSEB(15)-2					
CSEB(15)-3					

3.2.2: Mixing

The mixing process was conducted indoors in the laboratory at room temperature. The required quantity of soil, stabilizer, and water was stated in the design mix in Table 3.1. Soil and stabilizer were mixed together vigorously in a bucket by a handheld mixer (Figure 3.5) for approximately 1min before water is added. The mixing is continued for another 1 minute, or until a homogeneous mixture is formed. For the same mix design, it is imperative to make sure that all the materials are stirred consistently. The handheld mixer composed of an electric drill and a paddle as seen in the Figure 3.5. The speed of the paddle should not be too fast, to prevent the soil from creating ball-like particles. The consistency of the mix can be affected by the increasing number of ball-like particles.

Figure 3.5: Handheld Mixer
Source: Author

Once the mixture is prepared, it is immediately transferred into the manual press (Figure 3.6 & 3.7). It takes 2 mixtures to completely fill the press to the top. The manual press has a pressure capacity between 750-1500psi according to the manufacturer's specifications.

Figure: 3.6: Manual press filled with soil mixture
Source: Author

Figure 3.7: Molded CSEB
Source: Author

3.2.3: Production of fiber reinforced earth blocks

The production of fiber reinforced earth blocks is similar to the unreinforced blocks, with the exception of the fibers. Three inches long PET fibers (Figure 3.8) of about 0.25% by weight are used for each block. The test matrix for the fiber reinforced CSEBs is given in Table 3.2.

Table 3.2: Test matrix for fiber reinforced CSEB
Source: Author

		Stabilizer				
Block ID	**Soil (lb)**	**Percent by weight (%)**	**Weight (lb)**	**PET Fiber(lb)**	**Water to binder ratio**	**Water content (lb)**
FCSEB(5)-1	16.15	5	0.85	0.0425	0.2	0.14
FCSEB(5)-2						
FCSEB(5)-3						
FCSEB(8)-1	15.64	8	1.36	0.0425	0.2	0.14
FCSEB(8)-2						
FCSEB(8)-3						
FCSEB(10)-1	15.3	10	1.7	0.0425	0.2	0.14
FCSEB(10)-2						
FCSEB(10)-3						
FCSEB(15)-1	14.45	15	2.55	0.0425	0.2	0.14
FCSEB(15)-2						
FCSEB(15)-3						

Figure 3.8: Shredded PET Fibers
Source: Author

Adding PET fibers to the mix is done in a gradual process. It is added together with the dry materials as shown in Figure 3.9, and the mixing process is completed the same way as previously mentioned. The final homogenous mixture is then placed into the manual press to produce a fiber reinforced block as shown in Figure 3.10.

Figure 3.9: Soil, stabilizer, and fibers during the mixing process
Source: Author

Figure 3.10: Cast Fiber Reinforced CSEB
Source: Author

3.2.4: Curing

After molding the blocks, they are immediately wrapped in plastic bags for the next 4 days as shown in Figure 3.11 to slow down the hydration rate (ASTM D1632-10).

Figure 3.11: CSEB in Plastic Sheeting
Source: Author

The blocks require 28 days to allow the cement to complete the hydration process. After day 4, the plastic sheets are removed to allow the blocks to air dry. They are kept at room temperature for the remaining 24 days curing period (Figure 3.12).

Figure 3.12: Air dried blocks
Source: Author

3.3: Block Testing

Various laboratory tests are performed to understand the rate of deterioration of the blocks when exposed to moisture. This was crucial in determining which design mix is the most ideal for the purpose of this research.

3.3.1: Absorption Test (ASTM C67-11)

After the 28 day curing period, water absorption test is carried out to determine the water absorption capacity for CSEBs with various levels of stabilization with and without fibers. This test measures the quantity of water absorbed by the voids in the earth blocks when completely submerged under water. The blocks are completely submerged in water bath for a duration of 24hrs according to ASTM C67-11 (ASTM, 2011). Materials for the experiment consist of:

1) Measuring scale
2) Stop watch
3) Container
4) Thermometer

The water bath was kept at a constant temperature of about 70°F (21°C). The blocks' initial weights were recorded both before submersion and at 15 min intervals. The blocks were wiped with a sponge once they were removed from the water bath and weighed within the first 20 seconds. This process was repeated to obtain 3 more readings, after that the blocks were left in the containers for 24 hrs (Figure 3.13). Their final weights were recorded and the percentage water absorbed is calculated by the formula below:

$$\text{Water Absorbed (\%)} = \frac{A-B}{B}\ x\ 100 \qquad (3.1)$$

A = Final weight of submerged block

B= Initial weight of the air dried blocks

Figure 3.13: Submerged Blocks
Source: Author

At the end of the experiment the blocks are air dried once again.

3.3.2: Surface Erosion Test

There is no standard testing method for surface erosion, but a modified spray test, developed and used in Australia and New Zealand (Obonyo, Exelbirt, & Baskaran, 2010), is adopted in this research (Figures 3.14 -3.17). The modified spray test setup comprises of:

1) Pressure gauge
2) Garden hose
3) Spray nozzle
4) Measuring calipers

Figure 3.14: Pressure Gauge with Nozzle set up
Source: Author

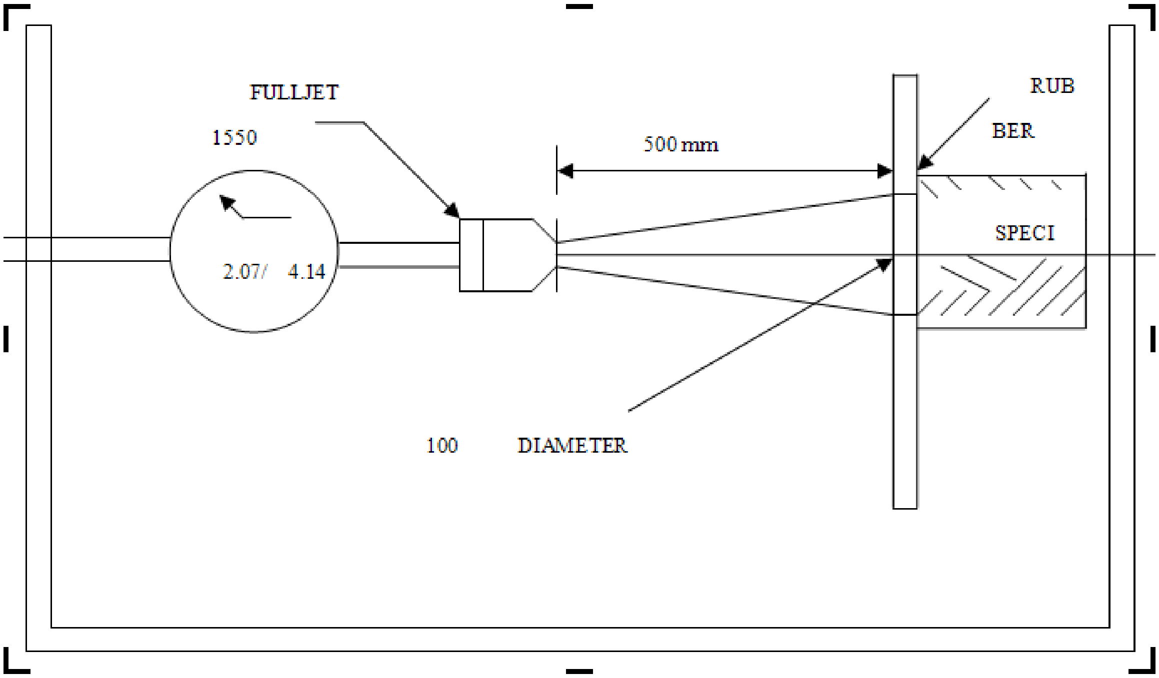

Figure 3.15: Schematic Diagram for the modified spray test
Source: (Obonyo E. B., 2010)

Figure 3.16: Spray test in progress
Source: Author

Figure 3.17: Measuring caliper for measuring depth of penetration
Source: Author

3.3.3: Wet Compressive Test:

The wet compressive strength test is carried out after the 28 day curing period. This will determine the strength of the blocks when submerged in water. The test is performed in accordance with the ASTM C67-11 (ASTM-2011). The compression machine as shown in Figure 3.18 was used to determine the crushing load of the blocks. For the testing procedure, the blocks were soaked in a water bath for 24 hrs. The blocks were allowed to dry for 30 mins to allow excess water on the surface to be removed. The units were then tested by placing them horizontally between platens. The maximum crushing load for each block is then given by the data acquisition system attached to the compressor. The maximum compressive strength is calculated using the formula below

$$C = P/A \qquad \text{(Equation 3.2)}$$

C= compressive strength (psi)

P= Applied load (lbf)

A= Area (in^2)

Figure 3.18: Compression Test Device
Source: Author

Chapter 4

Discussion of Results

. The performance of cast Compressed Stabilized Earth Blocks (CSEB), are in this chapter analyzed and discussed in relation to standard requirements for durability and strength.

