INNOVATIVE APPROACH TO PRODUCE SOIL-BASED BUILDING PRODUCTS

Samarappuli Nirosha Malkanthi

(178067M)

Degree of Doctor of Philosophy in Civil Engineering

Department of Civil Engineering

University of Moratuwa
Sri Lanka

April 2021

INNOVATIVE APPROACH TO PRODUCE SOIL-BASED BUILDING PRODUCTS

Samarappuli Nirosha Malkanthi

(178067M)

Dissertation submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Civil Engineering

Department of Civil Engineering

University of Moratuwa
Sri Lanka

April 2021

Declaration of Candidate and Supervisor

"I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)."

Signature: *UOM Verified Signature* Date:27.04.2020

The above candidate has carried out research for the PhD Dissertation under my supervision.

Name of the supervisor: A.A.D.A.J. Perera

Signature of the supervisor: Date:

Abstract

Innovative Approach to Produce Soil-Based Building Products

Keywords: Reduced Clay & Silt, Soil Washing, Soil Blocks, Roof Tiles, Burnt-Bricks

Soil as a building material has been used in different forms which include mud, adobe, rammed earth and bricks. Also, Compressed Stabilized Earth Blocks (CSEBs), a form of soil blocks with different additives, including cement, fly ash, and lime, have been investigated by many researchers for their advantageous properties. A literature review established that compressive strength significantly depends on the clay and silt (finer) content and 25% finer content produces the optimum results. However, investigators have not considered the amounts of other large particles. Furthermore, most of the researchers have adopted the method of adding different materials to soil in order to reduce the finer content in the soil. This study focused on an innovative approach to reduce finer content by washing and to utilize finer part of soil for different soil-based products simultaneously. Washing of soil is introduced as a method to reduce the finer content and soil with reduced finer content was investigated for production of compressed stabilized earth blocks. Further, the water re-cycling and its optimization for the washing process too was investigated. The separated finer content together with fly ash was investigated for the production of other soil-based productions namely roof tiles and burnt-bricks.

This study also investigated the use of theories of particle packing optimization which changed the soil grading while enhancing the properties of CSEBs. It established the changing of soil particles in different ranges to fit the soil grading to an optimization curve. Moreover, the use of fly ash as a finer replacement to the washed soil produced significant improvements in CSEB properties made with washed soil compared to that of CSEB made with un-washed soil. Laboratory testing clearly showed that the use of washed soil with 5%-10% finer content improved the compressive strength of the CSEB by 50% with different percentages of cement stabilization. In addition, significant improvements in dry densities and water absorption ratios of blocks were also observed with this particle size distribution modification. Industrial scaled soil blocks made with the selected optimum finer content of 7.5% and 7% cement stabilization verified that the blocks properties meet the requirements given in the standards SLS 1382 and SLS 855.

The soil washing process reduced the finer content in the soil producing a considerable amount of finer that could be used to produce building materials like roof tiles and burnt bricks. This extracted finer alone was difficult to be used, however adding fly ash gave significant enhancements to properties of roof tiles and burnt bricks. In fact, the study showed that 25% addition of fly ash to the extracted finer was more desirable. Roof tiles made with extracted finer and 25% of fly ash reported that the breaking strength, water absorption and permeability of tiles meet the requirements given in SLS 2. Burnt bricks made with extracted finer and 25% of fly ash also reported that the compressive strength, water absorption, and efflorescence meet the requirements given in SLS 39. Moreover, the properties of wire-cut bricks made with extracted finer and 25% fly ash also satisfied the requirements in SLS 39. The process optimization established that up to 60% water can be re-cycled. Cost analysis for the building materials considered in this study showed that the unit price of each product was significantly low compared to the current market price. Therefore, further research could be done to streamline all the processes and products considered in this study.

Acknowledgement

Without the guidance and encouragement of many well-meaning people, this thesis might not be a successful one. First and foremost, I would like to express my heartfelt gratitude to my supervisor, Professor A.A.D.A.J. Perera, for his great teaching, suggestions and comments throughout my research. Professor Perera is a great mentor who guided while giving me all the freedom and encouragement to accompany with my ideas. Next, my deepest gratitude goes to Professor Anura Nanayakkara, and Professor Kumari Gamage for their continuous encouragement, comments and guidance as my examiners of bi-annual review panels.

I graciously acknowledge the support of Senior Professor Sujeewa Amarasena, the Vice-Chancellor of the University of Ruhuna, Senior Professor Gamini Senanayake former Vice-Chancellor of the University of Ruhuna and Dr. Nayana Alagiyawanna, former Deputy Vice-Chancellor of the University of Ruhuna. Further, my sincere gratitude goes to Dr. Chandana Perera, former Dean, Faculty of Engineering and Professor Sudeera De Silva, former Head of the Department of Civil and Environmental Engineering for giving me all the necessary instruction and support. Thanks, are also to Dr. H.P. Sooriyaarachichi, Dean, Faculty of Engineering and Dr. Neetha Dayanthi, Head, Department of Civil and Environmental Engineering for their valuable support.

I wish to extend my sincere thanks for the support I received from all the Technical officers and Lab-Attendant of Department of Civil Engineering, University of Moratuwa. Very special and heartfelt thanks are for the colleagues in the Management Division including Ms. Priyantha, Rukma, Harsha, Sachindra, Rizna, Chameera and Himahamshi, Malsha for their gracious associations throughout the last three years.

Also, I thank all the academic and non-academic staff of the Faculty of Engineering, the University of Ruhuna for their kind-hearted help to fulfil my research work.

I acknowledge the sacrificial dedication of my loving husband Hasantha and our daughter Adithi for their encouragement and corporate by managing all the works while I was busy with my works on this research.

Table of Contents

List of Figures

List of Tables

CHAPTER 1 : INTRODUCTION

1.1. General Introduction

Earthen materials have been used by global Civil Engineering constructions in different forms, such as mud, adobe, rammed earth and bricks. A mixture of sand and clay forming a solid wall with the support of a wooden formwork is known as a rammed earth wall. Adobe blocks are made of clay with or without natural fibres and prepared in moulds which are slightly larger than those used to make bricks [1]. Approximately 30% of the world population live in buildings made of earthen materials [2]. In fact, raw earth as a building material has many advantages as explained by many researchers [1], [3], [4], [5]. However, soil in its natural state lack strength, durability and stability in dimension. Aubert et al. [6] have shown the mechanical weakness and the absence of standard procedures to measure strength and stiffness as some demerits of earth-based construction. Nevertheless, it is possible to overcome deficiencies by stabilizing the soil used to produce building materials [7]. Murmu and Patel [8], in their extensive literature survey, have shown the advantages and disadvantages of using earth-based building materials. They have demonstrated that eco-friendliness, low thermal conductivity and availability in abundance as inherent advantages. Further, they highlighted the strength reduction and dimensional instability in earth -based building materials as they contacted with water for a long time as the foremost disadvantages.

Compressed Stabilized Earth Blocks (CSEB), a form of soil blocks with different additives including cement, fly ash, lime, etc. as stabilizers have been investigated by many researchers for its improved properties [7], [9], [10], [11], [12], [13], [14]. Compressed earth blocks have been introduced as an alternative building construction substance to traditional masonry substances and are cost-effective and environmentally-friendly [15]. Additionally, it is considered as an evolution of adobe [16]. In practice, CSEB is made of soil having sufficient clay. Cement up to 10% is used as the stabilizer [7]. Hand-operated press (e.g. CINVA-RAM) or hydraulically operated machine-driven press are the mostly used method for blocks production [17]. CSEB is available as bricks, blocks, interlocking blocks, and hollow blocks.

Earthen constructions have many advantages. Thermal comfortability, creation of local employment and minimal environmental impact are such advantages. These could be validated for CSEB too. The use of earthen constructions is not limited to developing countries, even in developed countries like Australia; about 20% of the new building construction is occupied with earth-based construction projects [18].

Throughout the last decades, CSEB related research has been conducted worldwide. On the other hand, the popularity of CSEB as a common building material is not widely known as other building materials. Interestingly, the use of burnt bricks and cement blocks are dominant in Sri Lankan housing construction. As per statistics, the construction industry in Sri Lanka usually spends a high amount of cost for burnt bricks. However, soil block usage is rarely mentioned in statistics [19]. The two main challenges of CSEB are related to compressive strength and durability. As highlighted by Guettala et al.[20], the strength of CSEB is low due to moisture which causes weaknesses of CSEB. Walker [7] reported that the strength of saturated CSEB could become about half of that of dry strength when using soil with higher clay & silt (finer) content coupled with lower cement content. The amount of finer is the dominant player which differ the durability and strength of CSEB.

Even though CSEB acts as an environmentally friendly construction material, its application in an economical way targeting the commercial market has still not developed in many backgrounds. As per Jayasinghe and Perera [21], promoting the use of CSEB as an alternative construction material is very pertinent considering the economic and environmental friendliness.

CSEB has a history of more than two hundred years but, addressing the main issue has been limited to altering of clay & silt in the soil. In this context, addition of materials such as sand, quarry dust, fly ash, different soil and other similar materials have been practiced by many researchers. Literature provides evidence that the improvement of compressive strength has occurred by mixing the soil with some additives to change the finer content. However, it is hard to find a significant durability improvement in CSEB with these materials' addition. Furthermore, the literature says that the use of 5% to 20% finer content helped to improve compressive strengths. Such a conclusion cannot be seen in relation to durability. Additionally, sustainability issues of CSEB have been reported in Sri Lanka and other countries as major catastrophes of CSEB. With these known hindrances, still, the primary raw material for CSEB is lateritic soil. Generally, lateritic soil consists of 20% to 35% of clay & silt [22].

Generally, use of earthen materials for building construction is environmentally friendly. However, the usage of clay for brick production and sand for cement sand block production is associated with many environmental-related issues. In fact, clay mines need to be filled back appropriately and extensive sand mining could lower the river-beds. Interestingly, the current construction industry mainly focuses on sustainable, environmentally friendly building materials while embodied energy is one main concern. Embodied energy for soil-cement block (with 8% cement) is about 38% that of burnt bricks and about 58% that of steam-cured mud block masonry. Also, it is less compared to hollow-concrete block masonry [23]. Therefore, earth is an alternative walling material irrespective of its undesirable properties.

However, economic feasibility and commercial viability are two challenging aspects. The popularization of the use of soil blocks is hard to achieve due to low attraction and unhealthy economic background. Durability is one of the key concerns when considering aesthetic attraction and commercial viability. Removing of clay & silt to a certain extent may help to improve durability. Also, production practicability is another concern. With a high clay content, the production process may face problems, thus removing clay could help to ease the production process and lower the production cost.

The clay removal from soil could be carried out by soil washing with available industrial plants. The removed clay also can be used for other uses such as roof tiles, burnt bricks and ceramic tiles depending on clay properties. In addition, by adding certain pigments to clay its properties could be altered to become desirable for production. Therefore, the intended advantages of reducing clay from soil are two-fold; it helps to improve the properties of the soil block and the removed finer is a bi-product which could be used effectively. Also, the soil block production could be promoted for small scale entrepreneurs if they can be provided with necessary technological and financial support. In fact, if soil washing could be done in small scale plants, entrepreneurs would be able to run businesses as it is economically viable. With this background, this study leads to popularizing the use of Stabilised Earth Blocks while opening a window to look at the use of waste soil in different angles.

1.2. Research Aim and Objectives

This study was undertaken to introduce a novel method to produce soil-based building products to be used in the construction industry with the consideration of cost-effectiveness while emphasizing its durability and strength properties enhancement. This study mainly aims to provide a new direction for the production of CSEB with the usage of naturally available soil. Further, it includes an integrated approach to utilize natural soil as a building material. To attain the above aim the below mentioned objectives have been recognized.

1. Developing a process to reduce clay and silt from a given soil to produce CSEB
2. Analysing the performance of burnt bricks and roof tiles produced from removed clay and silt mixed with fly ash
3. Determining the properties of soil blocks produced from soil with reduced clay and silt
4. Analysing the cost of CSEB for different clay/silt combinations and brunt bricks and roof tiles produced from extracted finer

1.3. Problem Definition

Building materials are fundamental ingredients in infrastructure construction. Bricks, blocks, cement, sand, aggregates, etc. are the most commonly available conventional construction materials. The selection of building materials should be based on its energy consumption, cost, and sustainability with strength requirements. If the cost and sustainability could be achieved, the other two can also be attained since the strength would be improved with the addition of various ingredients and energy required for production. Therefore, cost-effective building materials with sustainability are a pertinent topic in the construction industry. Thus, CSEB has been considered as one such material that still needs improvements.

There are plenty of research conducted on CSEB with different soil mixtures and stabilizers. Most of the researchers have concluded that 15% of clay content would give optimum advantages considering their mechanical properties. Combined studies considering, varying finer percentage, varying cement percentage and different production issues were hardly available. Furthermore, the impact of the amount of larger particle was not considered in CSEB production. Therefore, this study mainly considered on the consequence of further reducing the finer content and controlling other larger particles amounts combined with varying cement percentages and various production issues.

Literature has provided evidence that the amount of finer content in the soil as the main barrier to achieve the strength and durability requirements of soil-cement blocks. Many researchers have selected specified places to obtain suitable soil or they have added materials like sand to alter the finer percentage in the soil. This study aims to introduce a method to remove the clay and silt from any soil to make blocks with the required strength and durability by washing soils and recycling the washed water and reusing the same in the process. With this washing process, it is expected to use coarse particles and finer particles for two purposes, namely CSEB production and other finer based productions respectively. Figure 1-1 illustrates the overall picture of the study considering the process and the project objectives.

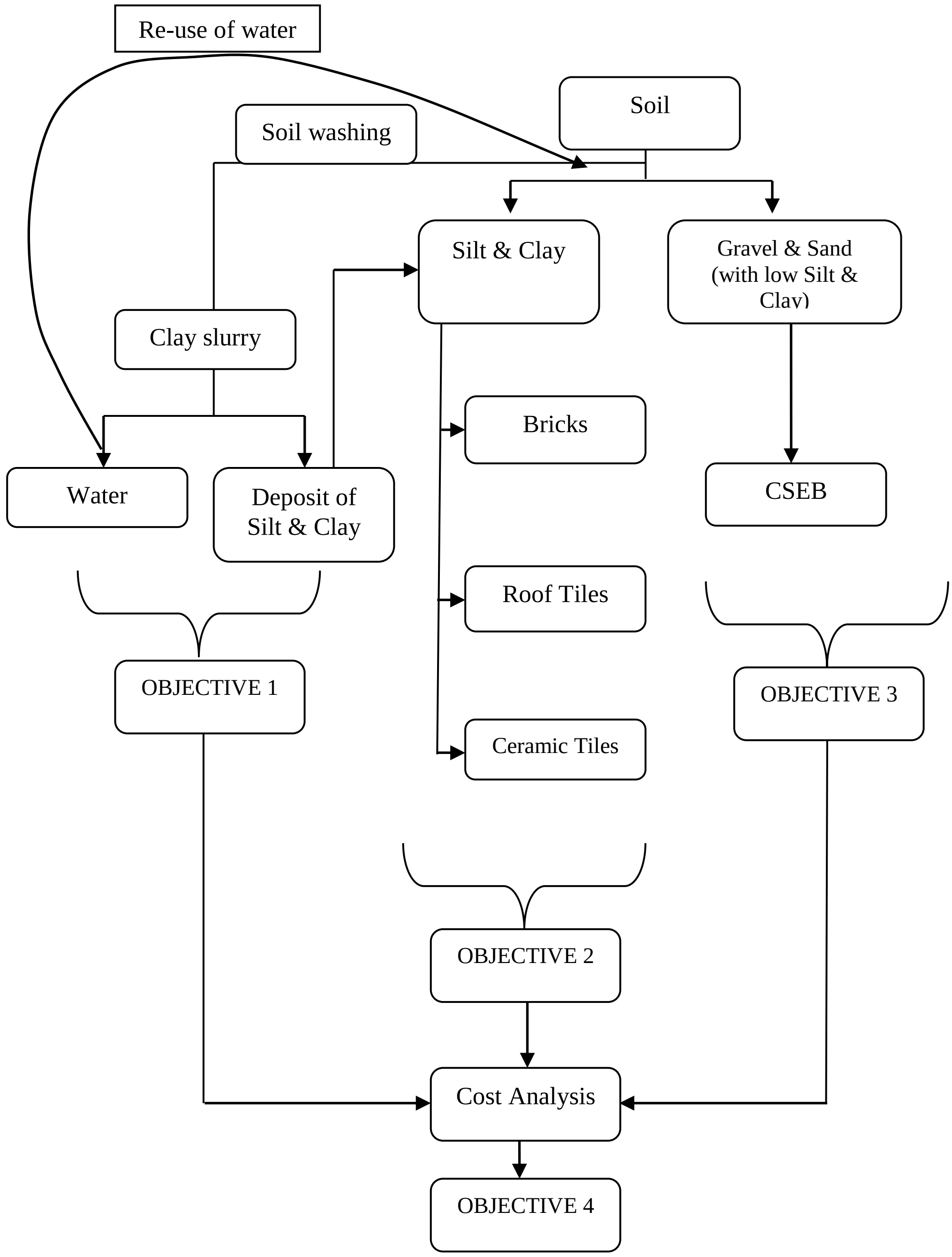


Figure 1-1: Overall Study Programme

1.4. Expected Advantages of the Research Project

Since the beginning of the civilization, the earth has been used as the principal building material. With the developments in the construction industry, many alternatives have been introduced. Those are associated with high costs, less comfort and unfriendly to the environment. A new trend in the construction industry is the use of sustainable building materials targeting green concepts. In fact, CSEB is one such green material. Energy consumption for CSEB production is less compared to that of burnt brick production while the cement usage is also less compared to that of cement blocks with a minimum transport cost for soil for CSEB production since they are locally available. The usage of soil from the construction site itself or its surroundings for CSEB production leads to maintain the natural appearance and colours that help buildings to integrate into the landscape [24]. Therefore, by popularizing CSEB, the above objectives could be achieved. Also, CSEB production does not require special skills, machineries and equipment. Experience by local people could also be utilized. Furthermore, people could be motivated to start their own business, which helps to solve the problems with unemployment to some extent. Furthermore, this study suggested reducing the clay and silting content by washing which does not require high technological knowledge. An Existing concrete mixing machine could be used as it is or with minor modifications. Separated clay and silt could be used for other building materials like bricks and roof tiles. Hence, this research showed an innovative approach to produce multiple building products with a proven end use.