4.1: Test Results and Soil Characterization

Soil samples obtained from Winnebago, Nebraska were analyzed for soil classification, clay content, water content, and other properties. The summary of results obtained from experiments are summarized in Table 4.1 below.

Table 4.1: Summary of the geotechnical data
Source: Author

Parameters	**Related ASTM**	**Winnebago Soil Properties**
Liquid Limit	D4318-05	30.85%
Plastic Limit	D4318-05	25.01%
Plasticity Index	D4318-05	5.84%
Clay Content	D422-07	8%
Average Water Content	D2216-05	22.84%

It was established that the soil sample contained 8% clay and Plastic Index (PI) of 6%, from the hydrometer and Atterberg’s test. According to Zami & Lee (2011), for soils with plastic index of less than 15%, cement stabilization is recommended. The water content of 22.8% was beneficial for the research especially during block production. It was recommended that for high strength blocks, small quantity of water should be added to the mix. As a result a water-binder ratio of 25% can be used resulting to about 2% of added water.

4.2: Absorption Test Results (ASTM C67-11).

This test was done to study the absorption rate of the unreinforced earth blocks by varying the cement content from 0 to 15%. After curing the blocks for 28 days, they were completely submerged in water and readings of the change in weight was recorded at 15 min intervals. After 1 hr, the blocks were left in the water bath for 24 hrs before the final readings were recorded.

4.2.1: Absorption test results for CEB and CSEB.

Three block samples of compressed earth blocks (CEB) were produced and tested for absorption. The nature of the swelling action of the clay particles of the CEBs, demonstrates presence of dispersive clays. As can be seen in Figure 4.1 the, CEBs totally disintegrated after the first time interval. This is as a result of the lack of stabilizer in the mix, which hindered the binding force between particles. The blocks in general did not gain weight, but instead there was a reduction due to the disintegrations (Table 4.2).

Figure 4.1: Submerged compressed earth blocks after 15mins
Source: Author

Table 4.2: Compressed Earth Blocks
Source: Author

	Water absorbed by weight (lb)	
Specimen	0min	15min
CEB-1	15.74	13.09
CEB-2	15.82	13.06
CEB-3	16.44	15.06

The experimental results for the absorption test for cement-stabilized earth blocks are tabulated in Table 4.3, and shown in graphical representation in Appendix B.. According to the data obtained, the 28 day average water absorption values for the 12 CSEB samples tested varies from 9% for the 15% cement stabilized to 13% for the 5% cement stabilized CSEBs. This means that, they have met the recommended maximum water absorption value of less than 15% recommended by British Standards (Molla, 2012). A previous research conducted by varying cement content 5, 7.5, and 10% gave similar results (Kabiraj & Mandal, 2012). Although their CSEBs with 5% cement content had an average absorption rate of 19% versus 13% in this project, both sets of blocks with 10% cement content recorded average water absorption of 10%.

Physical inspection of the blocks after 24hr submersion showed that, 5% stabilized blocks as shown in Figure 4.2 were the most affected from block disintegration compared to 8, 10, and 15% cement content. This shows that above 5% stabilization is the most effective and agrees with Kerali’s comment that durability of the blocks depends on the amount of cement present in the blocks (Kerali, 2001).

The results from the water absorption test conducted confirm that, CSEBs do absorb water. The data also demonstrate that increasing cement content reduces the water absorption rate of the blocks. Increasing cement content from 5% to 15% showed a reduction of 5% in the total water absorbed by the CSEBs. This phenomenon is shown in a graphical representation in Figure 4.4. Figure 4.3 shows the relation between the water absorption rate and dry density of the blocks. The absorption rate decreases with increase in dry density of the blocks. One of the 15% specimens absorbed more than the other 2, this can also be attributed to the density of the block (Figure 4.3).

Table 4.3: Water Absorption Test Results for CSEBs without Fibers
Source: Author

Specimen	**Water absorbed by weight (lb)**						**% Water Absorbed**	**% Water Absorbed Average**
	0min	**15min**	**30min**	**45min**	**60min**	**1440min**		
CSEB(5)-1	15.87	17.73	17.97	18.04	18.05	18.18	12.71	13
CSEB(5)-2	15.43	17.68	17.72	17.74	17.77	17.81	13.36	
CSEB(5)-3	15.97	17.83	18.04	18.13	18.17	18.31	12.78	
CSEB(8)-1	15.96	17.93	18.13	18.15	18.16	18.29	12.74	11
CSEB(8)-2	17.2	18.52	18.8	18.9	18.95	19.16	10.23	
CSEB(8)-3	17.05	18.48	18.75	18.84	18.87	19.07	10.59	
CSEB(10)-1	17.13	18.5	18.8	18.92	18.99	19.15	10.55	10
CSEB(10)-2	16.7	18.2	18.45	18.55	18.6	18.75	10.93	
CSEB(10)-3	16.88	18.32	18.6	18.7	18.76	18.91	10.74	
CSEB(15)-1	17.85	18.94	19.2	19.32	19.41	19.63	9.07	9
CSEB(15)-2	16.4	19.08	19.33	19.43	19.52	19.73	16.88	
CSEB(15)-3	18.05	18.09	18.37	18.44	18.47	18.57	2.80	

These findings are important in explaining the absorption potential of CSEBs. It also confirms that, increase in cement content helps the durability of blocks in flooding situations. Density calculations and block dimensions are also tabulated in Appendix.

Figure 4.2: After 24hr submersion of the 5% stabilized blocks
Source: Author

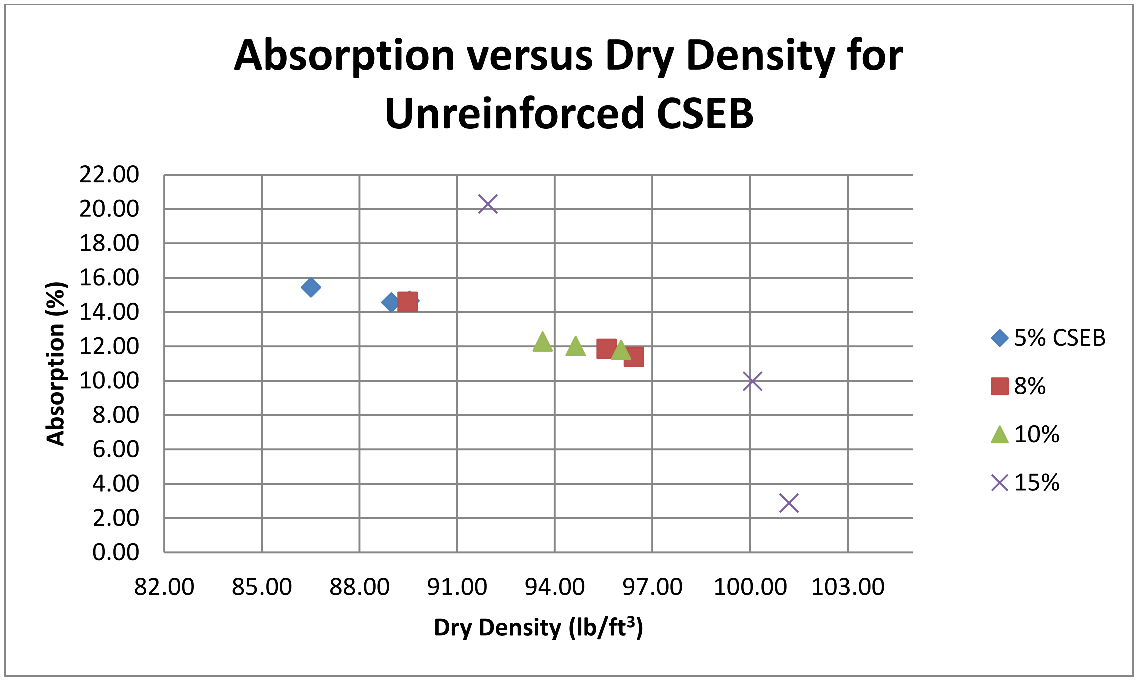

Figure 4.3: Water Absorption versus Dry Density for CSEBs
Source: Author.

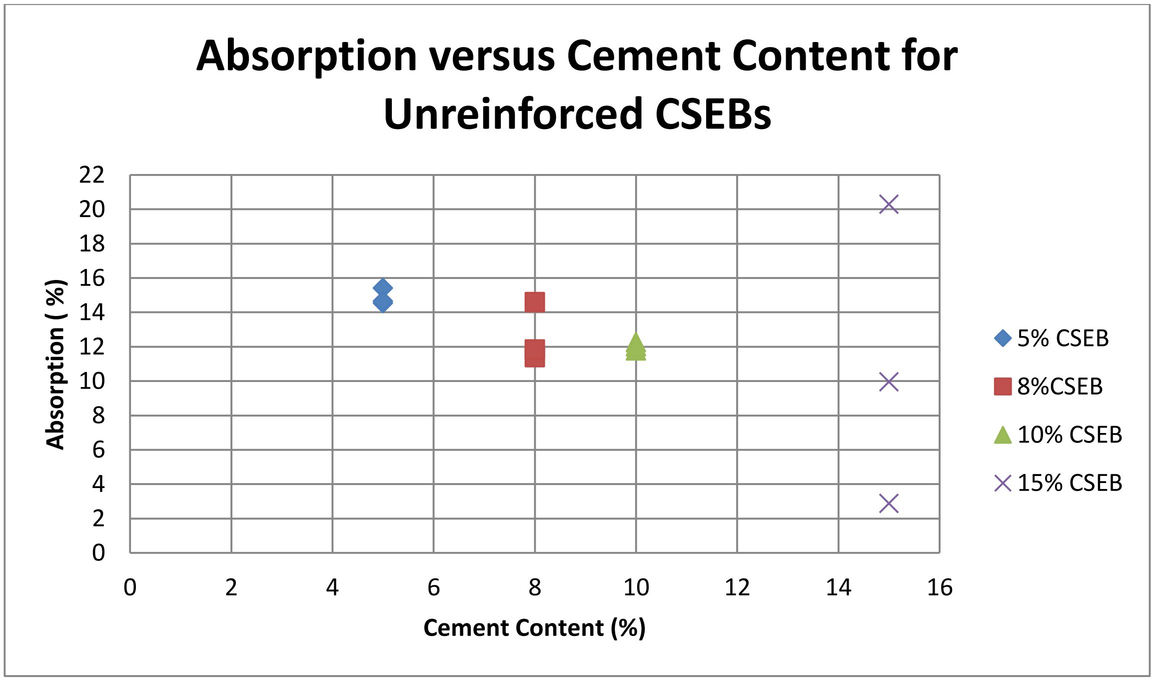

Figure 4.4: Water Absorption versus Cement Content for CSEBs
Source: Author.

4.2.2: Fiber reinforced CSEBs

The results of the water absorption test for CSEBs with fibers is tabulated in Table 4.4. The average water absorption for the different cement content ranges from 16% for blocks with 5% cement and 12% for CSEBs with 10% cement. From the data obtained, the inclusion of PET fibers increases the water absorption of the blocks. When compared to the unreinforced CSEB, fiber reinforced CSEBs absorbed about 3% more than the latter. Considering the recommended absorption value of less than 15% (Molla, 2012), 10 and 15% cement content blocks with fibers still meet the requirements.

From previous research where 0.5% Jute fiber was added to 5% cement content, average water absorption of 20% was recorded (Kabiraj & Mandal, 2012). The addition of jute fibers showed a difference of 4%, when compared to the PET fibers. This observation confirms the theory from previous literature that natural fibers absorb more water than synthetic fibers (Obonyo, Exelbirt, & Baskaran, 2010). However it is important to note that synthetic fibers still increase absorption.

Table 4.4: Compressed earth block 5% stabilized with PET fibers
Source: Author

Specimen	**Water absorbed by weight (lb)**						**% Water Absorbed**	**% Water Absorbed Average**
	0min	**15min**	**30min**	**45min**	**60min**	**1440min**		
FCSEB(5)-1	15.45	17.83	17.92	17.93	17.92	18.07	16.96	16
FCSEB(5)-2	15.56	17.87	17.95	17.95	17.94	18.09	16.26	
FCSEB(5)-3	15.46	17.73	17.73	17.72	17.7	17.88	15.65	
FCSEB(8)-1	15.63	17.66	17.85	17.86	17.86	17.99	15.10	15
FCSEB(8)-2	15.71	17.77	17.93	17.94	17.95	18.08	15.09	
FCSEB(8)-3	15.77	17.8	17.97	17.98	17.98	18.13	14.97	
FCSEB(10)-1	16.75	18.22	18.55	18.68	18.7	18.8	12.24	12
FCSEB(10)-2	16.74	18.14	18.45	18.64	18.71	18.82	12.43	
FCSEB(10)-3	16.86	18.3	18.61	18.78	18.82	18.91	12.16	
FCSEB(15)-1	15.67	17.61	17.84	17.86	17.87	17.99	14.81	14
FCSEB(15)-2	14.96	17.23	17.24	17.26	17.26	17.4	16.31	
FCSEB(15)-3	16.28	17.88	18.16	18.28	18.29	18.4	13.02	

CSEBs with 5% cement and 0.25% fiber (Figure 4.5) showed some physical deterioration around the edges as expected, but the structural integrity was intact. The increment of cement content in fiber reinforced CSEBs contributed positively in the reduction of water absorption. The absorption rate gradually decreases as shown in Figure 4.7 up to 10%. This trend is similar to the CSEBs without fibers, but 3% higher. The average water absorption for the 15% fiber reinforced blocks was unexpectedly higher than the 10% stabilized blocks by 2%. This anomaly could be attributed to the low densities of the 15% cement stabilized specimens as shown in Figure 4.6. The density of the 15% cement blocks were lower than the 10% blocks, as a result they recorded higher water absorption rate.

Figure 4.5: 5% stabilized earth blocks after submersion test
Source: Author

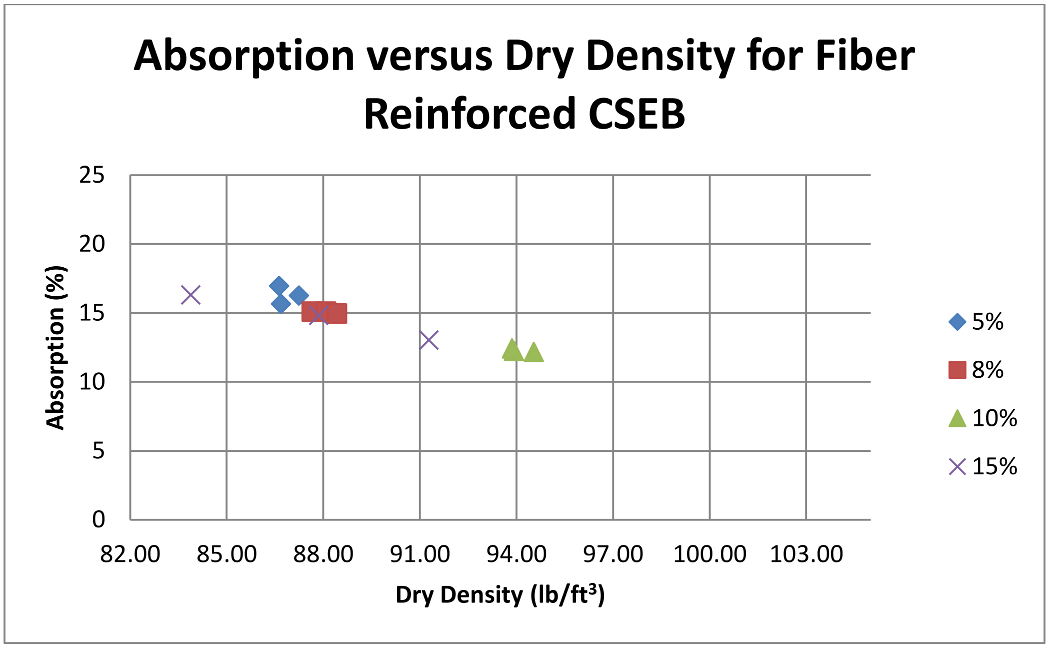

Figure 4.6: Water Absorption versus Dry Density for Fiber Reinforced CSEBs
Source: Author.

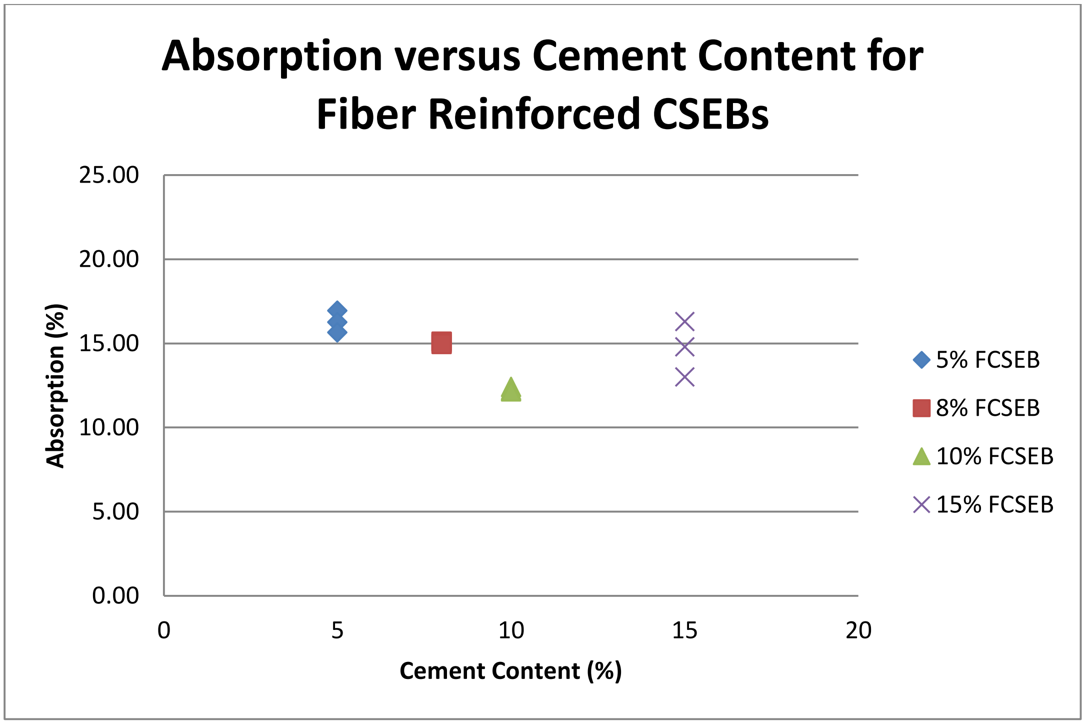

Figure 4.7: Water Absorption versus Cement Content for Fiber Reinforced CSEBs
Source: Author