1.5. Organization of the Thesis

This thesis has been prepared to provide details and descriptions of the research project, Innovative Approach to Produced Soil-based Building Products which was conducted as a partial fulfilment for the Degree of Doctor of Philosophy in Civil Engineering. Even though the research focused on soil-based building materials, the main concern was the production of CSEB with reduced clay and silt. While emphasizing on CSEB, production of other building materials is discussed appropriately. Chapter One discusses the general information about the history of earth-based construction materials, especially CSEB, existing problems with CSEB, project objectives and its advantages. Chapter Two provides a comprehensive literature review. It focuses on related research, their important findings and the research gap to be filled with this study. Chapter Three discusses the research methodology. It is equipped with all the experimental setup used to achieve the project objectives. In Chapter Four, all the results obtained from experiments were deliberated and presented both graphically and in tabular format. Chapter Five focuses on cost analysis of products while the Chapter Six concludes the research findings emphasizing the experimental results. Also, it provides recommendations for further studies.

1.6. Summary

This chapter briefly discussed the background related to the Compressed Stabilized Earth Blocks (CSEB) and the problems associated with the present context to produce CSEB. With that, study aim and objectives were identified whilst providing an overall picture of the study. Additionally, the intended advantages of doing this study were explained too. Finally, it presented the organization of the rest of the thesis. The next chapter broadly discusses the findings from the literature related to CSEB production with different perspectives. Also, it highlights important aspects for burnt bricks and roof tiles since those two building materials are considered in this research.

CHAPTER 2 : LITERATURE REVIEW

2.1. General Introduction

The previous chapter introduced the background to the thesis with a detailed explanation of the aim and objectives of the study. Further, the problem in brief and the method of achieving the solutions to the issues were stated too. This study focused on an innovative approach to produce soil-based building materials. Compressed Stabilized Earth Blocks (CSEB) were considered as the main soil-based material for the study. CSEB are made of soil with considerable clay & silt (finer) content and by adding stabilizers. Some of the important aspects to be considered are the effect of clay and silt content on the properties of CSEB. This chapter focuses on these basic aspects considered to produce CSEB together with past researchers' recommendations to alter the finer content and the limitations of reducing finer content. A considerable number of past research publications were reviewed in this regard. In addition, roof tiles and bricks production-related studies were also described since this study focuses on producing roof tiles and bricks with extracted clay and silt.

2.2. Overall View of the Literature Review

Figure 2-1 illustrates the overall view of the literature review. The main concern in this study was the production of CSEB by reducing the clay and silt content. Therefore, this study focused on literature related to CSEB production, its mechanical and physical properties, different materials used with main raw materials, etc. Also, the influence of soil grading was related to the particle packing technology. Other than CSEB, literature was related to roof tiles and burnt bricks too.

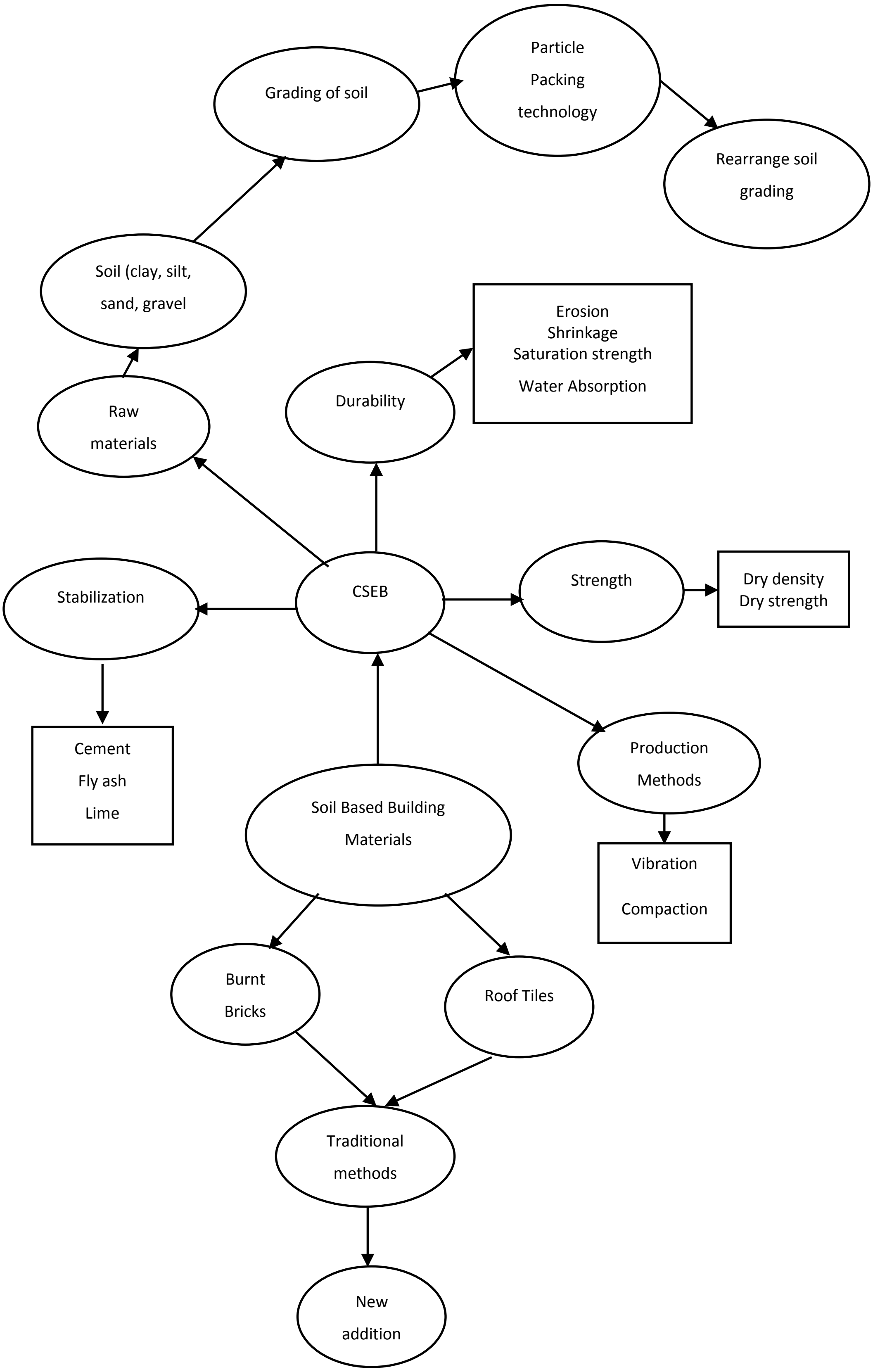


Figure 2-1: Overall Picture of the Literature Review

2.3. Use of Earth as a Building Material

Different constructing substances have been used from the beginning of civilization. It is believed that the earliest humans lived in caves. Later, they turned to use traditional substances like mud and clay to construct simple dwellings around them. Also, wooden substances such as logs, sticks, thatch, brush were incorporated with earthen substances.

Aside from natural substances, nowadays concrete, cement-sand blocks, burnt bricks, etc. have become the most common composite materials in use. Human civilization has developed with various styles of construction materials considering the factors like time for construction, labor requirements, design consideration, and costs. Furthermore, the construction industry tends to use alternatives like earth blocks due to its advantageous features.

Masonry has been used over centuries by builders and architects due to its beauty, versatility and durability. The most famous historical symbols such as the Egyptian Pyramids, the Colosseum in Rome, India's Taj Mahal, the Great Wall of China have been built with masonry. Most of the historical masonry structures have proven that masonry is resistant to fire, earthquakes, and sound. At the same time a considerable portion of the world’s population live or work in buildings made with earthen materials.

Masons widely use burnt bricks and cement-sand blocks as constructing materials. In fact, the use of Sun-dried clay bricks as a building material has a history of more than 6,000 years. As illustrated by Jayasinghe [25], the availability of raw material for the production of bricks and cement blocks are short; hence, many alternatives have been developed as walling materials. As per history, earth is a very old building material which has been used in different forms like mud, adobe, rammed earth and burnt bricks. Interestingly, CSEB has been gaining more popularity due to its sustainability and environmental friendliness. Alam et al. [26] have explained by referring to many past researches about raw earth being one of the oldest construction materials which is still widely used all over the world even though many advanced building materials are available at present. Other than CSEB, mud blocks [27], [28] and mud bricks [29] are also used as earth-based building materials.

2.4. Compressed Stabilised Earth Blocks

Compressed Earth Block (CEB) is a building material made with damp soil by compressing at a high pressure. They are also known as pressed earth blocks. The raw material to form CEB is usually a mix of fairly dry inorganic subsoil, non-expansive clay and aggregate. Mechanical press is needed to form compressed earth blocks. CSEB is an extension of CEB adding a chemical binder such as Portland cement [30].

The history of CSEB declares that the architect Franqois Cointereaux in the 19^{th} century in Europe made the first attempt to form small rammed earth blocks by using a hand rammer. To arrive at a regular block in size and shape with denser, stronger and water-resistance, Cinva Ram has been produced in 1950'[31]. After that, CSEB production has been receiving considerable attention from researchers to enhance their properties. Most of the researchers have considered the production of CSEB with natural soil by changing its clay and silt content by adding different materials such as sand, fly ash, quarry dust, sawdust, etc. Related research to CSEB production is described in the following sections.

Sri Lanka Standard Institution has published standards giving the required specification for CSEB [32], [33], [34]. Similarly, other countries have their own setup standards and guidelines to define the requirements related to CSEB. For example, Nepal has its own specifications and norms [35].

2.5. Advantages of Compressed Stabilized Earth Blocks

Compressed Stabilized Earth Blocks (CSEB) are associated with many advantages over other major masonry units such as cement blocks and burnt bricks. It is obvious that the production of CSEB needs local materials, which are bio-degradable. Also, limiting deforestation could be considered as a major advantage. Walker [7] has explained the use of local materials and their maximum utilization as advantages of CSEB. Morel et al. [3] also has illustrated many benefits of using CSEB for house construction with minimal impact to the environment. Rigassi [36] has explained the major advantages of using CSEB comprehensively. Those advantages cover the production process, quality of the product, available standard norms, and architectural pleasing. Rigassi [36] further explained the advantages of the use of CSEB with its tendency to social acceptance, technical performance, flexibility of usage, standards and models, highly practical nature of the technology, genuine architectural merit and as an alternative to importation. According to Harris [37], CSEB consumes less energy and it is a recyclable material compared to other building materials. Some other advantages are; locally available soil can be used for CSEB production hence, transport cost is minimum, it produces more aesthetically appearance building, and it provides local job opportunities strengthening local economy [38]. According to the explanation given by Jayasinghe et al. [39], use of CSEB has many advantages for developing countries. One major advantage is the savings in cost with the construction of wall using CSEB. CSEB walls appearance is same as the finish of wire cut bricks. Moreover, local people could engage in block production as a small-scale business since the technology requirements for block production is fairly less.

The advantages of earth-based building material are discussed in terms of embodied energy. Table 2-1 shows the initial embodied energy and CO_2 emission for different types of earth-based building materials. According to that, embodied energy and CO_2 emission is less for the wall construction with CSEB compared to the walls with other soil-based products. With this less CO_2 emission, the adverse effects on the environment could be reduced. Also, the manufacturing cost of the unfired bricks is comparatively low with fired bricks [40]. Udawaththa and Halwatura [41] have studied the embodied energy of mud block versus bricks and blocks. Their findings revealed that mud blocks consume significantly less energy for production. They have also shown that the thermal performance of mud blocks is high compared to bricks and blocks [42]. Also, Jayasinghe has demonstrated the life-cycle cost of CSEB is less or similar compared to other conventional building materials [43].

Table 2-1: Energy Emission Comparison between Different Types of Blocks

Type	Initial Embodied Energy per m^3 of Wall	Pollution Emission (Kg of CO2) per m^3 of Wall
CSEB wall	631 MJ / m^3	56.79 Kg / m^3
Kiln Fired Brick	2,356 MJ / m^3	230.06 Kg / m^3
Country Fired Brick	6,358 MJ / m^3	547.30 Kg / m^3

(Source: www.earth-auroville.com)

National Engineering Research and Development (NERD) Centre of Sri Lanka is promoting the use of CSEB and they have stipulated several advantages of using CSEB. CSEB is an alternative for the use of sand for block making, and for clay for brick making. Hence, sand mining and clay mining could be minimized reducing the impact on the environment. Houses made with CESB as a green product are comfortable due to low heat generation within the house. Also, 15%-50% cost could be saved (according to availability of soil).Creating new employment is another advantage too [44].

Walker [7] has emphasized on non-availability of standards and guidelines for builders and manufacturers as a major disadvantage. But, sufficient standards are now available as SLS 1382 Part I, Part II and Part III [32],[33], [34] in Sri Lanka.

2.6. Raw Materials for CSEB Production

Every soil is usually not suitable for making CSEB. Top soils and organic soils cannot be used in this background. According to SLS 1382 [32] definition, suitable soil for CSEB production should be with 65% or more sand and gravel with the maximum particle size 12mm. Also, 5% to 20% silt content and 10% to 15% clay content are necessary. Optimum water content is determined by performing a drop test.

CSEB are produced mainly taking soil as the raw material. These soils consist with two main parts; inert and active material. Gravel, sand and silt are considered as inert while clay is the active part. Inert materials perform as a skeleton while clay acts as a binding agent. This inert: clay proportion should be carefully selected as it contributes to the properties of the CSEB [45]. Small amount of finer content is necessary for CSEB production since it needs to bind all the particle together. However, controlling of maximum clay content is also an important aspect to limit the shrinkage to ensure effective stabilization. Therefore, controlling of finer content is essential. Content of finer and amount of cement (as a stabilizer) mainly affects the compressive strength of CSEB. A finer content of less than 35% has been recommended by many researchers, [7], [46], [47], [48], [49], [50], [51], [52].

Using laboratory testing or field testing, soil should be identified for CSEB manufacturing. By performing those tests, the particle size distribution, plasticity characteristics, compressibility and cohesion, should be determined and the compatibility should be checked with the available standards so that soil could be identified as suitable or not. If the available soil is unsuitable for CSEB production, it could be modified or reconstituted by adding sand. Fitzmaurice [48] says, there is a possibility that an unsuitable soil could be modified by adding sand when there is an excess of clay or silt. However, there could be economic issues since sand is comparatively expensive. Instead of adding sand to reduce the finer content, some researchers have studied alternative materials that can be used to lower the finer content [53], [54], [55]. By doing all these things, the researchers aimed to reduce finer content. Preliminary testing done by Malkanthi & Perera [22] shows that soil having up to a minimum of 5% clay and silt content could be used for CSEB production and it gave significant strength and durability properties. In fact, they have shown a method to reduce the clay and silt content by soil washing.

2.6.1. Clay and Silt

Many soil mechanics related literature mainly classifies soils as coarse-grained or fine-grained. Clay and silt are fine-grained soil. The compressive strength of blocks with varying clay and silt content and varying cement content is often considered as a research variable for CSEB. As Morel et al.[56] mentioned, the compression capacity of the masonry structure is governed by the compression strength of the masonry units (stone, bricks, blocks). The Sri Lanka Standard for CSEB has defined 10% to 15% of clay and 5% to 20% of silt as the required range [32]. It is clear that Sri Lanka Standard permits clay and silt to be 15% to 35%, which could be determined by a wet sieve analysis. A hydrometer test is required to determine the clay and silt content. Jagadish et al. [57] have defined 10% to 15% as the desirable clay range. According to the research work of Walker [7], compressive strength increases with the decrease of clay content (Table 2-2). Other authors also have reported similar findings.

As per the results of Walker [7] in Table 2-2, compressive strength is increasing with the reduction of the clay content. Also, it provides evidence that the high compressive strength could be achieved with high cement content. However, Walker as well as many other researchers have limited clay content to 15% in their studies.

Danso et al. [58] have used fibre reinforcement with two different soil types having more than 40% finer content for soil blocks production. For these selected soil types, blocks achieved 3 N/mm^2 as the maximum compressive strength even with fibre reinforcement.

Table 2-2: Relationship of Compressive Strength and Clay Content as Presented by Walker[7]

Soil-cement ratio	**Clay soil content %**	**Saturated compressive strength (N mm^{-2})**	**Dry compressive strength (N mm^{-2})**
10:1	100	1.45	4.44
	80	1.88	4.22
	70	1.82	5.05
	60	1.74	4.17
	50	2.5	5.37
	40	4.01	7.21
	35	4.37	7.86
	30	4.35	7.12
	25	4.51	6.94
	20	4.58	7.79
	15	4.51	7.14
15:1	100	0.92	4.73
	70	1.27	4.11
	60	1.47	3.52
	50	1.59	3.00
	40	4.52	6.41
	35	3.38	4.40
	30	3.01	4.49
	25	3.02	3.93
	20	2.87	5.42
	15	2.87	5.39
20:1	100	0.66	5.07
	80	0.85	3.58
	70	0.80	2.53
	60	0.80	2.84
	50	1.32	2.93
	40	2.38	3.88
	35	2.68	3.54
	30	2.34	4.21
	25	3.12	4.84
	20	2.99	4.43
	15	2.91	-

2.6.2. Gravel and Sand

Gravel and sand in soil are usually considered as coarse particles. Sand particle size varies from 0.06 to 2 mm. It shows frictional behaviour in a dry state and a good cohesion property with moisture. The shape of the blocks can be ensured due to the cohesiveness of clay in the soil. The gravel particle size varies from 2 to 20 mm. Also, the behaviour of gravel does not show a significant difference in the dry state with the presence of moisture.

The main concern of most research work in the past was controlling the finer content of the soil to make CSEB. The focus on changing the amount of gravel, sand or gravel and sand is negligible. The effects of coarse particles on properties of CSEB have not been considered. The Sri Lanka standard for CSEB has put only a minimum limit of 65% for sand and gravel [32]. This limitation is given with the purpose of controlling the finer content rather than controlling sand and gravel

2.6.3. Water Content

There is no specified water content defined in Sri Lanka standards for the manufacturing of CSEB, while the drop test has been introduced as the controlling method. It helps to control the water content which leads to optimum moisture content. Jonathan [59] have investigated the optimum water content for earth-based construction materials. The quality and the quantity of water have a greater influence on the strength of CSEB. Hence, it should be with drinking water quality without salty or brackish [35].

Swapna [60] has also emphasized on the quality of water as another essential factor. Quality of drinking water that is free from suspended particles and dissolved contaminants was recommended in this context. Various researchers have performed various tests on water like pH test, Hardness test, and Chloride tests.

2.6.4. Soil Stabilization

The concept of stabilization of soil as a walling material is not a novel method and goes back a few decades in history. Fitzmaurice [48] has clearly explained this concept. Stabilization is defined as a means of adding admixtures with soil with the intention of improving its volume stability, strength, permeability and durability [61]. Mechanical stabilization, physical stabilization, and chemical stabilization are the commonly employed stabilization methods. Through mechanical stabilization in the form of compaction, density and compressive strength could be improved by changing the structure of the soil. Physical stabilization includes sieving of soil to remove unnecessary and large particles, which leads to changing composition and texture. Chemical stabilization is the addition of other binders [62]. Stabilization has another different classification, such as chemical stabilization or fibre reinforcement [18]. Manufacturing of CSEB usually is carried out with soil stabilized using cement, lime or other suitable chemicals. Extensively used stabilizer is Portland cement since it has the ability to reduce the liquid limit. In addition, it helps to increase the plasticity index resulting in more workability of soil. Furthermore, with the addition of cement, the cohesiveness of soil may increase causing higher compressive strength.

The quality of the soil and project requirements determines the type of stabilizer needed. Plasticity of soil is an important factor for stabilization and the main function of the stabilizer is reducing the swelling properties of soil [63]. Cement is the preferred stabilizer for sandy soils and to achieve a higher strength quickly. Lime is suitable for clayey soil and takes a longer time to harden. Many past researchers have studied the properties of CSEB with varying stabilizers and quantities. As Fitzmaurice [48] explained, the addition of a stabilizing agent makes soil strong and durable and it enables the material to retain its shape. Also, Portland cement is the widely used stabilizer and it reacts chemically or physically with the soil constituents to give stable, rigid products in the presence of water. To get the maximum benefit from the stabilizer, it should be thoroughly mixed with clay [26].

SLS 1382 [32] recommends 5% cement as the minimum amount for the stabilization. However, Walker [7] has emphasized that the use of more than 10% of cement as a stabilizer is not economical. Also, the use of less than 5% of cement is often too fragile for secure handling. Alam et al. [26] also have concluded the same 5-10% range for cement and lime stabilizer. Michael et al. [18] as explained, the cement stabilization is generally in the range of 3-10% and more than 7.5% cement is not cost-effective for low-cost housing projects with the support of many other research. Rigassi [36] also suggested 5-6% of cement stabilizing to obtain satisfactory results. Heathcote [17] has explained the mechanism of soil stabilization with cement to reduce the plasticity of the soil with the addition of small amounts of cement. He has shown that the addition of more cement leads to enhancement of strength similar to granular soil. Further, his studies showed a strong linear relationship between strength and cement content. In a study conducted by Swapnil [60], increment of compressive strength from 1.45 MPa to 2.42 MPa was noticed for 0% to 10% cement stabilization respectively. Walker's study [7] based on different clay content and different cement content as stabilizer also present similar behaviour, as shown in Figure 2-2 (Based on data available in Table 2-2).

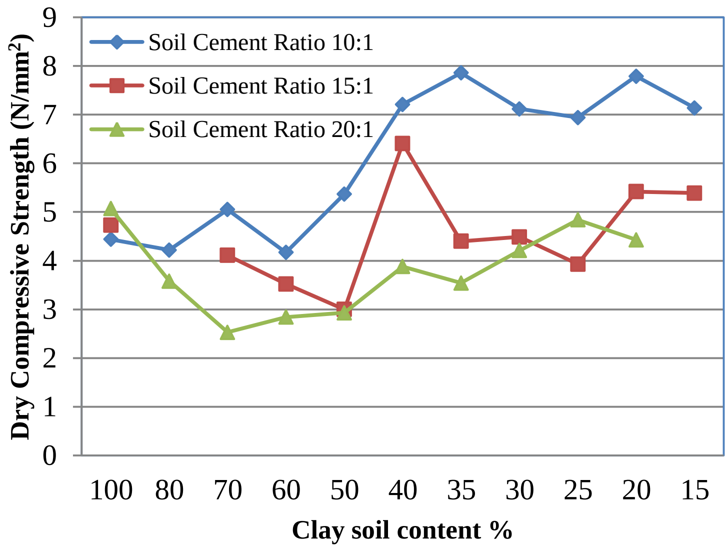


Figure 2-2: Relationship of Dry Compressive Strength and Clay Content as per Walker [7]

Other than the conventional stabilizers, some researchers have tried other alternative stabilizers. Rasvi et al.[64] have used waste burnt brick powder as the stabilizer. Their studies show that burnt brick powder and ash from brick kiln could be used as a soil stabilizer to improve soil properties. Türkmenet al.[65] have used gypsum as a stabilizer for earth bricks. Their studies showed a significant improvement in compressive strength and shrinkage of bricks with gypsum.

Not only the stabilizers, block performance depends on the energy requirement for compaction, characteristics of soil such as particle size distribution and plasticity limit, liquid limit, moisture content, drying regimen and other factors also have a significant impact [66].

2.7. Characteristics of CSEB

Many past researchers have tested characteristics of CSEB. However, the available standards are limited. SLS 1382 specifies physical characteristics as mentioned in Table 2-3.

Most of the researches focused on improvement of physical and mechanical characteristics by changing the soil content, cement content and adding different additives. Based on the studies by Venkatarama & Kumar [51], [52] on compressed stabilized rammed earth (CSRE), strength and performance were influenced by grading characteristics and composition of soil, dry density, amount of cement, etc. Similar argument could be made for CSEB too.

Table 2-3: Physical Characteristics of CSEB (SLS 1382; Part 1)

Physical Characteristics	Specified Limits
Dry Density	>1750 kg/m3
Total Water Absorption	<15%
Dry compressive strength	Grade 1: >6.0 N/mm2
	Grade 2: >4.0 up to 6.0 N/mm2
	Grade 3: 2.8 up to 4.0 N/mm2 (not applicable for interlocking blocks)
Wet compressive strength	Grade 1: >2.4 N/mm2
	Grade 2: >1.6 up to 2.4 N/mm2
	Grade 3: 1.2 up to 1.6 N/mm2 (not applicable for interlocking blocks)
Flexural strength (bending strength)	>0.5 N/mm2
Pitting depth (Erosion resistance)	< 10 mm
Linear expansion of block upon saturation with water	< 0.10%

2.7.1. Compressive Strength

The compressive strength of CSEB has been investigated by many researchers since it is the most dominant feature of blocks [7], [38], [51], [52], [56], [67]. It normally depends on soil type, stabilizer and compaction pressure. Compressive strength is usually tested as dry and wet. Wet compressive strength is generally weaker than the dry strength as shown by many researchers mainly Walker [7] and Heathcote [17]. Bahar et al. [68], have explained, the wet compressive strength is about 60% of its dry compressive strength. Most of the literature provides evidence for the increment of dry compressive strength with the decrease of clay and silt content. As Heathcote [17] explained, with the same cement content, compressive strength could vary significantly. Even with 0% cement content, strength could vary widely (Figure 2-3).

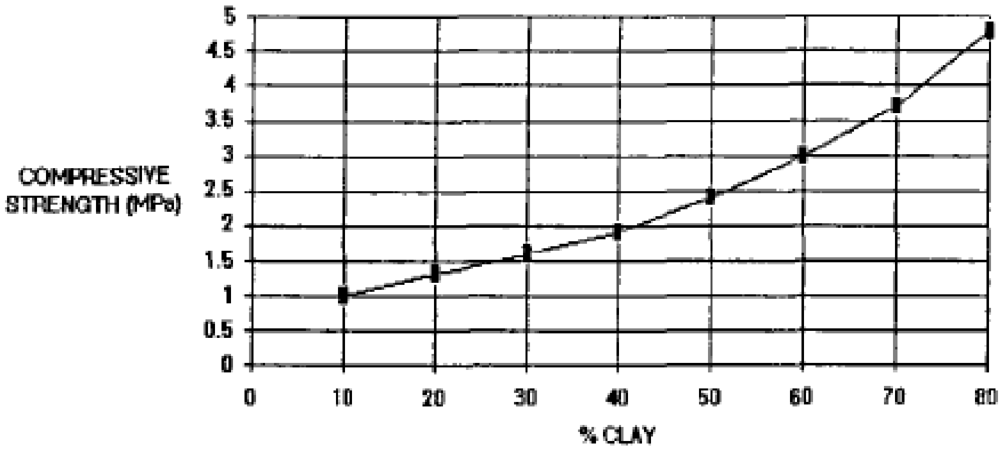


Figure 2-3: Compressive Strength Variation with Clay Content as per Heathcote [17]

The influence of cement stabilization on compressive strength was largely tested by many researchers. Figure 2-4 is the comparison made by Morel et al.[56] based on previous studies.

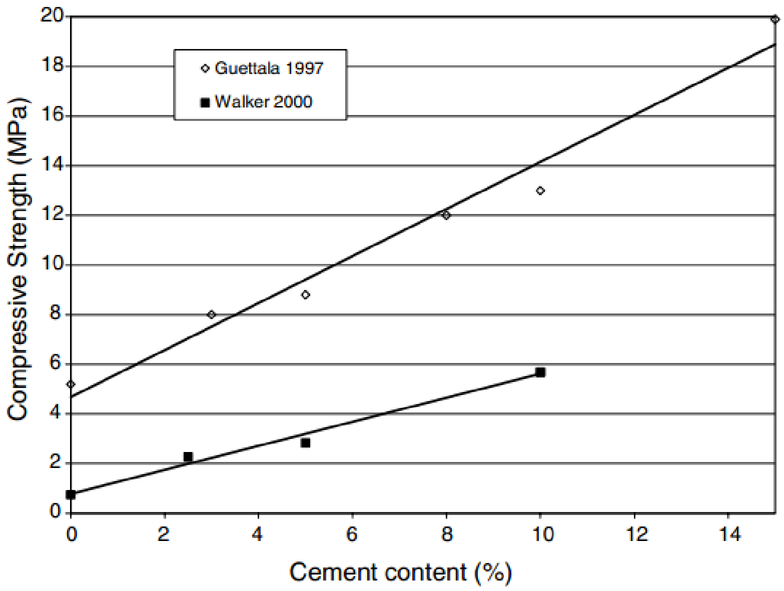


Figure 2-4: Effect of Cement Content on Compressive Strength

2.7.2. Durability

The effect of finer content on compressive strength has been studied by many researchers. However, durability issues associated with soil blocks have not been addressed sufficiently.

Use of soil-based construction is usually considered as a low-quality construction method targeting the lower income community compared to other masonry and reinforced concrete. The main durability issues associated with soil blocks are caused due to lack of water-resistance of soil blocks and erosion [68].

Water absorption is usually a phenomenon that is governed by the amount of clay in the soil used as well as the cement content used as stabilizer. High water absorption leads to reduction in both strength and durability of earth bricks. Hence, the determination of rate of water absorption of earth bricks is of prime importance to ensure the required properties of earth bricks [38]. As per McGregor et al. [69], stabilization mechanism relates to water absorption. Danso et al. [58] have also tested on wearing resistant of soil blocks and erosion only for high clay and silt contents. Therefore, it is important to re-visit the aspects of clay and silt, its role in making blocks and its compressive strength. Rigassi [36] has illustrated the effects of clay and silt on CSEB. Further, Rigassi has suggested apparent density, thermal insulation and durability should be tested other than the main characteristics such as dry and wet compressive strength. Further, he has explained the importance of focusing on durability and maintenance of the finished building considering factors such as the properties of raw materials used, the method of processing soil into a building material, and energy requirements for block production.

The durability of masonry units directly relates to the decay of the physical properties of the conventional building. As a result, essential properties to be evaluated include fire resistance, weather strength, and the impact of other accidental and environmental factors. As per ASTM Test [70], durability generally satisfies by 6 -7% cement content except for those with very high clay content.

Walker [7] also has proved this with wire brush test and drying shrinkage test. Drying shrinkage results are shown in Figure 2-5.

Effect on shrinkage with curing time has been tested by Bahar et al. [68] and, their results showed that shrinkage increases significantly during early days irrespective of the stabilization. After that, the increment of shrinkage is low. Hence, curing for the early days reduces the drying shrinkage and cracking.