4.3: Surface Erosion Test Results

The modified spray test was conducted to study the performance of CSEBs, when under high water pressure of 10psi for a duration of 30mins. Blocks with 5-15% cement with and without fibers were tested.

4.3.1: Unreinforced CSEB

The results from the surface erosion test for the unreinforced CSEBs are presented in Table 4.5. As stated in Chapter 3 the CSEBs were subjected to high water pressure of 10psi for a total duration of 30mins. This is important in estimating the behavior of the blocks under severe rainfall in windy/stormy conditions. From previous research (Obonyo, Exelbirt, & Baskaran, 2010), it was established that the rate of surface erosion in CSEBs should not exceed 1mm/min (0.04in/min) to meet durability requirements. From the data obtained, all sets of CSEBs passed this requirement, meaning that they can withstand severe water surface erosion.

Table 4.5: Surface penetration test results for unreinforced CSEB
Source: Author

Specimen	**Time(mins)**	**Depth of Penetration(in)**	**Rate of Erosion(in/min)**	**Average Erosion (in/min)**
CSEB(5)-1	15	0.15	0.0083	0.01
	30	0.25		
CSEB(5)-2	15	0.32	0.015	
	30	0.45		
CSEB(5)-3	15	0.1	0.0067	
	30	0.2		
CSEB(8)-1	15	0.04	0.003	0.001
	30	0.09		
CSEB(8)-2	15	0	0	
	30	0		
CSEB(8)-3	15	0	0	
	30	0		
CSEB(10)-1	15	0.03	0.0033	0.0011
	30	0.1		
CSEB(10)-2	15	0	0	
	30	0		
CSEB(10)-3	15	0	0	
	30	0		
CSEB(15)-1	15	0	0	0
	30	0		
CSEB(15)-2	15	0	0	
	30	0		
CSEB(15)-3	15	0	0	
	30	0		

As expected, 5% stabilized CSEBs were the ones most affected from water pressure, with an average of 0.01in/min as shown in Figure 4.6. In comparison with another research conducted with stabilized earth blocks (Obonyo, Exelbirt, & Baskaran, 2010), surface erosion of 0.00005in/min was recorded. This value corresponds to most of the readings for this research.

Figure 4.8: Depth of penetration through the blocks
Source: Author

There was no surface erosion on CSEBs with 15% cement content. This can be attributed to the increase in cement content (Figure 4.7). It can therefore be concluded that cement stabilization plays a vital role in the durability and performance of CSEBs under heavy rainfall situations.

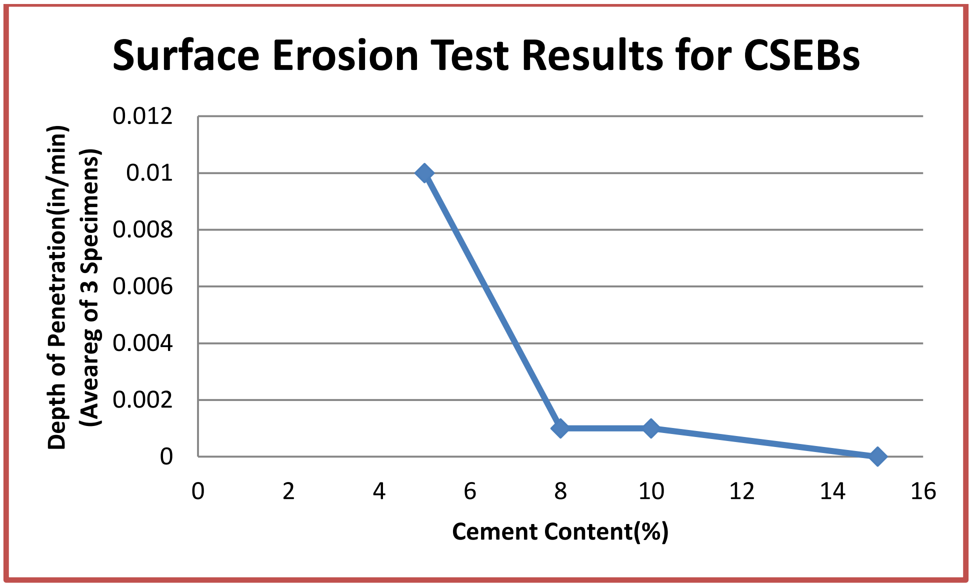

Figure 4.9: Relationship between surface erosion with water sprayed at 10psi and CSEB cement content
Source: Author

4.3.2: Fiber Reinforced Blocks

The results for the surface erosion test for fiber reinforced CSEBs are tabulated in Table 4.6. Also the average of all the different sets of blocks met the 0.01in/min requirement suggested by Obonyo, Exelbirt and Baskaran (2010). Comparing CSEBs with and without fibers, the former recorded almost zero erosion for both 10 and 15% cement content as shown in Figure 4.9. Fiber reinforced CSEBs with 5% cement content, recorded 50% less erosion than the unreinforced CSEBs.

Table 4.6: Surface penetration test results for CSEB with fibers
Source: Author

Specimen	**Time(mins)**	**Depth of Penetration(in)**	**Rate of Erosion(in/min)**	**Average Erosion (in/min)**
FCSEB(5)-1	15	0.05	0.005	0.0063
	30	0.15		
FCSEB(5)-2	15	0.05	0.004	
	30	0.12		
FCSEB(5)-3	15	0.24	0.01	
	30	0.3		
FCSEB(8)-1	15	0.14	0.0057	0.0046
	30	0.17		
FCSEB(8)-2	15	0	0.003	
	30	0.09		
FCSEB(8)-3	15	0.13	0.005	
	30	0.15		
FCSEB(10)-1	15	0	0	0
	30	0		
FCSEB(10)-2	15	0	0	
	30	0		
FCSEB(10)-3	15	0	0	
	30	0		
FCSEB(15)-1	15	0	0	0
	30	0		
FCSEB(15)-2	15	0	0	
	30	0		
FCSEB(15)-3	15	0	0	
	30	0		

The inclusion of fibers in the mix design contributed in the reduction of surface erosion on the blocks. It should be noted that CSEBs with smooth surfaces perform better than those with fibers protruding on the surfaces. When fibers show on the surface of the blocks, there is a possibility for the water to penetrate between the soil mixture and fibers causing the surface of the blocks to erode more easily.

Figure 4.10: Surface penetration through CSEB with fibers
Source: Author

As previously mentioned the increase in cement also has a positive effect in the reduction of surface erosion in CSEB. This relationship is further proven by the graphical representation shown in the Figure 4.11.

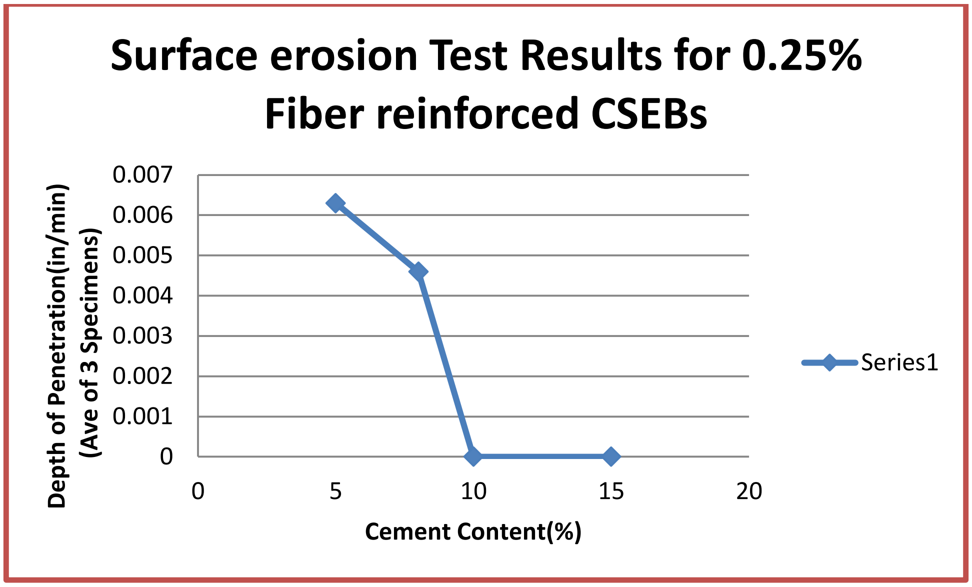

Figure 4.11: Relationship between surface erosion with water sprayed at 10psi and FCSEB cement content
Source: Author

4.4: Wet Compressive Test:

The wet compressive strength test was performed to investigate the strength of the blocks after they have been submerged in water for 24hrs and then tested. This was important to compare the dry strength to the wet strength.