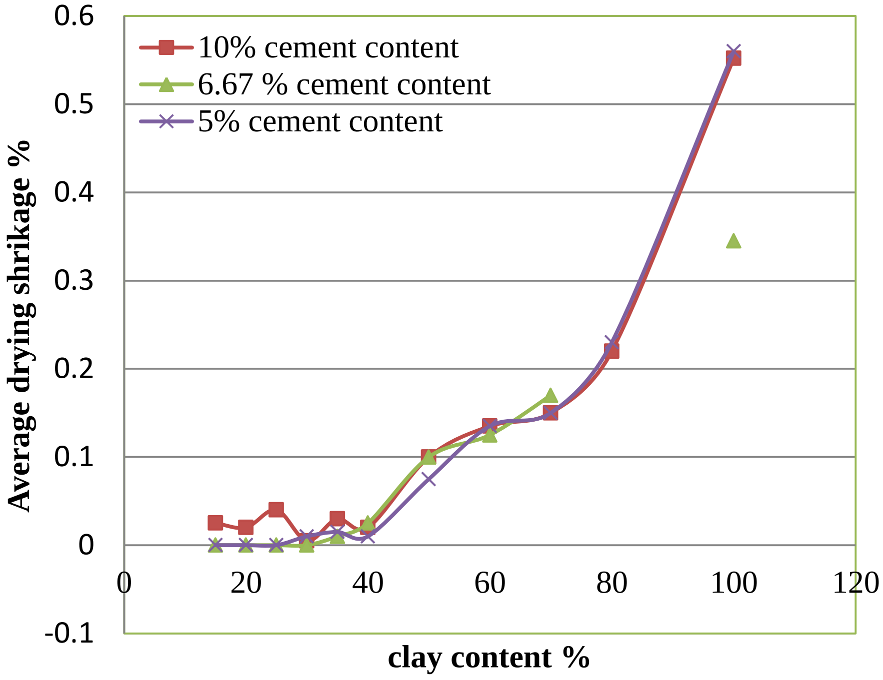


Figure 2-5: Relationship between Average Drying Shrinkage and Clay Content: Walker[7]

The durability of CSEB could be explained in terms of different particle sizes in the soil. Particles of sizes varying from 0.002 and 0.06 mm are silt and it does not show cohesiveness. It does not significantly contribute in bonding the particles of CSEB. It has cohesive properties in the presence of water, but it swells and shrinks as the moisture level varies. For the durability of CSEB, swell and shrink are not viable criteria. This property is also present in gravels and sands, and the presence of silt in

CSEB differentiates it from cement: sand blocks. In CSEB, however, silt fills the voids left by gravel and sand, increasing density. In the presence of cement as a bonding agent, the end result is an improvement in compressive strength.

Clay behaves differently than silt, sand, and gravel. It has particles that are less than 0.002 mm in size and has coherent properties. This cohesiveness is caused by a thin layer of water coating the clay particles. It also aids in the formation of a bond between all clay particles and the sand and gravel particles. Clays, unlike sands and gravel, are more susceptible to humidity changes. Clay absorbs more water in high humidity, creating a thin layer of water and losing compressive strength after reaching the maximum moisture content. These cracks cause water to seep in later and reduce the compressive strength of the material. The presence of cement in CSEB acts as a moisture buffer, maintaining the compressive strength and toughness of the material. A more scientific approach for this effect of swelling and shrinkage of clays explained by general soil mechanics theory where it says moisture content which is less than the “liquid limit” clay display cohesiveness while moisture content more than the liquid limit clay act similar to a liquid, thus losing all its cohesiveness.

2.7.3. Dry Density

Maximum dry density is derived in terms of water content and the compact effort for a given soil. Compaction helps to increase the soil density by decreasing the air volume within soil particles. The dry unit weight usually varies with the water content for a given compact effort which is not linear. Firstly, the unit weight increases and comes to a maximum level then consequently it decreases. The corresponding water content for the maximum unit weight is the optimum water content [71].

Mechanical effort made to manufacture CSEB depends on the type of soil block and the type of machine. In the case of mud concrete, less effort is made to increase the compressive strength thus generally it requires a higher cement content such as 8% or more to get an acceptable compressive strength. On the other hand, hydraulically operated machines put pressure of more than 21 N/mm^2, and the original soil volume is reduced by about half in manufacturing CSEB [30]. The civil engineering construction applications using soils such as road sub-base, dams and other structures use mechanical effort to improve the compressive strength of soils. Proctor compaction test gives the best measurement for density, moisture and mechanical effort and the relationship between different types of soils is shown in Figure 2-6 [71].

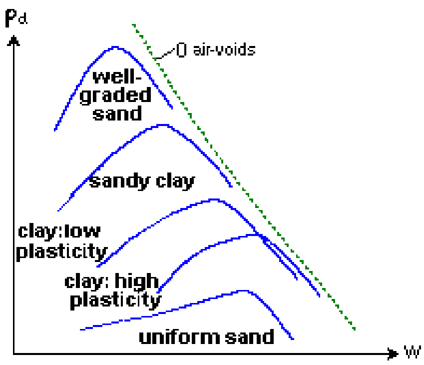


Figure 2-6: Optimum Densities of Different Types of Soils

It is important to note that well-graded sand has the highest compressive strength while uniform sand has the lowest. As the content of clay increases, the optimum density drops suggesting that there is an optimum clay content to balance the dry density and the compressive strength. Walker [7] has given experimental results of different soils for density and compressive strength. Heathcote [17] also has reported similar findings. This work clearly shows that to achieve better density and compressive strength, it is best to keep the clay content as minimum as possible. Technically, a clay content of 0% is best but due to other variables, there is an optimum clay content.

2.8. Compaction Methods and Production Alternatives

The primary goal of soil compaction is to increase the density of the soil, lower the voids ratio, decrease soil porosity, water permeability, and water resistance, and improve its resilience [68]. Also, dynamic compaction, static compaction and vibro-static compaction are the main compaction methods.

Today's construction equipment market is equipped with varieties of block making machines. The block properties usually depend on the compaction ratios that are achieved in those machines. However, those machines are costly. Hence, the affordability of highly sophisticated hydraulic or motor operated machines is less for developing countries like Sri Lanka. As a result, a plain, cost-effective manually operated machine with a high compaction ratio should be chosen [50]. In fact, AURAM RAM and CINVA-RAM are popular and commonly available machines.

SLS standard [32] defines the minimum compaction ratio (height of mould/ height of block) as 1.65. Machines could be either manual or mechanical presses while volume or weight batching could be used to maintain the compaction ratio.

2.9. Curing Methods

Curing is essential to gain the compressive strength to its maximum. When cement is used as a stabilizer, curing is essentially required for the hydration process of the cement during the different ageing periods up to 2 months giving strength to the block. Also, for stabilized blocks, effective movement of stabilizers within the block occurs with proper curing.

After making the blocks, curing is the main function. The first seven days is the period for primary curing of the blocks. It is done by sprinkling water regularly and covering with polythene [7]. After seven days, blocks could be stacked under polythene to complete the curing process.

Rigassi [36] suggested that cement stabilized blocks must be kept in a humid environment for at least seven days. To prevent the forming of shrinkage cracks, quick drying of the surface of the blocks should be minimized. Therefore, the blocks should be covered from the direct sunlight and the wind. Covering using waterproofing plastic sheets is also a satisfactory method of curing to maintain 100% relative humidity. After 28 days, strength improvement is not significant. High temperatures increase the strength obtained, and black plastic sheeting can be used to raise the temperature.

As per SLS standard [32], blocks would be usually kept moist for 14 days by sprinkling water daily and covering with a polythene sheet. Direct sun and wind should be avoided in this context. The blocks shall remain undercover for further 14 days before construction to allow sufficient strength development and initial shrinkage to take place. Compressive strength gain is usually related to the curing age. Wasiri et al. [67] have shown, based on experimental data, that the compressive strength increases with curing age.

Steam curing is also one productive method and the use of steam curing process could lead to quick production of stabilized soil blocks. The blocks could be made ready for use in construction within three days of moulding [72]. However, it is an energy-consuming method compared to wet curing and air-drying curing.

2.10. Durability of Walls with CSEB

Durability refers to a building's and its parts' ability to perform their necessary functions over time and under the control of agents [73]. Thus, the durability of walling material is a key to make sure the long life-span of a building, i.e., with high durability. Compressed Stabilized Earth Blocks are made with soil adding different ingredients to improve its performance characteristics. Properties of soil are the dominant factor for CSEB properties. There are many research studies conducted on the amount of clay and silt content to get more strength and durability. Many of the researchers have concluded that the clay and silt content of 5-20% would give desirable properties for the strength of blocks while durability still remains as an issue. Arandara & Jayasinghe [74] also have shown that the strength is proven as adequate but there are still issues with durability. There are many studies that have been done related to durability of CSEB considering various properties related to durability and the following sections explain those.

2.10.1. Durability Problems

Arandara & Jayasinghe [74] have identified cracks on plaster, water absorption, erosion of walls due to heavy rain, separation of wall plaster and inadequate plinth level as major durability issues associated with CSEB walls. They have also highlighted that the un-stabilized or less-stabilized CSEB is a major reason for these problems. CSEB contains a certain amount of clay and silt even after stabilization which causes cyclic expansion and shrinkage [49]. Therefore, linear expansion on saturation and weight loss of blocks needs to be considered. Rainwater absorption is another problem in this background. Walker has mentioned that [7], governing factor for drying shrinkage of CSEB is the plasticity index. That is drying shrinkage tends to increase with the increase of clay and silt content. Also, Walker showed that drying shrinkage increases even at low plasticity with the increase of cement content. Cement stabilized blocks usually give high compressive strength. However, Islam et al. [75] have shown that durability issues cannot be solved with cement stabilization when the clay content is high which is effective in increasing the strength but ineffective in improving the ductility of the blocks.

The durability of CSEB wall is an important aspect in this study. Hence, the properties related to the durability of CSEB were given a vast attention. Also, it is necessary to identify the related test for CSEB. Table 2-4 provides an overall idea of all these aspects.

Table 2-4: Summary of Literature Review on Durability of CSEB

Author(s)	**Used soil properties**	**Factors studied**	**Method adopted**	**Conclusion**
Kariyawasam & Jayasinghe (2016) [76]	Sandy lateritic Gravelly lateritic Clayey lateritic	Wet compressive strength, water absorption, accelerated erosion	Strength testing after soaking in water for 24 hours Water absorption compared to dry mass after soaking in water for 24 hours accelerated erosion test	Blocks made with Sandy lateritic soil show wet/dry strength ratio of more than 0.4 (As per SLS 1382) Blocks made with sandy lateritic soil show less than 20% water absorption with more than 2% of cement stabilization Less than 10mm when widespread stabilizer is above 2% of cement
Arandara & Jayasinghe (2007) [74]	Soil blocks and rammed earth houses	Durability problems	Field survey by visual inspection	Identified issues are; cracks in wall plasters, water absorption, erosion of walls due to driving rain
Esther et.al (2010) [77]	Soil with 13 % finer stabilized with different stabilizers	Depth of erosion and Rate of erosion	Erosion test	Cement stabilized soil blocks having less depth of erosion and rate of erosion compared to lime and fibre stabilization but higher than the interlocking blocks.
Reddy & Latha (2014) [49]	Coarse-grained soil and fine-grained soil	Weight loss Rate of water absorption	Cyclic wetting and drying test Soaking duration in water	Lowest weight loss for CSEB is reported when optimum clay contents are 10.5% and 14% for fine-grained and coarse-grained soils respectively. At optimum clay contents, water absorption is 14% and 18% for CSEB using coarse-grained and fine-grained soil respectively
Walker (1995) [7]	With a board spectrum of plasticity characteristic, formed by mixing clay soil and river sand	Saturated compressive strength Resistance to weathering		Saturated compressive strength decreased with reduction of cement and increasing plasticity index. Reduced with increasing clay content. Durability improved with increasing cement content and reduced clay content. Adequate durability was noted when the plasticity is below 15-20.

		Drying shrinkage		When plasticity index below 20, steady increase in drying shrinkage and when plasticity index exceeded 20, drying shrinkage increased rapidly.
Bahar et al. (2004) [68]	Finer 62% Sand 30.3% Grave 7.7% Added sand to modify the soil	Shrinkage Permeability Water absorption		Minimum of 0.74mm for 15% cement and 5% sand. 1.12mm for 5% cement and 15% sand. Permeability is decreasing with increased cement content. Water absorption is increasing with increased cement content.

2.11. Application of Particle Packing Technology for CSEB

As per the past studies, most of the researchers have added different ingredients to improve the performance of Compressed Stabilized Earth Blocks. Mainly, properties of soil are the dominant factor for CSEB properties. Various researchers have found different soil particle combinations and ingredients. Particle packing technology is one important aspect of concrete technology to select appropriate sizes and shapes of aggregates. The purpose of this section is to review particle packing technology and its application in different areas and to match it to CSEB production.

2.11.1. Concept of Particle Packing Density

Particle packing technology considers optimizing different particle sizes and amounts to increase the particle packing density [78]. It also states that the degree of how well the solid particles of the aggregate are evaluated in terms of packing density is the packing of aggregates for concrete [79]. The ratio of the aggregate particles' solid volume to the bulk volume filled by the aggregate is known as packing density. Figure 2-7 shows the particle packing concept. Figure 2-7 (a) shows the large particles have filled the container with large voids, and then smaller particles are filled to reduce the void (Figure 2-7 b). After that, tiny particles are filled to reduce voids furthermore to increase the density (Figure 2-7 c).

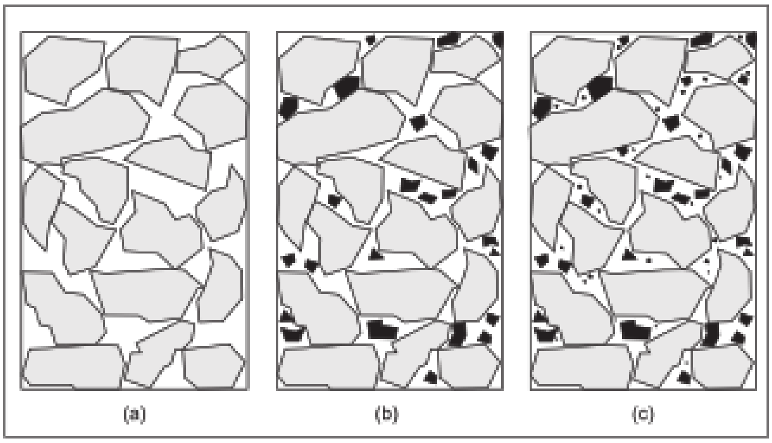


Figure 2-7: Illustration of the Particle Packing Concept [80]

When well-graded soil is used for the CSEB, it is more useful to increase the mechanical properties of the soil blocks. To increase the packing density, particles should be chosen to fill the voids between large particles with smaller particles. The concept of particle packing optimization has been used by researchers in the field of concrete technology like high-performance concrete [81] and interlocking paving blocks [82]. These researchers have focused on an ideal grading curve, which represents the grading with the greatest density. By selecting a proportion so that the soil grading represents an ideal curve, particle packing could be improved.

Different past studies are available worldwide on particle packing density with this optimization concept. All this research falls under one of the following particle optimization methods.

1. Optimization curves: Groups of particles, with a specific particle size distribution, are combined in such a way that the total particle size distribution of the mixture is closest to an optimum curve. The following are such optimization curves.

$$p(d) = \left(\frac{d}{d_{max}}\right)^q$$ ---------- Equation 2-1

Fuller and Thompson (1907) cited in Fennis (2012)

Where;

P(d)= size cumulative distribution function

d= particle diameter being considered (m)

d_{max}= maximum particle diameter in the mixture (m)

q= parameter (0.33-0.5) which adjusts the curve for fineness or coarseness

Fuller used Equation 2-1 with q=0.5 and Andreasen (1930) cited in Fennis (2012) suggested q in a range of 0.33-0.5.

Equation 2-1 was modified by Funk and Dinger (1980) as in Equation 2-2 with the adjustment factor q=0.37 for optimum packing.

$$P(d) = \frac{d^q - d_{\min}^q}{d_{\max}^q - d_{\min}^q}$$ ---------- Equation 2-2

d_{min} = minimum particle diameter in the mixture (m)

Other than the above two equations, Power [83] has proposed a maximum density line. It gives a direction to select correct proportion of aggregates to get the maximum density. Figure 2-8 shows the graphical representation of Equation 2-1, Equation 2-2, and power line taking particle size between 0.075 mm and 12 mm.

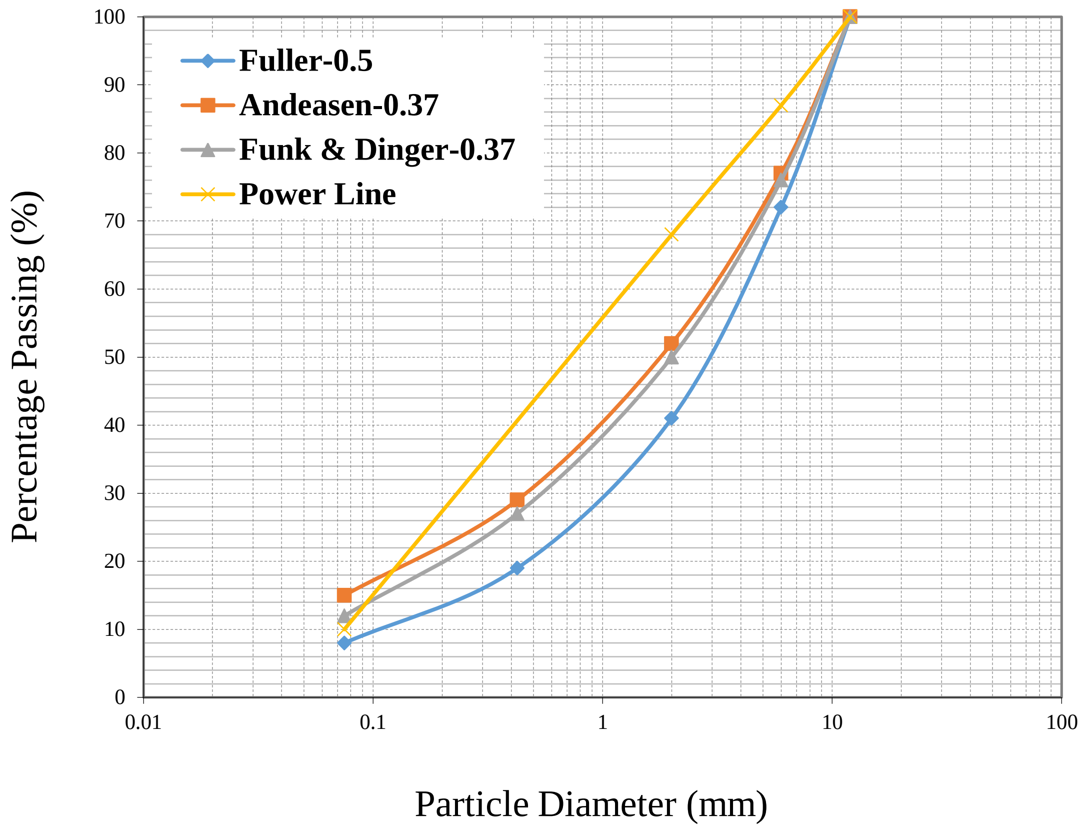


Figure 2-8: Graphical Representation of Theoretical Optimization Curves of Particle Packing

Fennis and Walvaren [78], have shown with their experiments that when the packing density is high, a high compressive strength could be achieved and full experimental results are shown in Table 2-5.

Table 2-5: Experimental Results by Fennis and Walvaren (2012)

Composition		Mixtures			
		A1	A2	A3	A4
CEM I 42.5 N	[kg/m³]	260	110	44	125
CEM III/B 42.5	[kg/m³]	-	-	66	-
Fly ash SMZ Maasvlakte	[kg/m³]	-	88	65	75
Quartz powder M600	[kg/m³]	-	62	85	-
Ground IBA	[kg/m³]	-	-	-	50
Aggregates 4-16	[kg/m³]	1193	1162	1160	1157
Sand 0-4	[kg/m³]	718	867	866	864
Glenium 51 [% kg/kg of powders]	[%]	0.8	0.8	1.2	1.2
Effective amount of water	[kg/m³]	162	103	103	112
Water/cement ratio	[-]	0.62	0.94	0.94	0.90
Water/powder ratio	[-]	0.62	0.40	0.40	0.45
Estimated density (1% air)	[kg/m³]	2351	2409	2408	2402
Packing density CIPM	[-]	0.886	0.897	0.898	0.890
Rheological properties					
Slump	[cm]	20	3	12	14
Air content	[%]	0.9	1.8	0.9	0.9
Density	[kg/m³]	2366	2406	2424	2456
Mechanical properties					
2-day cube compressive strength	[N/mm²]	13.9	15.2	7.2	12.9
7-day cube compressive strength	[N/mm²]	24.2	25.2	17.6	22.9
28-day cube compressive strength	[N/mm²]	32.1	39.6	33.5	37.9
56-day cube compressive strength	[N/mm²]	36.4	39.9	35.3	48.0
90-day cube compressive strength	[N/mm²]	36.4	53.1	39.1	55.1
7-day tensile splitting strength	[N/mm²]	2.0	2.1	1.4	2.0
28-day tensile splitting strength	[N/mm²]	2.5	2.7	2.5	3.0
56-day tensile splitting strength	[N/mm²]	2.6	2.7	3.0	3.3
90-day tensile splitting strength	[N/mm²]	2.7	3.7	2.6	4.0
28-day prism compressive strength	[N/mm²]	29.5	26.6	20.0	29.1
28-day modulus of elasticity	[N/mm²]	30500	32500	30500	30500

2. Particle packing models: these are analytical models that calculate the overall packing density of a mixture based on the geometry of the combined particle groups. These models are discrete; hence, it considers definite sizes of different particles.

3. Discrete element models: these are simulation of virtual particle structure from a given size distribution.

Considering the nature of the above mentioned three optimization methods, optimization curve is used to compare the soil used in this study.

2.12. Use of Fly Ash for CSEB Production

Fly ash is a small, glass-like material that is recovered from gases emitted by coal-fired power plants. The particles are usually spherical in shape and vary in size from 0.5 μm to 100 μm [84]. SiO_2, Al_2O_3, Fe_2O_3 and occasionally CaO are the main chemical components present in fly ashes [85].

Fly ash is one soil stabilizing agent which occurs naturally from the coal combustion process, and has shown similar characteristics as volcanic ash. In modern coal combustion plants, combustion temperature reaches approximately 2800 F. Bottom ash and fly ash form non-combustible minerals, which naturally occur from burning coal. The flue gases from coal-burning carries off the fly ash which is collected and stored in silos for further uses.

Because of its cementitious value, fly ash is used in a number of applications. It reacts chemically in the presence of water and forms cementitious compounds, which contribute to the strength and compressibility of compacted soils. It has a long history as an engineering material, and it has been used successfully in geotechnical applications [86]. Fly ash could increase the strength and durability, since it is able to handle itself to greater loads. Also, it is more resilient and lasts longer. It could withstand chemical attacks such as salts, soil sulphates etc. Spherical shape of fly ash particles provides good workability, and it has an ability to reduce the concrete setting time. The use of fly ash provides many positive environmental impacts; it conserves landfill spaces, leads to reduction of greenhouse gases.

Fly ash has little cementitious properties compared to cement and lime. Most of the fly ash is classified as secondary binders, which cannot induce the desired effect when they stand alone. However, the presence of activators could form a cementitious compound that would be able to improve the strength of soil [87]. The highest compressive strength of CSEB was achieved when it was incorporated with 10 % of fly ash. The lowest water absorption was experienced by CSEB when the fly ash percentage was 15% [88].

ASTM C618 [89] has classified fly ash into three classes; class N fly ash, class F fly ash and Class C fly ash. The major differences between these classes are the percentage of calcium, silica, alumina, and iron content in the ash. Fly ash is a product that is created by burning coal, thus it is the properties of coal that affect the properties of fly ash. ASTM C618 defines the chemical and physical requirements for these three classes. Table 2-6 illustrates the chemical requirements of fly ash in different classes as per ASTM C 618.

Table 2-6: Chemical Composition of Fly Ash

Chemical Requirements	**Class N**	**Class F**	**Class C**
SiO_2, Al_2O_3, Fe2O3 (min %)	70.0	70.0	50.0
SO_3, Max %	4.0	5.0	5.0
Moisture content, max %	3.0	3.0	3.0
Loss of ignition, max %	10.0	6.0	6.0

Class N fly ash is raw or calcined natural pozzolans. Class F fly ash are produced from the burning of harder, older anthracite and bituminous coal. This type of fly ash shows a pozzolanic character in its natural condition and contains less than 7 % of lime (CaO). Class C fly ash is produced from the burning of younger lignite or sub-bituminous coal. It has pozzolanic properties, and it shows self-cementing properties. This type of fly ash hardens and gets stronger over time when coming into contact with moisture. In the natural condition, it contains more than 20 % of lime (CaO). It has more content of alkali and sulphate too.

2.12.1. Use of Fly Ash for Building Materials Production

Literature proves that fly ash has been used for many building material productions like bricks, blocks roof tiles, etc. This section explains the test results of a few of those studies.

Aakash and Davendra [90] have used fly ash for clay bricks production in the field. They have used fly ash range from 5-50% from wet mass of soil. Results show the variation of dry compressive strength as shown in Figure 2-9. As per test results, 15% fly ash replacement has given a high compressive strength. According to [90], water absorption is also minimum when the fly ash content is 15%. As a conclusion, they have suggested that fly ash bricks give a satisfactory performance as load-bearing elements when 15% fly ash mixing with 85% clay. Therefore, a considerable amount of disposal fly ash could be used in an efficient and profitable way.

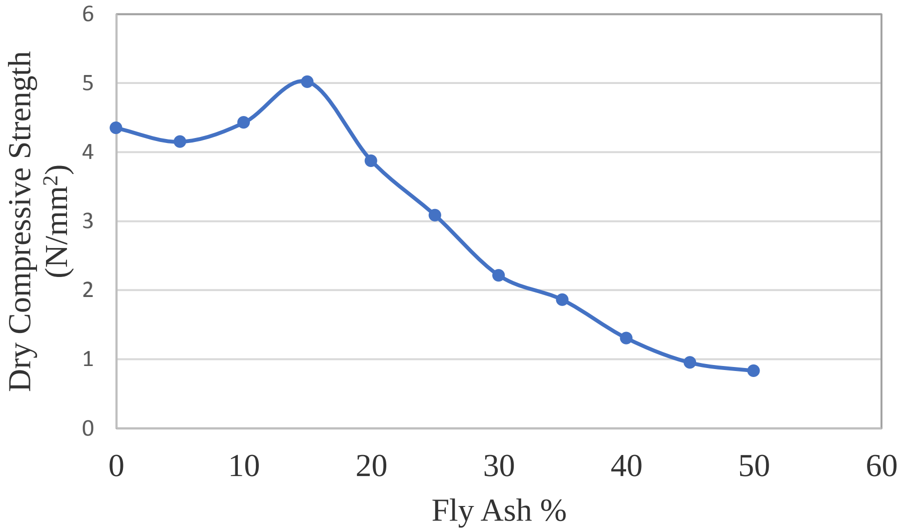


Figure 2-9: Compressive Strength Variation with Fly Ash [90]

Andreas [91] has studied on development of low-cost fly ash bricks. For that, three different fly ash/sand combinations namely; 50/50, 70/30 and 90/10 with Liquid Sodium Silicate (5, 10, 15 and 20%) have been used. This study has revealed when the fly ash contribution is high, a high compressive strength could be achieved, but desirable water absorption could be achieved with the minimum usage of fly ash (50%).

Karthik et al. [92] have used fly ash as a stabilizer to improve the soil properties. They have suggested, the use of a small addition (3% to 9%) that would improve soil properties and 6% gave the optimum results.

Egenti et al. [93] have used high carbon fly ash for compressed earth blocks. As per their studies, they have varied the fly ash content from 0%- 50% in 10% interval keeping cement content constant. Blocks with 0% fly ash have shown the maximum compressive strength and lowest water absorption. While using fly ash, they have concluded that 25% of fly ash gives an optimum compressive strength.

Thushar et al. [94] have used both lime and fly ash for soil blocks. They have shown that the unconfined compression strength of the laterite soil with 5% fly ash and 15% lime was found to be around 2.5 times more when compared to the strength of natural laterite soil sample. Also, they have shown, the average compressive strength of the blocks tested after 28 days of curing period was more than the minimum compressive strength of fired bricks as per IS: 1077 (1992). The water absorption value obtained for 28 days curing period was below the minimum value as specified in IS: 1077(1992).

2.13. Lime Stabilization for Compressed Stabilized Earth Blocks

Lime is the oldest stabilizer known to man. When lime is applied to clayey soil, the properties of the soil alter. That is, the calcium ion in lime interacts with the metallic ion in clay soil, resulting in cat-ion exchange. As a result, a diffuse hydrous double layer surrounds the clay particle. Electrical density varies around the particle as a result of this layer, bringing the particle closer together and creating flocks known as flocculation. This is the main factor influencing the engineering properties of lime-treated clay soils [95].

When lime is added to the clayey soil, lime initially satisfies the affinity of the soil. There is no lime that remained for the pozzolanic reaction before it satisfies the affinity of the soil. It is called lime fixation, with lime addition to clay soil it fixes to the soil and prevents it from conducting any other reactions. The lime fixation has an optimum level of lime. Above this optimum level the plastic limit remains unchanged but helps to improve the strength of the soil [95].

After the cat-ion exchange, the other reaction that takes place is between silica and aluminium in the clay material. The addition of lime creates an alkaline environment that produces aluminosilicate, which is slowly solution and they are the precipitation at the hydrated cementations reaction. The reaction takes time and the strength development occurs gradually and for the maximum reactivity, pH of the pore fluid in the voids should be around 12.4 [95]. In the lime stabilization aluminium, clay compounds react as the pozzolanic material. Pozzolanic is the inorganic compound which hardens in the water if it is combined with lime [11].

In the past researches different ranges of lime percentages were used as a stabilizer, Alavez-Ramirez et al. [54] used lime only, lime combination with sugarcane baggase ash (SBA) and cement only as stabilizers for CSEB production. The plasticity index and the liquid limit for the soil were 12% and 25.28% respectively. Clay percentage of the soil was 23.1 and the silt percentage of the soil was 4.3. Soil type was sandy clay. 7 days, 14 days and 28 days compressive strength were checked for the CSEB. Alavez-Ramirez et al. [54] used 10% lime without SBA as a stabilizer and got 28 days dry compressive strength as 16.5 Mpa. For 10% cement 23.5 Mpa of compressive strength was achieved. Miqueleiz et al. [96] used highly clayey soil for the production of CSEB, lime used as the stabilizer between 3%-18% with 3% increment; highest 7 days compressive strength achieved as 6 Mpa for 9% lime, highest 28 days compressive strength achieved as 8 Mpa for 15% lime, high 90 days compressive strength achieved for 18% lime as 12.5 Mpa. Raheem et al. [97] used laterite soil sample for CSEB preparation and lime was used as stabilizer with 5 – 25 percentage. High 7 days compressive strength was achieved as 0.6 Mpa for 10% lime and high 28 days compressive strength was achieved as 1.25 Mpa for 10%

lime. Also cement stabilization was compared at the end of the conclusion, the conclusion was that cement stabilization was better than lime stabilization.

Guettala et al. [20] used 8% lime as a stabilizer and varied the percentage of sand from 0 to 40%. The dry compressive strength of 40 percent sand (clay 21.6 percent) was 15 MPa, and the wet compressive strength was 5 MPa. Bell [95] used 0-10 percent lime to stabilize the CSEB, and the optimal percentage of lime was found to be between 4 and 6 percent. Ngowi [98] used 0-15 lime percentage as a stabilizer and got the optimum level at 15%. Akpokodje [99] used different types of soil with different clay and silt percentages and lime was used as one of the stabilizers with the percentage of 0- 12. For the clay and silt percentage of 85%, 64%, 41%, 30%, 29% high strength was achieved at lime percentages of 12%, 6%, 10%, 12%, 12% respectively. Izemmouren et al. [100] used lime and natural pozzolans for their research. 6%, 8%, 10%, lime was used in this research the clay and silt percentage in the soil was 57.4. 10% lime contributed to the maximum 28 days compressive strength with 4.8Mpa of dry compressive strength and 3.4 Mpa of wet compressive strength. Bogas et al. [101] indicated from the past research reviews, 6-12 lime as the effective average percentage.

2.14. Soil Washing Procedure

Soils having considerably high clay content are difficult to use as a construction material. Usually, Compressed Stabilized Earth Blocks need maximum 25% clay and silt content to get the desired properties. Soils with considerably high clay content are not appropriate even for backfilling work. In Sri Lanka, such soils are available in plenty arising as waste material from large-scale civil engineering projects such as expressway constructions. These soils contain more than 40% clay and silt content.

Separation of clay by washing is not an easy method. Most of the industrially available washers are used for sand washing. In other countries, very large-scale plants could be seen as soil washers. These washers are used mainly in the sand mining industry.

In the world, there are large-scale soil washing plants which implement soil separation into fractions of different particle size. Most of them are done to clean contaminated soils. In the process of soil remediation, soil washing was used as a volume reduction method.

In the soil washing, hazardous materials are removed and they are concentrated into a small volume. The contaminants mostly contain in silt and clay of soils. Thus, to remedy contaminated soils first it needs the separation of silt and clay from sand and gravel [102]. It can be done by soil washing. After that, the reduced volume with highly contaminated soil fraction could be disposed by an appropriate method according to the regulations. In soil, the more there are silt and clay, the more difficult it will be to separate particles into fractions according to size. Soil washing can be used as a volume reduction technique to reduce the final volume up to 10% of the initial volume. Hence, further treatment of the volume could be greatly reduced. The hazardous contaminated soils could also be treated on-site. A wide variety of contaminants could be removed using the soil washing method.

Separation of clay, silt and sand fractions from soil has been described by [103], [104], [105]. This was done by sieving, sedimentation procedure and electrophoresis. To separate soil particles from each other the bond between individual soil particles needs to be disrupted. The agents responsible for the bonds are known as "cementing agents". Commonly available cementing agents in most soils are listed by Baver [106] and they are organic matter, colloidal clay, and dehydrated colloidal oxides of iron and aluminium. The difficulty to disrupt the bond depends according to the soil type. Different types of chemical and mechanical methods are used to separate these bonds.

The clay and silt separation proposed for this study is through soil washing while the used water could be re-usable. For that water should be treated too. Alum and polymer are industrially available water treatment agents. These alum, polymer or combination of alum and polymer act as turbidity removal agent [107], [108], [109], [110], of water.