4.4.1: Wet Compressive Strength Test Results for unreinforced CSEBs.

The average wet compressive strength values are tabulated in Table 4.7. The values range from 75 psi for 5% cement content, to 1,000 psi for 15% cement content. In comparison with another research conducted by Kerali (2001), where cement content was varied from 3-11% showed a similar trend. The results showed that, 5% cement content recorded 359 psi and 11% cement content recorded 1,303 psi (Kerali, 2001). Their results showed that, 5% wet compressive values were over 300% more than our values obtained.

Table 4.7: Wet compressive strength for CSEB
Source: Author

Cement Content	**Block ID**	**Load(lbf)**	**Compressive Strength (psi)**	**Average Compressive Strength (psi)**
5%	CSEB-1	5900	82	75
	CSEB-2	4810	67	
8%	CSEB-2	33300	463	431
	CSEB-3	28700	399	
10%	CSEB-1	42100	585	547
	CSEB-2	36900	513	
	CSEB-3	39000	542	
15%	CSEB-1	77800	1081	1001
	CSEB-2	86500	1202	
	CSEB-3	51900	721	

Figure 4.12: CSEB after compression test.
Source: Author

The cement content directly influences the compressive strength of the blocks. As shown in Figure 4.14 increase in cement content improves the compressive strength of the CSEBs with an almost linear relationship.

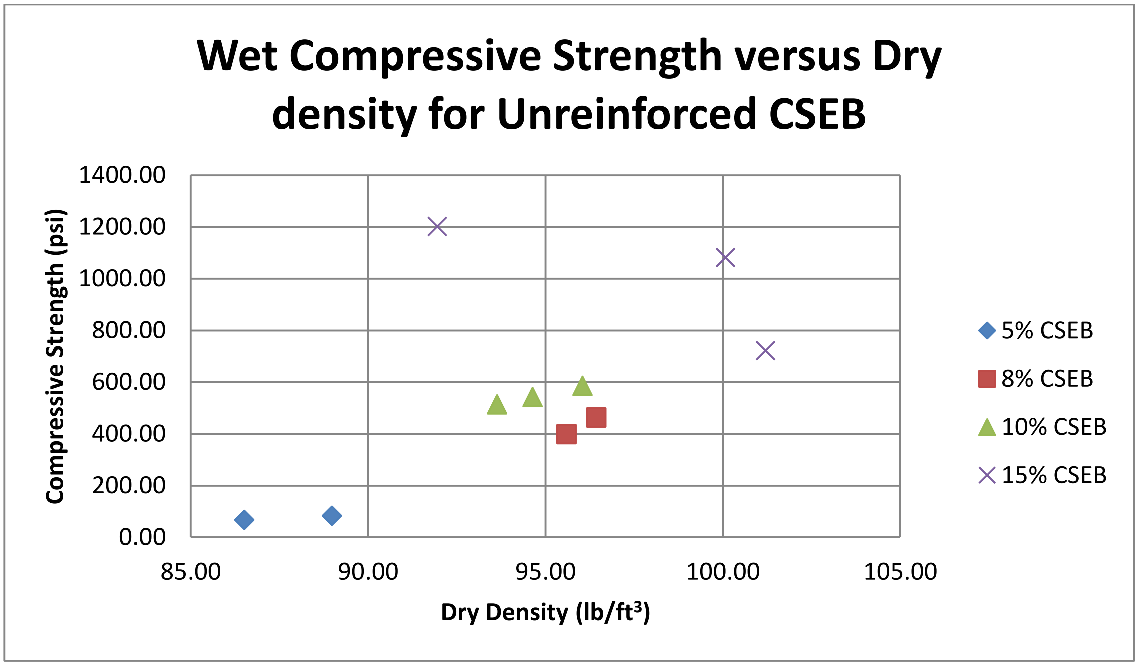

Figure 4.13: Wet Compressive Strength versus Dry Density for CSEBs
Source: Author

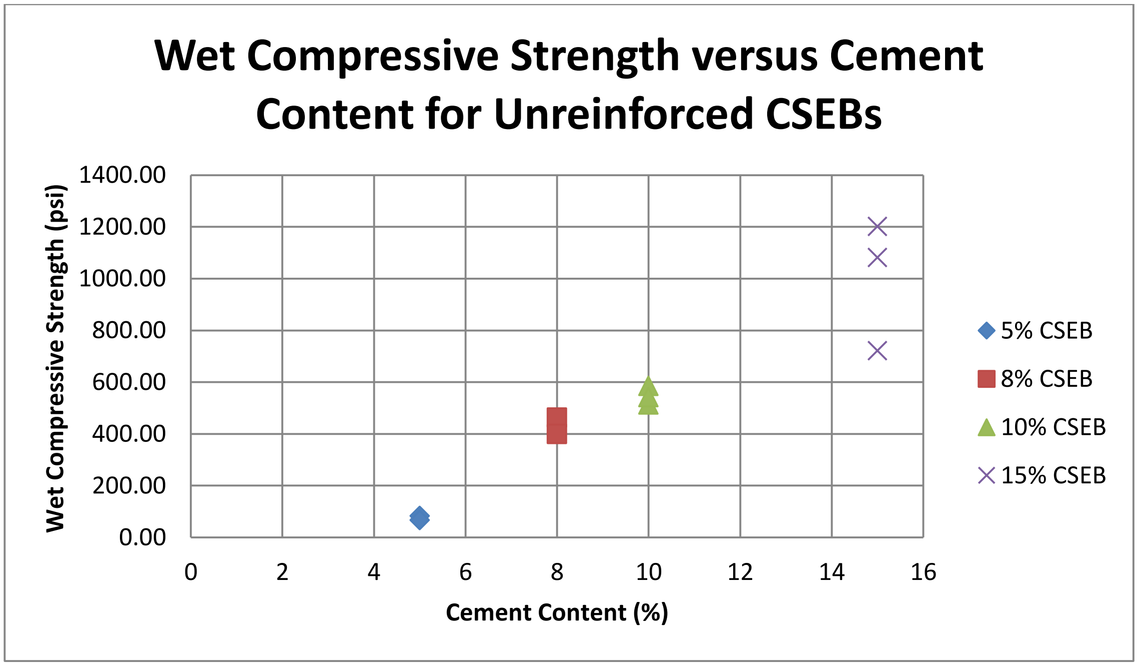

Figure 4.14: Wet Compressive Strength versus Cement Content for CSEBs.
Source: Author

At a companion study to this research, compressive test was conducted on 15 samples of CSEBs, made of soil containing 9% clay (Erdogmus, Garcia, & Wagner, 2013). From the results obtained, 5% cement recorded about 400psi, which showed an increase of about 400% compared to wet compressive test. CSEBs stabilized with 15% cement recorded about 900psi, which was 10% lower than the wet compressive values. The dry densities of the blocks could have a major impact on the strength of the blocks. As shown in Figure 4.13, increase in density increases the compressive strength of the blocks. 10% stabilized blocks also recorded higher dry compressive strength by more than 40% over the wet compressive values (Erdogmus, Garcia, & Wagner, 2013). Kerali (2001) suggest that the dry compressive strength is usually higher than the wet compressive values. However, as can be seen the results from this research presents a reverse trend.

4.4.2: Wet Compressive Strength for Fiber Reinforced CSEB

The ultimate compressive strength measured for the CSEBs with different cement percentages are shown in Table 4.8. As can be seen, these are higher than the corresponding values for the unreinforced blocks. Therefore based on this dataset inclusions of PET fibers seem to contribute to an increase in compressive strength. One anomaly as shown in Figure 4.15 shows that specimens with 15% cement recorded lower wet compressive strength values than the 10 % cement stabilized blocks with fibers and even 15% cement blocks without fibers (Table 4.7). This anomaly can be attributed to the low densities of the specimens as shown in Figure 4.15. The calculated densities were lower than expected, when compared to the 10% stabilized blocks. This also affected the expected trend in the compressive strength recorded, as stated earlier.