2.15. Clay Roof Tiles and Bricks Production

Sun-dried or burnt-bricks, roof tiles and ceramic tiles are produced using clay as the raw material. The heterogeneous property of brick due to clay could incorporate a significant percentage of waste material to its body [111]. Suitable clay for these products is hard to find due to environmental issues. Therefore, sustainable alternative raw materials are needed for clayey products. Industrials wastes and other waste matters can be used in this context.

The utilization of the different type of wastes in bricks, tiles and ceramic tiles production have been investigated by many researchers. Those are: fly ash [90], [91], waste-brick [112], granite wastes [113], coal fly ash [114], borax waste and dewatering sieve borax waste [115], ceramic roof tile [116], waste tile and coal fly ash [117], sewage sludge [118], plastic and rubber related wastes [119], Nickle slug [120] and rice husk and ash [121], [122], [123], [124]. Other than that, some research studies have shown that the use of rice husk and ash leads to lightweight burnt bricks [125], [126]. Murmur and Patel [8], with their extensive literature study, have shown the usage of industrial and agricultural waste for brick production has been investigated by many researchers. All these researchers' aim was to find some alternative raw material for clay-based building materials.

2.15.1. Properties of Roof Tiles and its Raw Materials

A Roof is one of the most important parts of a building. It serves many purposes like shelter, and aesthetical appearance. In Sri Lanka Calicut tiles and the country tiles are the historically used roofing materials made with clay. Recently, asbestos, clay tiles and cement tiles are the most commonly used roofing materials. Over other roofing materials, clay roof tiles have advantages such as good thermal insulation, high fire resistance, long lifetime, resistance, sturdy colours, and a good appearance.

Since the roof costs about 10-15% of the overall cost, depending on the roof structure and other factors, asbestos sheets are widely used [127]. Because of the low cost, high roof covering, quick construction and good strength, asbestos roof covering have gained higher place over clay roof tiles. However, asbestos sheets are found to be a health-related hazards material. Therefore, Sri Lankan government has decided to ban the usage of asbestos sheet. World Health Organization also has warned on this.

In Sri Lanka, properties of roof tiles are governed based on SLS : 2 : 1975 [128]. Table 2-7 gives the requirements set in SLS :2: 1975 for clay roofing tiles.

Table 2-7: Specific Requirements of Clay Roof Tiles [128]

Characteristic	**Requirement**
Mass	Not more than 2.7Kg
Transverse Breaking Strength	Not less than 1kN
Water absorption	Not more than 18%
Water permeability	No water droplets have fallen from the underside of the tiles

The main raw material for clay roof tiles is clay. Recent research has shown the addition of different materials to clay such as industrial waste, rice husk ash, etc. as mentioned in section 2.15.

2.15.2. Properties of Burnt bricks and its raw Materials

In the modern construction industry, different types of bricks are in use. Those are; burnt clay bricks, sand-lime bricks, concrete bricks, and fly ash bricks. These names are given based on the materials used and the method of manufacturing. Out of that burnt clay bricks usage is very common [129]. Bricks are one of the oldest building materials on the planet. Its popularity as a building material has not waned, owing to its durability, ease of handling, aesthetic appearance, and low cost. [130]. Suitable clay or shales are shaped to standard size to form clay bricks. They are then fired at a temperature of 900–1150°C for a period of 8–15 hours [131]. The particle size of clay is usually the most important factor to check the suitability of raw materials. As per [132], particle size lower than 0.1mm is the most suitable size. But, some researchers have used particle size more than 0.1 mm also in smaller quantities in the raw material [123]. Colour is another main important aspect and it is determined according to the chemical composition [131]. Burnt bricks properties are usually determined according to the standards available. In Sri Lanka, SLS 39: 1978 defines the properties of burnt clay bricks [133]. Table 2-8 gives necessary requirements of burnt bricks.

Table 2-8: Specific Requirements of Burnt clay Bricks [133]

Characteristic	**Type 1 (Machine made bricks**	**Type 2 (Hand-made bricks)**	
		Grade I	**Grade II**
Characteristic compressive strength average not less than (MPa)	10	4.8	2.8
Water absorption not more than	18%	28%	28%
Efflorescence- highest permissible rating	Slight	Moderate	Moderate

2.16. Findings from Literature Review

Earth-based building materials have been investigated by many researches. The main findings from the literature are;

1. Lateritic type soil has been used for soil blocks production
2. Clay and silt content in the soil were varying from 5% to 35 % and more in some research
3. To change the amount of clay and silt content, sand, fly ash, or similar materials have been used
4. Cement has been used as the main stabilizer
5. Fly ash, lime and similar materials also have been used in some occasions
6. Other than the clay and silt content, proportions of other larger particle have not been paid attention
7. With the above-mentioned materials, strength performance has been achieved my many occasions
8. To find the durability performance, the researchers limited to saturated compressive strength and water absorption
9. Use of erosion tests, shrinkage tests are very rare
10. Many researchers have tried to find an alternative to the clay as a raw material to produce bricks and roof tiles. Still, finding of alternatives are essential.

With these findings, this study was mainly focused on reducing the clay and silt content by soil washing. Thus, soil with reduced clay and silt was used for CSEB production. Other than the clay and silt content, the proportion of larger particles was also taken into consideration. All the strength properties, as well as durability properties, were tested in this context.

2.17. Summary

This chapter commenced by reviewing the history of CSEB production. All the raw materials used for CSEB production and properties of CSEB based on past research was discussed. Related standards were also considered. With that, the research direction for the present study could be finalized. Next consideration in this study was production of roof tiles and bricks. Hence, related literature for these products was discussed. Based on study on past research, the appropriated methodology could be formulated, which will be described in the next chapter.

CHAPTER 3 : RESEARCH METHODOLOGY

3.1. General Introduction

The previous chapter discussed the overall information related to the CSEB considering the raw materials used and their properties. Based on that, the direction of the present study formulated. This chapter focuses on the methodology adopted to achieve the project objectives considering past researches. Further, this chapter gives an overall idea on the materials used, methods adopted to produce the products namely CSEB, roof tiles and bricks. Then the applicable testing to confirm the properties of said products referring to related standards is clearly explained.

3.2. Overall Study Programme

The study is mainly experiment-based. First, a comprehensive literature review was carried out to understand the related studies and the research gap. Based on that, the problem statement was formulated. The main purpose of the study is to produce CSEB from a soil with low silt and clay content. Accordingly, the experimental stage was started with soil selection. The selected soil for this study was abandoned soil generated from expressway construction in the central area of the country. Initial soil testing revealed that the soil contained about 28% of silt and clay. Therefore, washing of the soil was done to reduce the finer content. With washing, the soil was separated into two parts namely finer and coarse. Finer part consists of silt and clay while the coarse part mainly consists of sand and gravel.

Sand and gravel part were mainly used for CSEB production while the silt and clay were used for other clay-based productions. Overall view of the experimental study is shown in Figure 3-1.

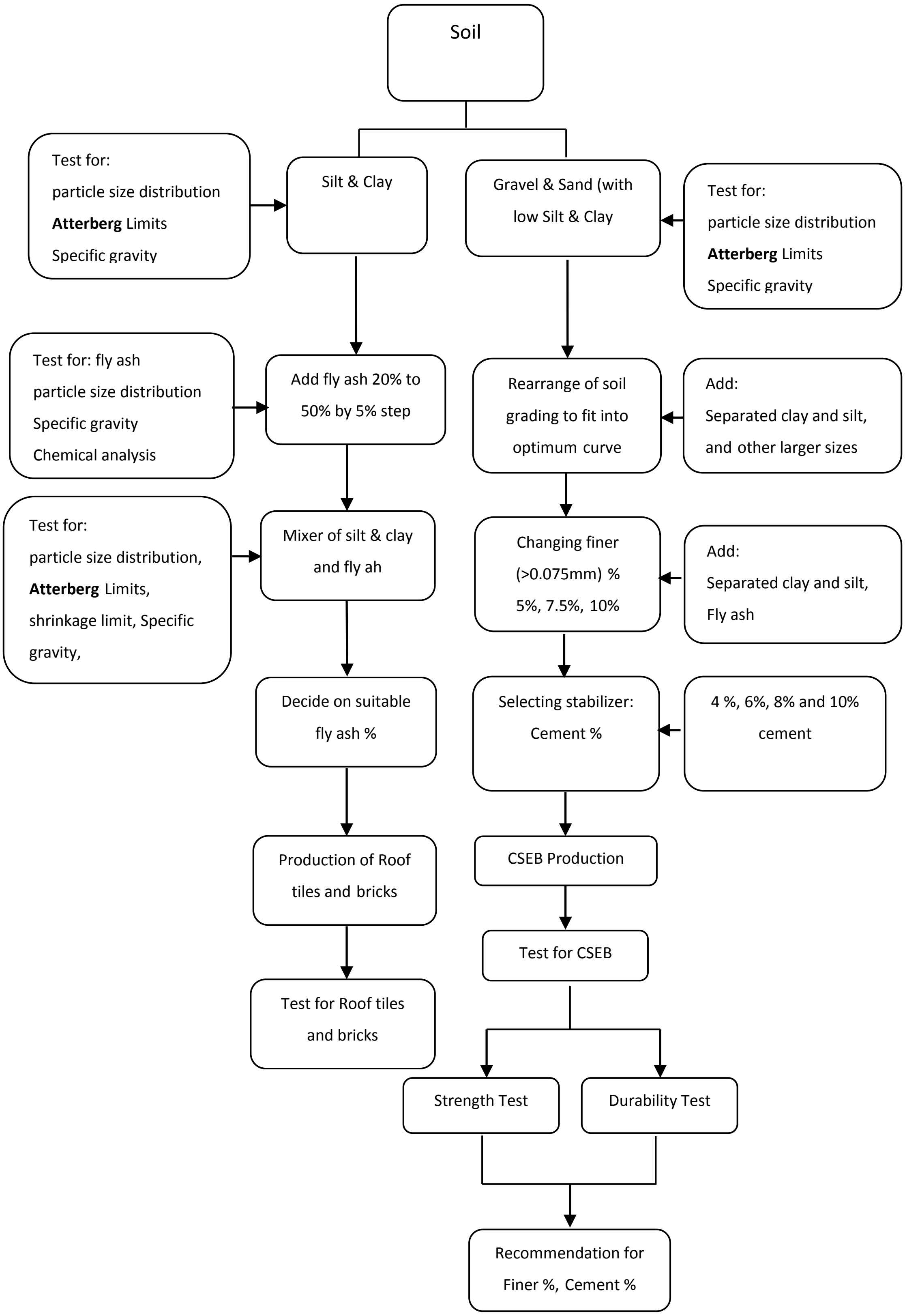


Figure 3-1: Overall View of the Experimental Study

3.3. Soil Washing

Purpose of soil washing was to reduce the finer content of the soil. With washing, finer content could be separated from soil and it was supposed to check the suitability of finer content to produce roof tiles and burnt bricks. Manual soil washing was done manually to check the feasibility of separating finer through washing. Then the commercially available concrete mixer was used for soil washing. This was done by taking soil into a 20*l* bucket. About half of the bucket was filled with soil and water was added to another 1/4 of the bucket. It was mixed well and the clay slurry was removed. After keeping the slurry for a few hours, some amount of clear water could be removed. The remaining clay slurry was put to a cloth to filter the remaining water to separate the clay. Then the clay was kept in the Sun to completely dry.

Manual washing was realized as not practical for larger quantity washing while the use of a concrete mixer was reliable. The 20*l* bucket was used to measure the soil and water. One 20*l* bucket of soil and the same amount of water were put into the concrete mixer and the mixer was made to function for a known time and one soil bucket was washed for different times. Figure 3-2 shows the use of a concrete mixer for soil washing.

This process was done by changing the mixer rotation time and the number of washing cycles. Results revealed that washing twice for one to two minutes rotation time gave an optimum yield of finer. To make the sedimentation process of finer accelerated, Alum was used in this context. Optimum Alum dosage also was determined by performing a Jar Test. After soil washing, the clay slurry was separated into a container while the gravel part was put for drying under the Sun. The Jar test revealed that, after 30 minutes, the initial sedimentation of finer parts was fulfilled hence water could be re-used. Therefore, after 30 minutes, water was separated for re-use and the thick finer slurry was put to a cloth which was made as a filter.

Figure 3-2: Use of Concrete Mixer for Soil Washing

Figure 3-3(a), 3-3(b), and 3-3(c) show the used soil, separated finer and gravel part.

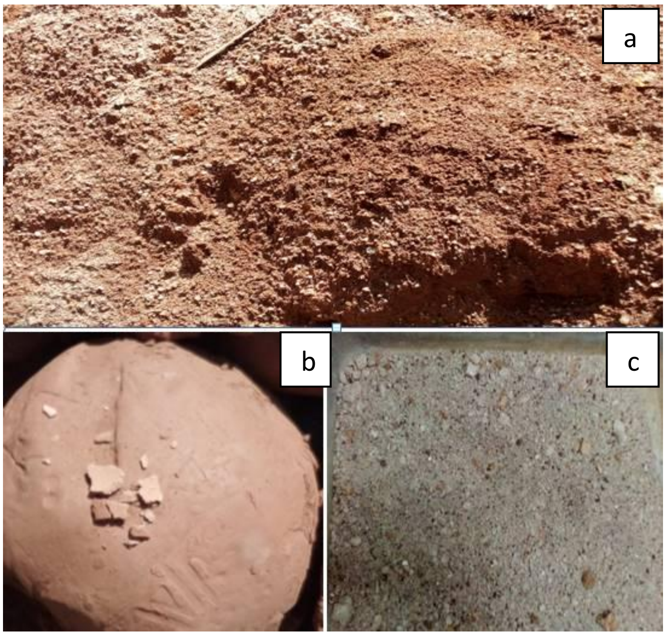


Figure 3-3: Used soil (a), Separated Finer (b) and Gravel (c)

Figure 3-4 shows the sample of clay slurry after 30 minutes sedimentation while Figure 3-5 shows the clay filtering process.

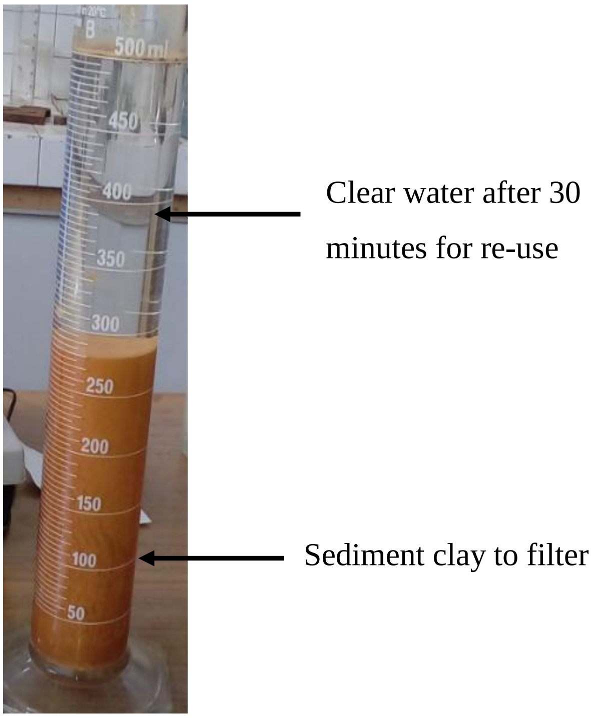


Figure 3-4: Sedimentation of Clay

Figure 3-5: Filtering of Clay for Drying

3.4. Required Materials for CSEB

Soil was the major raw material used for the CSEB production. The geotechnical analysis was done for the soil to analyse the characteristics of the soil. Atterberg limit test and Sieve analysis test were conducted for the soil to identify the plasticity index and particle size distribution. Wet sieve analysis as per ASTM 117 [134] was conducted to identify the silt and clay content accurately. Atterberg test was conducted as per ASTM D4318 [135]. Specific gravity test also was performed to identify the physical property of soil. The wet sieve analysis showed that the soil has 28% of silt and clay. Therefore, to reduce the silt and clay content, soil was washed as explained earlier. The washed soil has approximately 5% slit and clay content.

This soil was checked for particle size distribution and it revealed that modification was needed to get its particle distribution to fit into the optimization curves as described by the particle packing theories. Also, finer content was changed to 5%, 7.5% and 10% by adding the separated silt and clay. Earlier separated larger particles in the range of (2.0-6.0) *mm* and (6.0-12.0) *mm* were also added to get the re-constituted soil particle size distribution as per optimization curves.

As per the objective of the study, cement was used as the stabilizer and 4%. 6%, 8% and 10% of cement quantities were used.

For the next set of the experiments, fly ash was added to the mixer to make the finer content as 5%, 7.5% and 10%. This fly ash was taken from Lakvijaya Thermal Power Plant, Norechcholai, Sri Lanka. Furthermore, fly ash was tested for its specific gravity and particle size distribution.

3.5. Mix Proportion for CSEB

Initially, five soil types designated as S1, S2, S3, S4 and S5 were selected for preliminary testing. The S1 soil is industrially washed soil. The S4 and S5 soils are naturally available lateritic soils. The S2 and S3 soils were derived by washing the

S4 and S5 soils, respectively, to reduce the clay and silt content. These five soil types were first checked for grain size distribution and its relation to the particle packing concept. It is observed that blocks made with S1 soil is having less compressive strength but other properties are desirable. Hence S1 soil was selected to modify the grain size distribution to fit into optimization curves.

The mix for the CSEB was done by the weight batching. According to the finer content in the soil mix, separated finer and gravel particles was added. 4%, 6%, 8% and 10% of cement was used as the stabilizer. For fly ash mixed blocks, fly ash was added to make the finer content as 5%, 7.5% and 10%. At the beginning, the washed soil alone was used for CSEB with above-mentioned stabilizer amounts. Quarry dust was also used with few mixes to see the effect of quarry dust for the properties of CSEB. Table 3-1 shows all the mix proportions used for this study.

Table 3-1: Mix Proportion for Block Casting

<table>
<tr><th>Soil Type</th><th>Original Finer content %</th><th>Finer (%) by adding separated slit and clay</th><th>Finer (%) by adding fly ash</th><th>Cement percentage (%)</th><th>Remarks</th></tr>
<tr><td>S1</td><td>5</td><td>-</td><td>-</td><td>6</td><td rowspan="5">Check the effect of finer % for same stabilizer % (Total 45 blocks)</td></tr>
<tr><td>S2</td><td>19</td><td>-</td><td>-</td><td>6</td></tr>
<tr><td>S3</td><td>23</td><td>-</td><td>-</td><td>6</td></tr>
<tr><td>S4</td><td>33</td><td>-</td><td>-</td><td>6</td></tr>
<tr><td>S5</td><td>40</td><td>-</td><td>-</td><td>6</td></tr>
<tr><td>S1</td><td>5</td><td>5</td><td>-</td><td>4,6,8,10</td><td rowspan="3">S1 grain size distribution was modified to fit into optimization curves by adding separated finer and gravel.
Check for both 0% and 20% quarry dust
(Total 108 blocks)</td></tr>
<tr><td>S1</td><td>5</td><td>7.5</td><td>-</td><td>4,6,8,10</td></tr>
<tr><td>S1</td><td>5</td><td>10</td><td>-</td><td>4,6,8,10</td></tr>
<tr><td>S1</td><td>5</td><td>-</td><td>5</td><td>6,8.10</td><td rowspan="3">S1 grain size distribution was modified to fit into optimization curves by adding fly ash as a finer and gravel.
(Total 81 blocks)</td></tr>
<tr><td>S1</td><td>5</td><td>-</td><td>7.5</td><td>6,8.10</td></tr>
<tr><td>S1</td><td>5</td><td>-</td><td>10</td><td>6,8.10</td></tr>
</table>

3.6. Casting of CSEB

Soil types S1 to S5 were first used to cast CSEB. Out of these soil types, S1 is selected for further testing. This selected S1 soil is mixed with required amount of larger size particles which are separated from the same soil earlier. Then, soil finer or fly ash was added to make the finer particle percentage for 5%, 7.5% and 10%. For each finer content, 4% 6%, 8% and 10% of cement was used as the stabilizer. Figure 3-6 (a), (b) and (c) show the separated finer and gravel parts used to modify the soil grading to fit into the optimization curve. Figure 3-7 (a) and (b) show the mix of all parts and the mixing process.

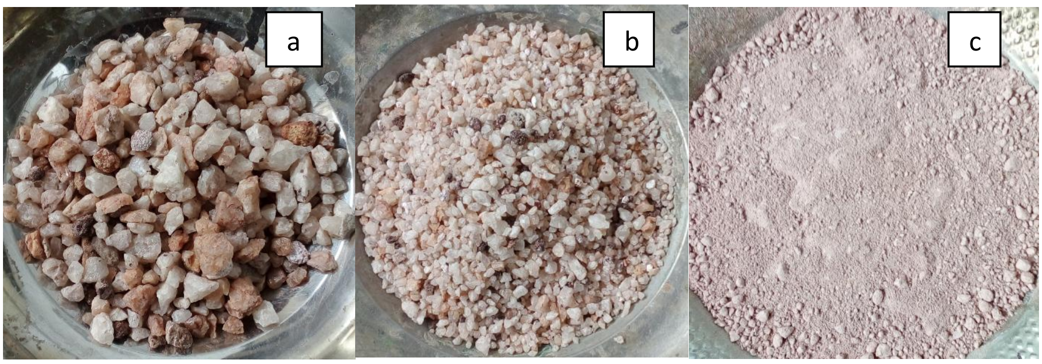


Figure 3-6: (a) Gravel (6-12) *mm* (b) Gravel (2-6) *mm* (c) Separated Fines

Figure 3-7: (a) Mix of Soil, (b) Soil Mixing

Since the mixture of soil has more gravel part and the casting was done using cement sand block making machine, water requirement is comparatively less. For the practical easiness of casting, 8-10% water (from the weight of soil) was sufficient. For one combination 9 blocks were cast resulting total of 234 blocks. 150 *mm* x 150 *mm* x150 *mm* blocks were prepared using the cement sand block making machine. Both the vibration and compaction were applied for block casting. Vibration time was regulated based on the preliminary test conducted. Cast blocks were cured using wet gunny bags and sprinkling water for 7 days and 28 days. Block making using the cement sand block making machine is shown in Figure 3-8.

Figure 3-8: Use of Block Making Machine for CSEB Production

3.7. Tests on CSEB

7 days and 28 days dry compressive strengths and dry density are the main determinants to check the strength requirements of CSEB. 28 days wet compressive strength, water absorption, erosion and shrinkage are the durability related measurements. All these parameters were tested as per SLS 1382 (Part 2) [32]. Compressive strengths of blocks were measured using the Universal Testing Machine. Each soil block was carefully positioned below the center of the upper bearing plate in the testing machine, and the load was gradually increased until failure. The compressive strength could be measured using the load at failure as per Equation 3-1. Reported compressive strength was the average of three specimens. Figure 3-9 shows the testing procedure and cast blocks.

$$\text{Compressive strength} = \frac{Failure\ load}{average\ bed\ face\ area} \qquad \text{---------- Equation 3-1}$$

Figure 3-9: Cast Blocks and Compressive Test Procedure

After keeping the blocks in the oven for more than 24 hours at 105^0C, the dry density of the blocks were determined (Equation 3-2). Each specimen was oven-dried to a constant mass, weighed and measured to determine the dry density.

$$\text{Dry density} = \frac{Dry\ weight}{volume} \qquad \text{---------- Equation 3-2}$$

To determine the water absorption of the blocks, oven-dried test specimens were immersed in water for 24 hours as in Figure 3-10, and the increase in the mass of each oven-dried test specimen was calculated and expressed as a percentage of the specimen's initial dry mass (Equation 3-3).

$$W = \frac{Saturated\ surface\ dry\ mass(g) - Oven\ dry\ mass(g)}{Oven\ dry\ mass(g)} \times 100 \qquad \text{---------- Equation 3-3}$$

Figure 3-10: Immersing of Blocks in Water

The durability tests, accelerated erosion test and shrinkage test were performed. Accelerated erosion test as defined in SLS 1382 [32] gives an idea on the erosion rate of the blocks. Specimen blocks are opened to continuous water spray for an hour. Every 15 minutes, the pitting depth was taken. This erosion test mainly considers the impact of rain on the block surface. Soil block was placed at a distance of 500 mm from the spray nozzle and water was sprayed with 50 kPa pressure. Figure 3-11 illustrates the erosion test apparatus setup.

Figure 3-11: Accelerated Erosion Test Setup

With the same testing, scaled off factor also was calculated. Scaled off factor gives an idea of how much particles are scaled off from the block surface after one hour of water spray. With this scaled off factor, it can be understood as to how the materials erode when rain pours. The scaled off factor is calculated as,

Scaled off factor = scaled off mass/Area of the block surface expose to water spray

The linear expansion of the block on saturation was determined by the difference in the lengths of the dry and saturated blocks. After repeated wetting and drying caused by the natural weathering process, a high value for linear expansion on saturation suggests significant damage to the block and wall surface [136]. The linear expansion was measured referring to both SLS 1382 and SLS 855. These two standards explain more or less similar procedure hence the procedure given in SLS 855 was mainly followed. Drying shrinkage measurement is needed to see the behaviour of wall panels upon drying and to see the shrinkage crack behaviour.

Figure 3-12 shows the apparatus and test procedure for both linear expansion and drying shrinkage. Test specimens were prepared as per SLS 1382 and SLS 855 for required testing. First, specimens were immersed in water for four days and the original wet measurements were taken using the dial gauge as in Figure 3-12. Then the samples were kept in the oven at 50 ^{0} C for minimum 44 hours. Dry measurements were recorded after taking the samples out of the oven and keeping for cooling. This cycle of drying, cooling and measuring was repeated until the constant length was attained. Last measurement was taken as the dry measurement. The lengths of the specimens were calculated after the dry measurement. The difference between the wet and dry measurements, expressed as a percentage of the dry length, was used to determine drying shrinkage.

Same specimens were used for wetting expansion calculation too. After taking the final dry measurement, the specimens were immersed in water for four days and wet measurements were taken using the dial gauge. The wetting expansion is the difference between the last wet and dry measurements expressed as a percentage of dry length.

Figure 3-12: Wetting Expansion and Drying Shrinkage Measurements

3.8. Manufacturing of Industrial Scaled CSEB

After conducting all the laboratory testing, the selected soil composition was used to make industrial scaled blocks (350 x 105 x 165) *mm*. For that, skilled labours were deployed. Figure 3-13 shows a block made through that process.

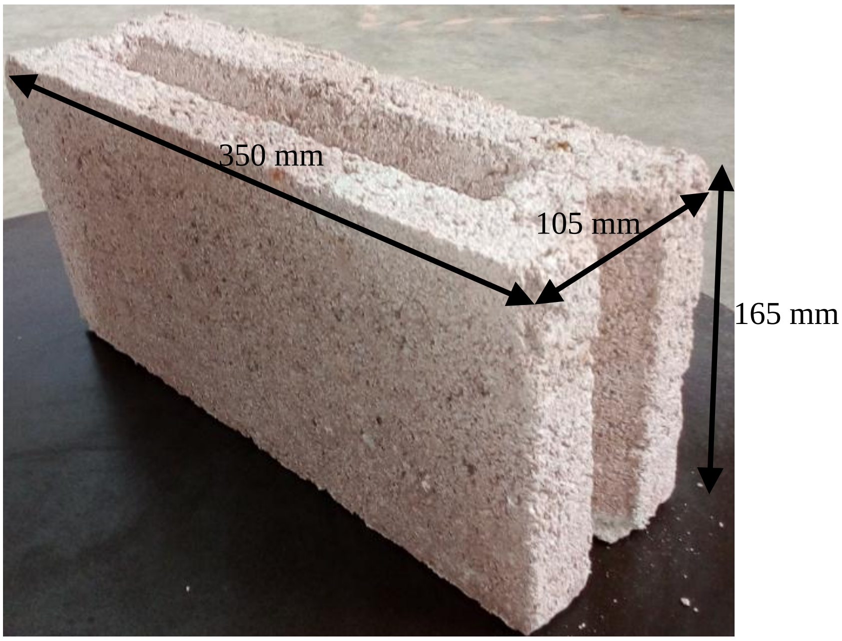


Figure 3-13: Industrial Scaled Block

These blocks were tested using the AMSLER testing machine to get the dry and wet compressive strengths as shown in Figure 3-14.

Figure 3-14: Use of Amsler Testing Machine for Compressive Strength Testing

3.9. Required Materials for Roof Tiles

Clay roof tiles are manufactured with suitable soil having more clay. In Sri Lanka, basically, two types of clay are used as raw materials with sufficient amount of water. ‘Kirimati’ (clay), and ‘Godamati’ (very clayey sand) are the two clay types used by the manufacturers at Wennappuwa / Dankotuwa area. Much stronger and heavier ‘Kirimati’ takes care of the mass and the strength of the tile. Kirimati is usually found at Bangadeniya and Dankotuwa areas while Godamati is available around Pannala. Mixing of Kirimati and Godamati is done at a ratio of 2:3.

For this research study clay was extracted from soil as explained in Section 3.2. Fly ash was added to clay as 25% of the clay weight. This percentage was determined by conducting crack control test and Atterberg Limit test for different mix of clay and fly ash. Chemical analysis, specific gravity and particle size were tested for fly ash hence the class of fly ash was identified.

3.10. Production of Roof Tiles

Clay and 25% of fly ash by weight of clay were mixed first in the dry state. Figure 3-15 shows (a) clay (b) adding fly ash (c) mix of clay and fly ash and (d) after mix with water. Then sufficient water was added to the mix. The mixture should not have any foreign materials such as roots, stones, etc. Clay sample should be mixed with fly ash properly. This mixture was taken to an industrial roof tile manufacturing company. Thereafter, the production of roof tiles followed the same way as industrial roof tiles production. For tiles, the clay mixture is extruded or moulded to obtain the shape required and then to cut the size.

The moulded green tiles are first dried in a normal environment to reduce the moisture content before loading into kilns. Proper firing in kilns helps to produce a good quality product. The firing of tiles was done at a temperature of 900^0C to 1200^0 C in tunnel kiln. Tiles were kept into tunnel kiln for 2 days.

Figure 3-15: Preparation of Clay Mix for Roof Tiles Production

3.11. Tests on Roof Tiles

SLS 2: 1975 defines the relevant testing for roof tiles. The cast tiles were tested to study the structural properties and durability properties. Therefore, the tiles were tested for dry mass, water absorption, transverse breaking strength and water permeability. ASTM international standards were also referred for testing.

For dry mass, the tile specimen was kept in an oven at 110 ^{0}C for minimum 24 hours until two consecutive weights in 2-hour interval become identical or the difference is not greater than 0.2%. Then the dry mass was weighted after keeping the tile specimens in room temperature for 4 hours without exposing it to dust and dirt.

Water absorption determines the durability of the clay roof tile. The roof tile was kept in the oven for 24 hours at the temperature between 105°C and 110°C and weighted (Wd). Then the tile was entirely immersed in water for 24 hours until no air bubble is observed, as shown in Figure 3-16. Consequently, the excess water was removed from the tile and weighted (Ww). Equation 3-4 was used to calculate the amount of water absorbed (Wa). The procedure was repeated for the other tiles and the average value was taken.

Percentage of Water Absorption (Wa) = $\frac{Ww - Wd}{Wd}100\%$ ---------- Equation 3-4

Where:

Ww =weight of the specimen after 24 hours immersion in clean water

Wd = weight of the dry specimen.

Figure 3-16: Tiles Immersed in Water

To determine the transverse breaking load, the clay roof tile was tested in three-point bending mode in which two lower support members were used to rest the bottom of the tile and the third member moving perpendicular to the plane and the mid-span of the tile to apply the load to the upper surface of the roof tile. The tile was tested in a horizontal plane.

This test was done by 3-point bending moment test apparatus (AS 2049). Both wet tiles and dry tiles were tested to measure the wet tile strength and dry tile strength. Figure 3-17 shows the testing process.

Figure 3-17: Transverse Strength Testing of Tiles

3.12. Required Materials for Bricks

In the modern construction industry, different types of bricks are in use. Those are; burnt clay bricks, sand-lime bricks, concrete bricks, fly ash bricks, etc. These names are given based on the materials used and the method of manufacturing. Out of that the usage of burnt clay bricks is very common. This is a very old building material.

Usually, bricks are made of clayey soil. This study used the extracted soil mixed with fly ash. As explained with roof tile production, clay mixed with 25% of fly ash gave the lowest linear shrinkage. For other fly ash addition also, linear shrinkage was not significantly large. Therefore, it was decided to cast bricks with varying fly ash percentages from 20% to 50% in 5% steps. Microscopic structure of clay and fly ash mixes were also analysed using Scanning Electron Microscope (SEM) test. Clay and fly ash were first mixed in the dry stage and sufficient water was added and mixed properly. The clay-fly ash mix was kept for few days before brick-making.

3.13. Production of Bricks

For the testing purpose, metal moulds were used as in Figure 3-18 (a). The size of a mould is (100 x 50 x 50) *mm*. Figure 3-18 (b) shows the bricks just after preparation. Figure 3-18 (c) shows the bricks after removing moulds after sufficient drying.