Table 4.8: Wet compressive strength for fiber reinforced CSEB
Source: Author

Cement Content	**Block ID**	**Load(lbf)**	**Compressive Strength (psi)**	**Average Compressive strength (psi)**
5%	FCSEB-1	11160	156	162
	FCSEB-2	13070	182	
	FCSEB-3	10550	147	
8%	FCSEB-1	27900	388	393
	FCSEB-2	29100	405	
	FCSEB-3	27800	387	
10%	FCSEB-1	78000	1084	1082
	FCSEB-2	77400	1076	
	FCSEB-3	78100	1085	
15%	FCSEB-1	36500	507	523
	FCSEB-2	27500	382	
	FCSEB-3	48800	678	

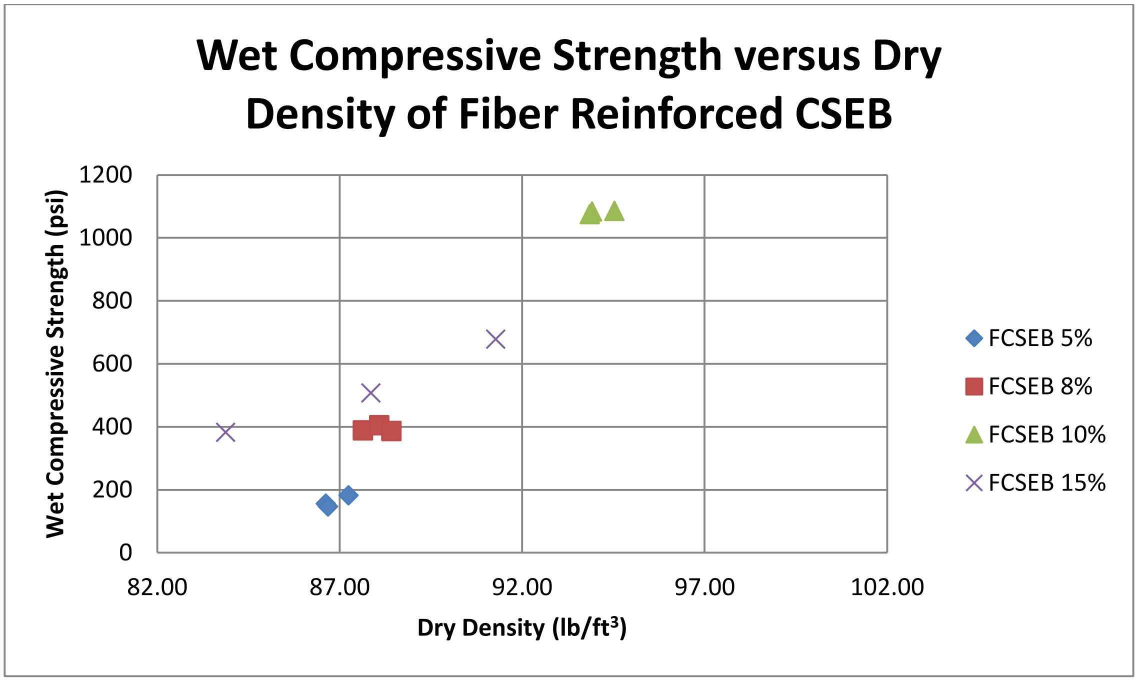

Figure 4.15: Wet Compressive Strength versus Dry Density for Fiber Reinforced CSEBs
Source: Author.

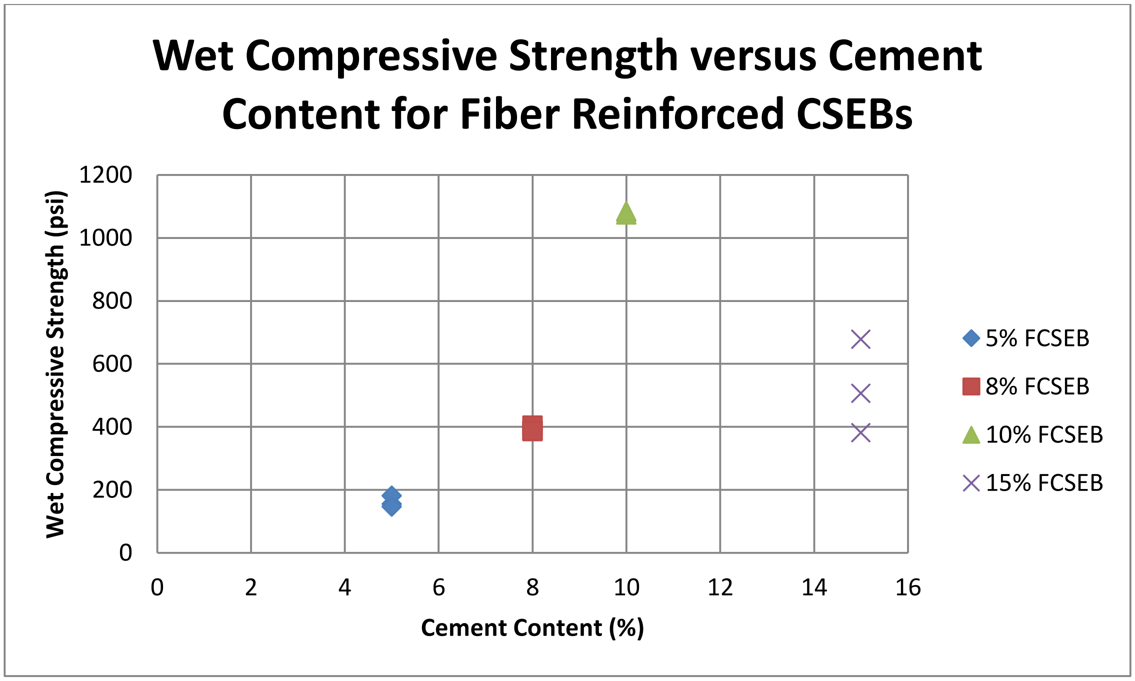

Figure 4.16: Wet Compressive Strength versus Cement Content for Fiber Reinforced CSEBs.
Source: Author.

Chapter 5

Conclusions

This project's ultimate goal was to study the effects of PET fibers and cement stabilization in compressed stabilized earth blocks to increase their durability in wet climates. To achieve this goal, 27 specimens were tested for: water absorption, surface erosion, and wet compressive strength. Three of the specimens were compressed earth blocks (CEB), 12 specimens were compressed and cement stabilized earth blocks without PET fibers, and 12 stabilized and reinforced with PET fibers. The following conclusions are drawn from the test data:

1) Cement stabilization reduces the water absorption of compressed earth blocks. Of the 12 specimens tested, on average there was 1% reduction in the absorption rate for CSEBs without fibers. For the fiber reinforced CSEBs, out of 12 specimens tested, 2% improvement was observed in water absorption. On average, for all four cement stabilization percentages (5, 8, 10, and 15%), specimens without fibers met the water absorption requirement of less than 15% absorption rate (ILO, 1987). For fiber reinforced CSEB only 10 and 15% cement stabilization content blocks met the requirements.
2) The density of the blocks plays a vital role in the rate of water absorption. Specimens with low densities and low cement content absorbed more water than denser blocks and high cement content. With 15% cement stabilization the water absorption rate was higher than blocks with 10% cement stabilization. This anomaly is as a result of poor compaction during production, depicted by the low

density of the blocks compared to the density of 10% cement stabilized specimens.

3) The inclusion of fibers in the mix design increases the absorption rate by 2%. This could be attributed to either the fibers absorbed water, or they create more voids between the particles to allow more absorption.
4) All 24 specimens tested for surface erosion met the requirements, and none of the blocks recorded erosion greater than 0.04in/min, which was designated as a limit by Obonyo, Exelbirt and Baskaran (2010). Cement stabilization contributed in the reduction of surface erosion, with 0.1% reduction per percent of cement addition.
5) The wet compressive strength also showed an improvement with cement stabilization. On average, out of 12 specimens, there was an increase of 150% for unreinforced CSEB. For fiber reinforced CSEBs specimens with 10% cement content showed a significant improvement of about 100%. The other specimens did not show significant improvements.

5.1: Final design recommendations:

After conducting the experiments presented in this thesis and reviewing the related literature, the following recommendations can be made: PET fibers increase the absorption rate of CSEB, therefore plain CSEB maybe a better option for this consideration alone. At 10% stabilization without fiber reinforcement, there was zero penetration of water by the surface erosion test and 10% absorption rate. With a wet compressive strength of 547 psi, these blocks (10% cement-no fiber) are a good option for water prone areas when only water absorption, water surface erosion and wet compressive strength are considered. It should be noted however that characteristics fibers do have a positive effect on surface toughness (zero surface erosion for various cement stabilization level), and have an acceptable level of absorption. Other benefits such as flexural strength, crack control capability and local toughness; fiber reinforced CSEBs can be a viable options.

5.2: Recommendations for future projects

1) This research project was limited to investigating the durability of earth blocks stabilized with cement and reinforced with fibers in wet and humid regions. A specific type of synthetic fibers (PET) was used in this study, but other types of synthetic fibers and varying cement content can be studied further.
2) Another area of investigation is to study the effects of varying compaction pressure and cement content to study the absorption rate.
3) The scope of this research was aimed at the absorption rate and surface erosion of blocks, but it can be further expanded to studying the shrinkage capability of submerged blocks, and surface abrasion of the blocks.
4) The arrangement of fibers during block production can be varied and studied for surface erosion in future work. Fibers can be laid in layers instead of randomly mixing them with the soil.
5) It will also be useful to investigate the behavior of cracked blocks with and without fibers, for water absorption.

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APPENDIX A

GEOTECHNICAL DATA

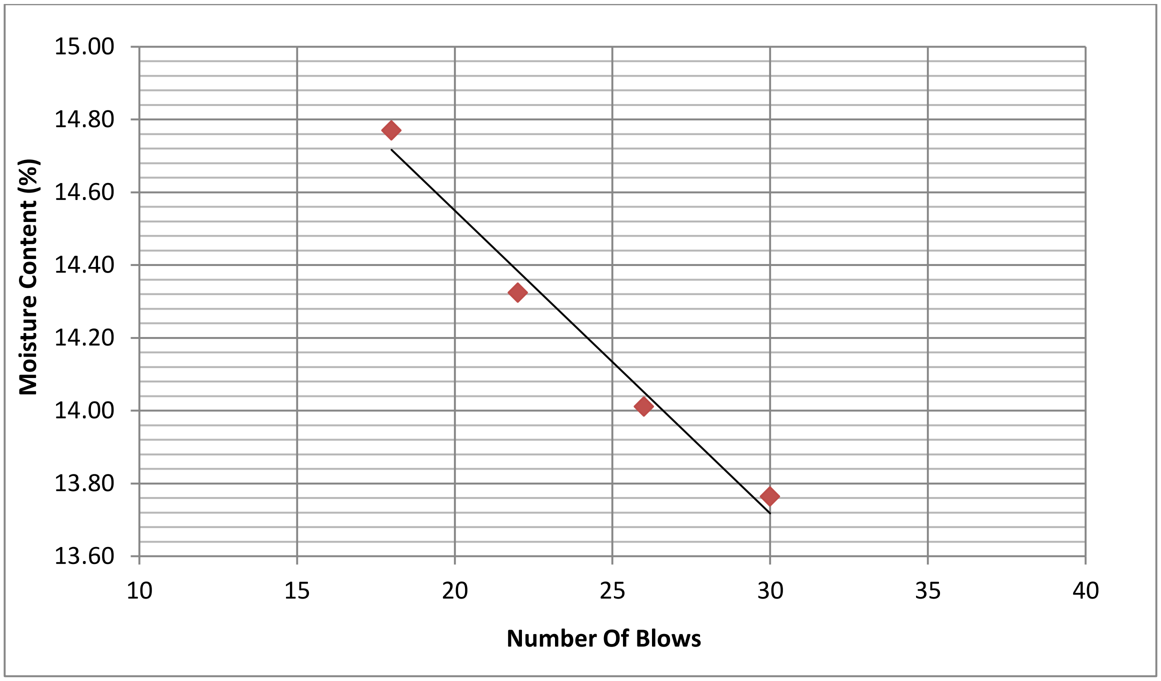

Figure 6.1: Moisture Content

Table 6.1: Sieve Analysis

Sieve #	Sieve weight (g)	Sieve with soil weight (g)	Retained soil weight (g)	Percent retained (%)	Percent Passing (%)
4	474.48	479.22	4.74	0.4	99.6
10	485.46	488.76	3.3	0.3	99.4
20	433.42	534.73	101.31	7.9	91.4
30	406.84	528.91	122.07	9.6	81.9
40	392.78	532.32	139.54	10.9	70.9
50	374.96	524.27	149.31	11.7	59.2
60	374.3	434.65	60.35	4.7	54.5
80	354.57	473.78	119.21	9.3	45.2
100	354.9	423.62	68.72	5.4	39.8
200	345.83	644.67	298.84	23.4	16.4
Base	373.7	582.87	209.17	16.4	0.0
Total	4371.24	5647.8	1276.56	4371.24	

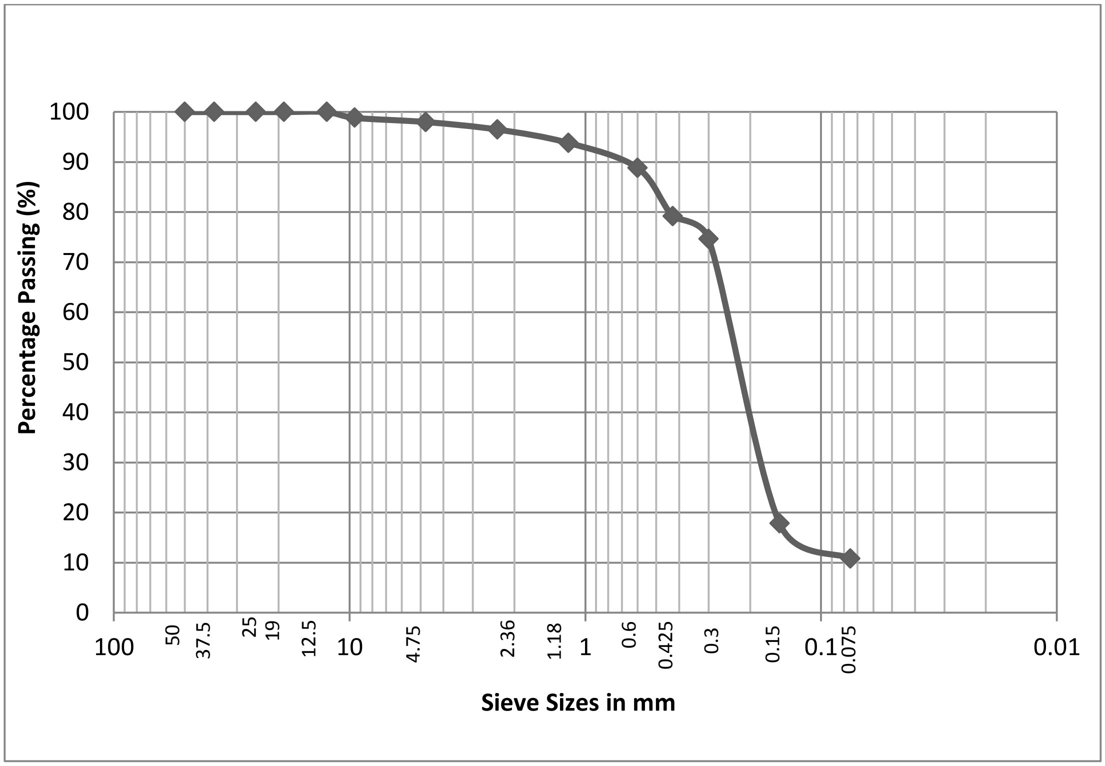

Figure 6.2: Particle Size Distribution Chart

APPENDIX B

GRAPHICAL REPRESENTATION OF TEST RESULTS AND PHOTOS

Table 6.2: Block Dimensions

Block Dimensions			
Length (ft)	Width (ft)	Height (ft)	Volume (ft^3)
1	0.5	0.29	0.15

Table 6.3: Dry density values for unreinforced CSEBs

Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
CSEB (5)-1	15.87	109.45	88.98	14.56
CSEB (5)-2	15.43	106.41	86.52	15.42
CSEB (5)-3	15.97	110.14	89.54	14.65
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
CSEB (8)-1	15.96	110.07	89.49	14.60
CSEB (8)-2	17.2	118.62	96.44	11.40
CSEB (8)-3	17.05	117.59	95.60	11.85
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
CSEB (10)-1	17.13	118.14	96.05	11.79
CSEB (10)-2	16.7	115.17	93.64	12.28
CSEB (10)-3	16.88	116.41	94.65	12.03
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
CSEB (15)-1	17.85	123.10	100.08	9.97
CSEB (15)-2	16.4	113.10	91.95	20.30
CSEB (15)-3	18.05	124.48	101.21	2.88

Table 6.4: Dry density values for fiber Reinforced CSEBs

Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
FCSEB (5)-1	15.45	106.55	86.63	16.96
FCSEB (5)-2	15.56	107.31	87.24	16.26
FCSEB (5)-3	15.46	106.62	86.68	15.65
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
FCSEB (8)-1	15.63	107.79	87.64	15.10
FCSEB (8)-2	15.71	108.34	88.09	15.09
FCSEB (8)-3	15.77	108.76	88.42	14.97
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
FCSEB (10)-1	16.75	115.52	93.92	12.24
FCSEB (10)-2	16.74	115.45	93.86	12.43
FCSEB (10)-3	16.86	116.28	94.53	12.16
Specimen	**Initial Weight (lb)**	**Density (lb/ft^3)**	**Dry Density (lb/ft^3)**	**Absorption (%)**
FCSEB (15)-1	15.67	108.07	87.86	14.81
FCSEB (15)-2	14.96	103.17	83.88	16.31
FCSEB (15)-3	16.28	112.28	91.28	13.02

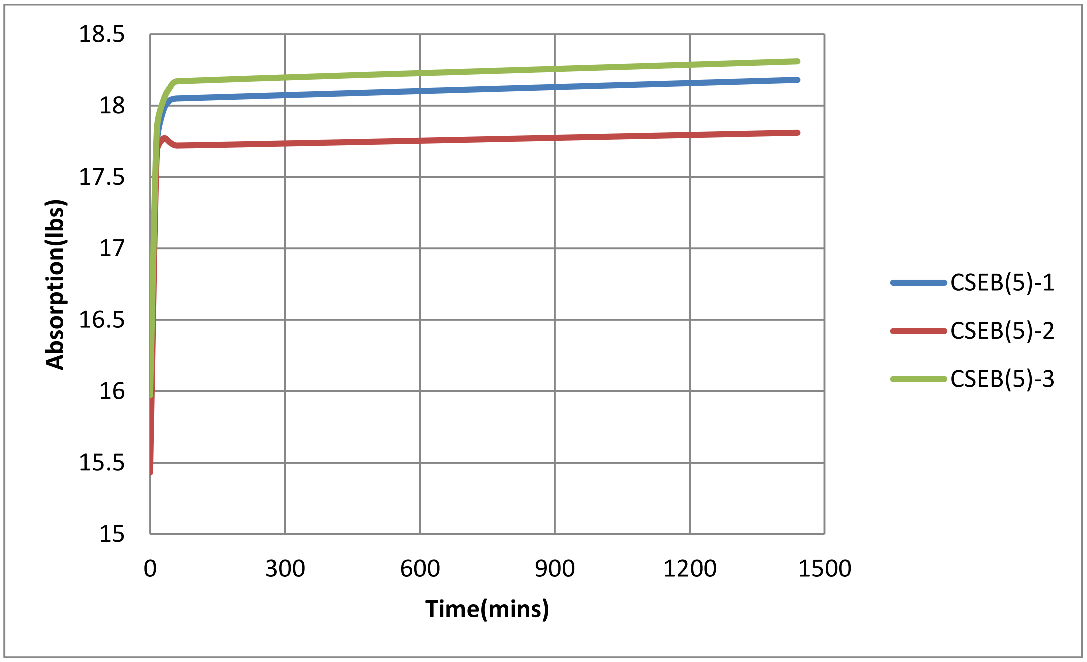

Figure 6.3: Absorption rate of 5% stabilized CSEB

Figure 6.4: 8% stabilized earth blocks after 24hrs submersion

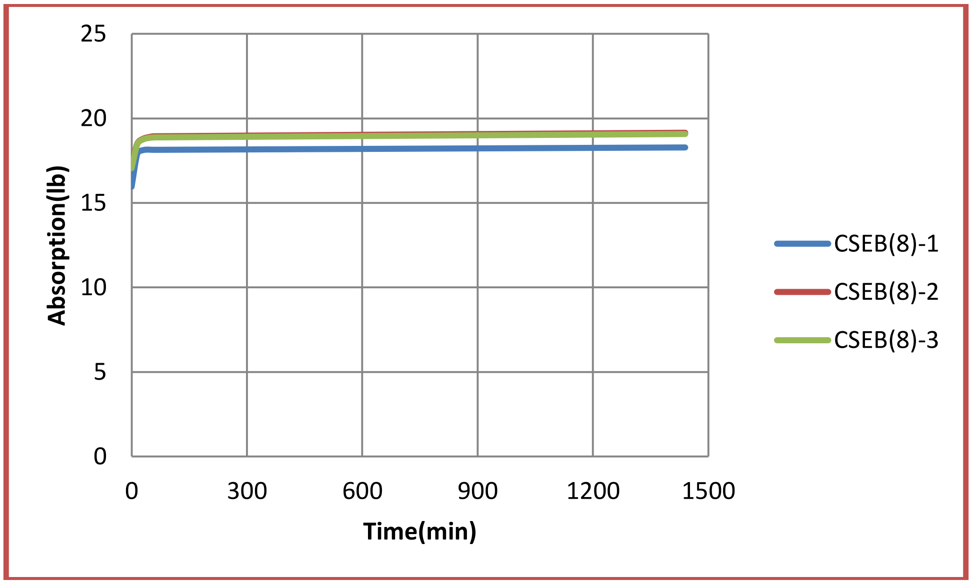

Figure 6.5: Absorption rate of 8% stabilized CSEB

Figure 6.6: Submerged 10% stabilized earth blocks after 24hr

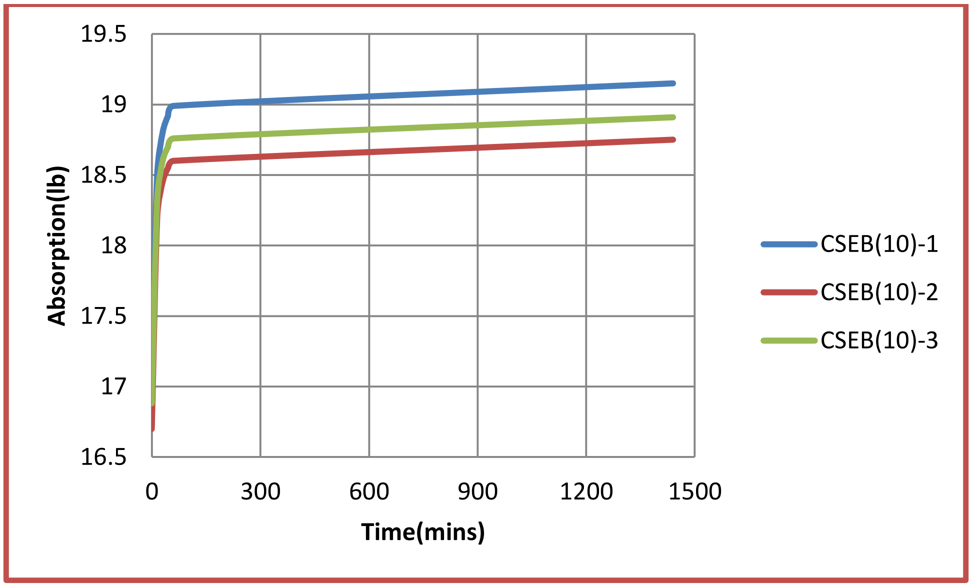

Figure 6.7: Absorption rate of 10% stabilized CSEB

Figure 6.8: Submerged 15% stabilized earth blocks after 24hrs

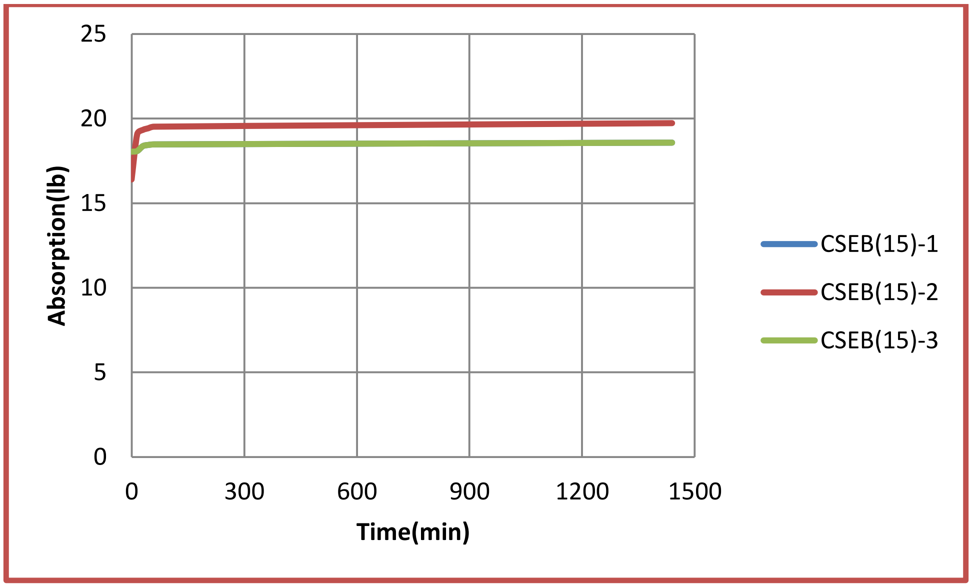

Figure 6.9: Absorption rate of 15% stabilized CSEB

Figure 6.10: Absorption rate of 8% stabilized CSEB with PET fibers

Figure 6.11: Absorption rate of 10% stabilized CSEB with PET fibers

Figure 6.12: Absorption rate of 15% stabilized CSEB with PET fibers

Figure 6.13: Surface penetration test set-up

Figure 6.14: Compressed CSEB

Figure 6.15: Compression test in progress