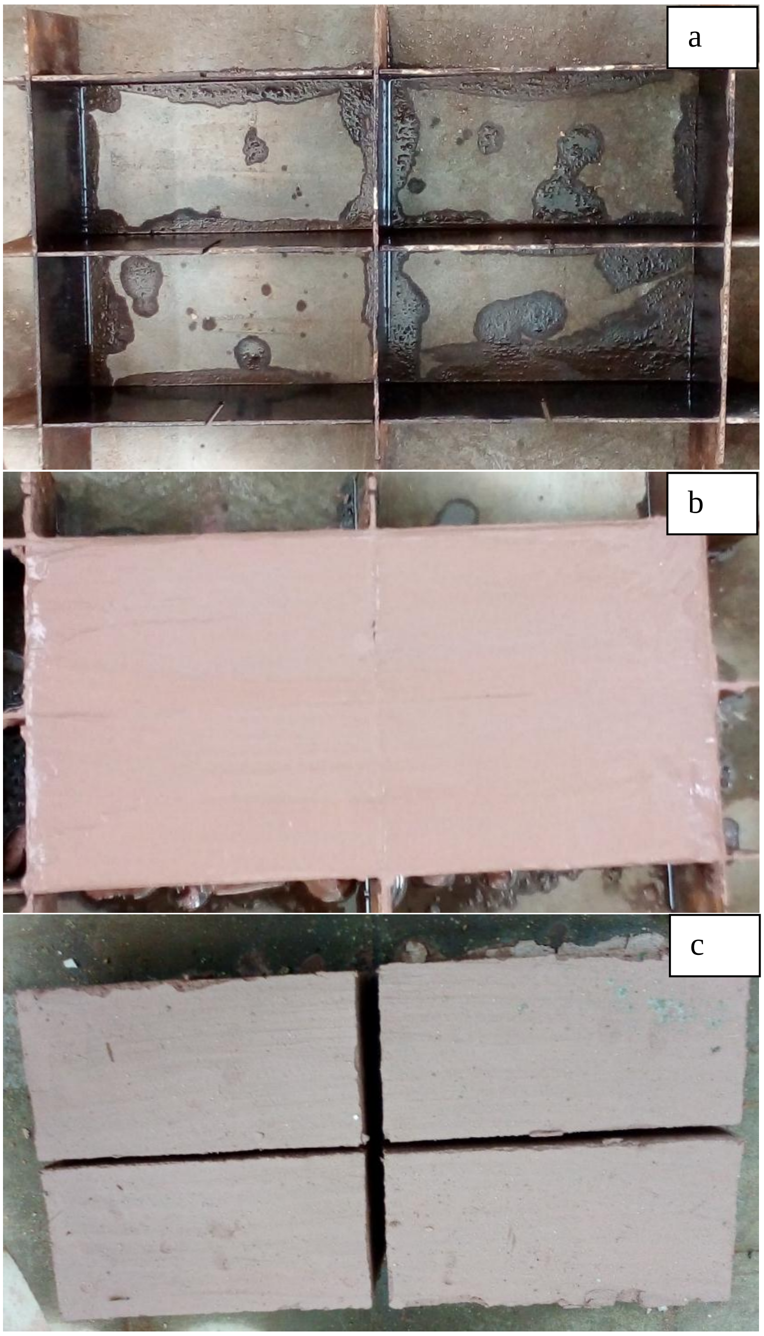


Figure 3-18: Clay Brick Making Process

The above mould was used for the easiness of making a considerable number of bricks. But the process was done using the standard type mould used for handmade bricks with the size (220 x 115 x 75) *mm*. The used mould dimensions are slightly larger than the standard brick size. This tolerance was kept to allow for the shrinkage. Figure 3-19 shows the mould while Figure 3-20 shows prepared bricks. The practical difficulty with this process is removing the mould. For that, mould oil was used for the easiness of removing the mould. It is evident that the wire-cut brick making machine would be easily used for brick making with this clay variety.

Figure 3-19: Wooden Mould for Brick Making

Figure 3-20: Prepared Bricks with Wooden Mould

Bricks were kept for drying without direct sunlight. After drying sufficiently, bricks were kept in the furnace for firing as in Figure 3-21. Bricks were fired for about eight hours with 1000^0C. After cooling, bricks were taken out. Final products are as in Figure 3-22.

Figure 3-21: Burning of Bricks in the Furnace

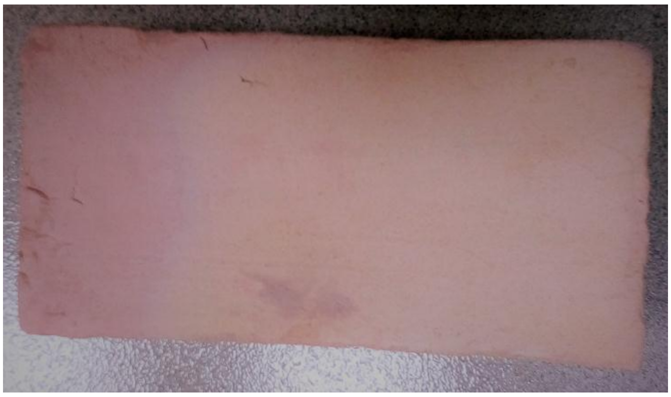


Figure 3-22: Burnt Brick

After firing and testing the bricks made with different fly ash addition, it was identified that the 25 % fly ash addition gave the optimum properties for bricks. Therefore, wire-cut bricks were made with extracted clay with 25% fly ash addition. Figure 3-23 shows prepared wire-cut bricks.

Figure 3-23: Wire-cut bricks with fly ash

3.14. Tests on Bricks

Bricks were tested mainly for strength properties and durability properties. Figure 3-24 shows the summary of tests conducted on bricks. Tests were performed as per the guidelines given in SLS, IS, ASTM standards and past researches.

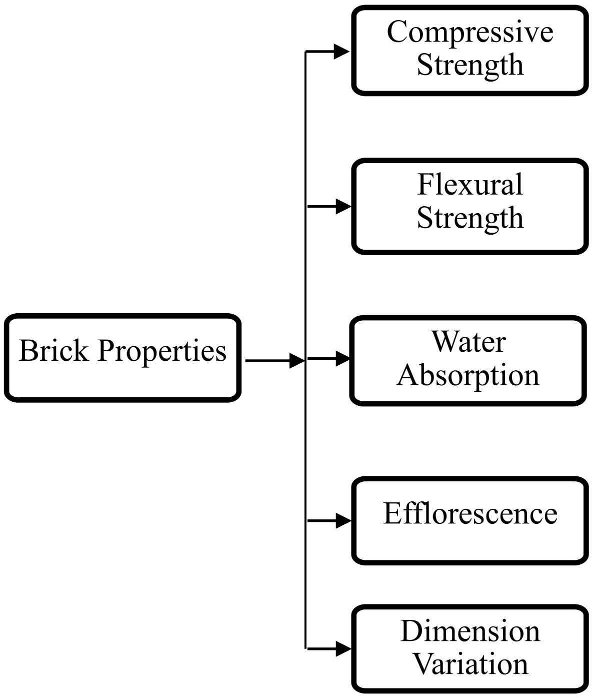


Figure 3-24: Summary of Tests for Clay Bricks

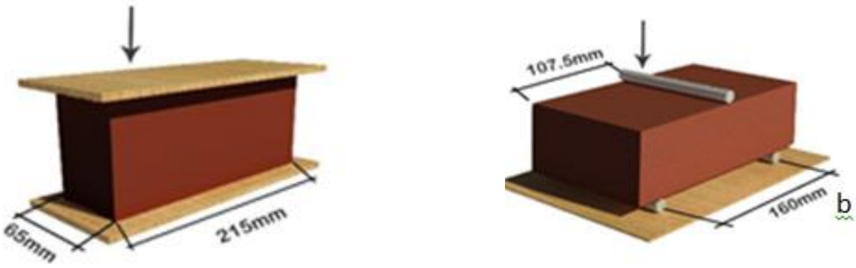
The compressive strength of bricks was determined as per SLS 39. First, bricks were filled flush with 1 cement: 1 clean sand to obtain a smooth flat surface (Figure 3-25). Then the brick was placed into the compression testing machine and compressive force was applied until the brick fails (Figure 3-26). For each mix proportion, three brick specimens were tested. The compressive strength was determined as in Equation 3-5. The average compressive strength was calculated and presented as the compressive strength of the bricks. For wire-cut bricks capping on the bricks was not necessary since their surfaces are nearly flat.

Figure 3-25: Preparation of Bricks for Compressive Test

Figure 3-26: Testing of Bricks for Compression Strength

Flexural bending test was conducted for bricks as per ASTM C 90-11a and strength was calculated as in Equations 3-6. Testing of bricks for flexural strength is shown in Figure 3-27**.** Schematic diagram in Figure 3-28 shows compressive and flexural tests procedure.

Figure 3-27: Testing of Bricks for Flexural Strength



(a) Compression Test (b) Flexural Test

Figure 3-28: Schematic Diagram for the Testing of Strength Properties of bricks

$$\boldsymbol{Compressive\ Strength} = {}^{\boldsymbol{P}}/_{\boldsymbol{A}}$$ ----------- Equation 3-5

$$\boldsymbol{Flectural\ Strength} = \mathbf{1.5}\boldsymbol{Pl}/(\boldsymbol{bd}^{\mathbf{2}})$$ ----------- Equation 3-6

Where P= ultimate applied load

A = the area of the bearing surface

l = span length

b = width of the brick at the mid-span section

d = depth of the brick at the mid-span section

For each test, three samples from each mix proportion were tested and the average value was computed.

Water absorption of bricks was also measured as the procedure explained in SLS 39. Oven-dried brick specimen at the temperature of 105°C - 110°C for 24 hours was weighted (W_d). Then the wet mass (W_w) was taken after immersing dried specimen in the water for 24 hours of time duration. The amount of water absorbed, with respect to the dry mass of the brick was calculated by using Equation 3-7. The above procedure was repeated for bricks with each mix proportions of clay and fly ash.

$$\boldsymbol{Wa}\ (\boldsymbol{Water\ absorption}) = \frac{\boldsymbol{Ww - Wd}}{\boldsymbol{Wd}} \boldsymbol{x100}\% \qquad \text{---------- Equation 3-7}$$

The appearance of salt crystals on the surface of burnt clay bricks is known as efflorescence. Efflorescence refers to the occurrence of sub fluorescence in the microstructure of a burnt clay brick, which has an effect on its resilience and serviceability. Since clay changes volume and porosity as it dries, it is important to do it in stages. As a result of the soluble salts present, these unregulated conditions can cause deformation on bricks, cracks, and/or efflorescence.

SLS 39 standard was followed up for the test of efflorescence in different brick samples. When there is water in the brick, it takes on a white or greyish color, which is made up of salt deposits that are left behind when the water evaporates. Additionally, efflorescence can appear on vertical walls as a powdery material. Figure 3-29 (a) shows the bricks which are ready for efflorescence test and 3-29 (b) shows bricks after completing the testing.

(a): Ready for Testing (b): Testing Completed

Figure 3-29: Testing of Efflorescence of Bricks

The ends of the brick were kept in a shallow flat-bottom dish having an area of approximately 0.10 m^2 containing 25 mm depth at room temperature (20°–30°C). After 7 days, most of the water was absorbed or evaporated. The specimen was then dried in an oven for 24 hours and compared by observing the top as well as all four faces of each specimen. Presence of efflorescence, which is non-quantitative, was classified as follows according to SLS 39.

1. Nil — when the deposit of efflorescence is imperceptible.
2. Slight — when the deposit of efflorescence does not cover more than 10 per cent of the exposed area of the brick.
3. Moderate — when the deposit of efflorescence is more than 10 per cent but less than 50% of the exposed area of the brick.
4. Heavy — when the deposit of efflorescence is more than 50 per cent but the deposits do not powder or flake away the brick surface.
5. Serious — when the deposits are heavy and powder or flake away the brick surface.

3.15. Summary

The chapter discussed the methodology adopted to reach the study objectives. All the test methods were clearly explained referring to the related specifications. Based on these test methods, the next chapter will explain the results with necessary discussions.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1. General Introduction

The previous chapter discussed the methods and materials used for the study. It explained the properties of all the materials and testing methods specifying the related specifications. Also, it emphasized on required properties of final products, namely CSEB, burnt-bricks and roof tiles explaining the test methods. This chapter focuses on the results obtained based on test methods applied. Further it describes the appropriateness of the results referring to the related standards.

4.2. Soil Washing Procedure

Soil washing was done with two purposes. The first one was to reduce the finer content from any soil with high clay and silt content. Soil with reduced clay and silt could be used to produce CSEB. The second purpose was to see the feasibility of using separated finer as a raw material for roof tiles and burnt-bricks production. Soil washing was done using an industrially available concrete mixer. Also, rotation time of the machine for washing and number of rotations were the main parameters which contribute to reducing the clay and silt content. An accelerated sedimentation process was also a key concern when using clay and silt for the production of bricks and tiles. Alum and polymer are the industrially used coagulant agents; hence both were used here to check the sedimentation. For this, Jar test was performed as shown in Figure 4-1.

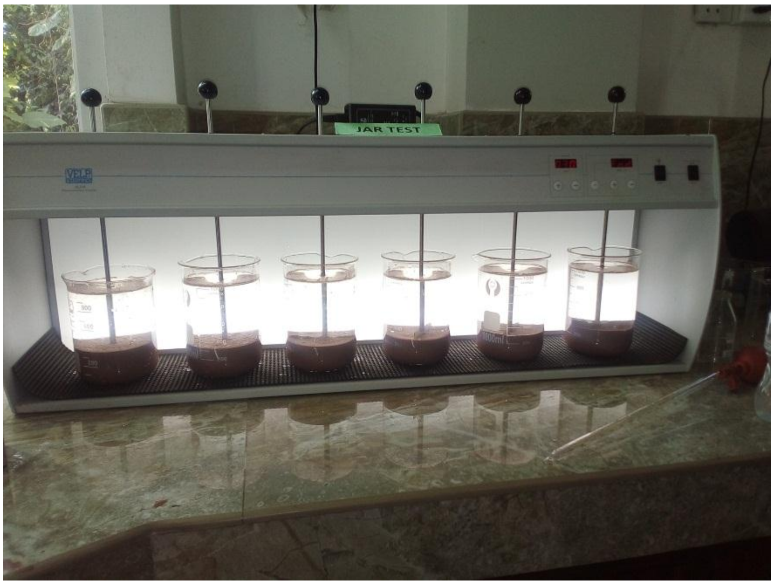


Figure 4-1: Jar Test Procedure

For sedimentation process, alum, polymer and a combination of alum & polymer were used. Table 4-1 shows the turbidity level of the water with those coagulants. The results show that 8 ppm alum and 5 ppm polymer combination give the lower turbidity level. When alum alone was used, 12 ppm of alum gives the lowest turbidity. There is no significant difference between turbidity with these two coagulants. Considering the cost, it was decided to use only alum for this soil washing process since polymer cost is high compared to that of alum.

Table 4-1: Turbidity Level with Alum and Polymer

8 ppm Alum constant						
Polymer (ppm)	2	3	4	5	6	7
Turbidity	9.4	6.89	3.75	2.65	5.1	8.5

5 ppm Polymer Constant						
Alum (ppm)	2	4	6	8	10	12
Turbidity	4.46	4.11	3.65	2.65	5.25	7.52

Alum only						
Alum (ppm)	6	8	10	12	14	16
Turbidity	4.67	3.1	2.83	2.58	2.97	4.01

Water reusable time was also determined by conducting the Jar test with the selected 12 ppm alum concentration. Turbidly level of water was checked every 5 minutes until it became almost constant. Table 4-2 gives experimental results for this purpose. These results show that after 30 minutes, water could be re-used. Then the amount of reusable water content was checked with a field experiment. Separated clay slurry was kept into a 20*l* barrel and after 30 minutes, the water level was checked. It was revealed that about 60% of water can be reused in this situation.

Table 4-2: Change of Turbidity with Time

12 ppm Alum						
Time	5	10	15	20	25	30
Turbidity	10	9.75	6.95	6.23	6.24	6.23

Soil washing time also was one variable to be decided. For that with the actual setup, soil samples were washed by changing the washing time from 0.5 minutes to 4 minutes for 5 numbers of washing. For every washing process, five cycles of washing were done by keeping the time constant and for each washing, sedimentation amount was checked after 30 minutes. Table 4-3 gives the sedimentation amount measured as clay column height in mm after 30 minutes for different washing time and with number of washing cycles while Figure 4-2 shows its graphical representation.

Table 4-3: Change of Sedimentation with Time and Number of Washing

		Clay column height (mm) after 30 mm)					Cumulative clay column height (mm)
Number of washing		**1**	**2**	**3**	**4**	**5**	
Time for one washing (min)	0.5	610	420	200	140	110	1480
	1	630	440	230	160	110	1570
	2	690	480	190	70	50	1480
	3	730	410	70	60	40	1310
	4	780	320	50	40	40	1230

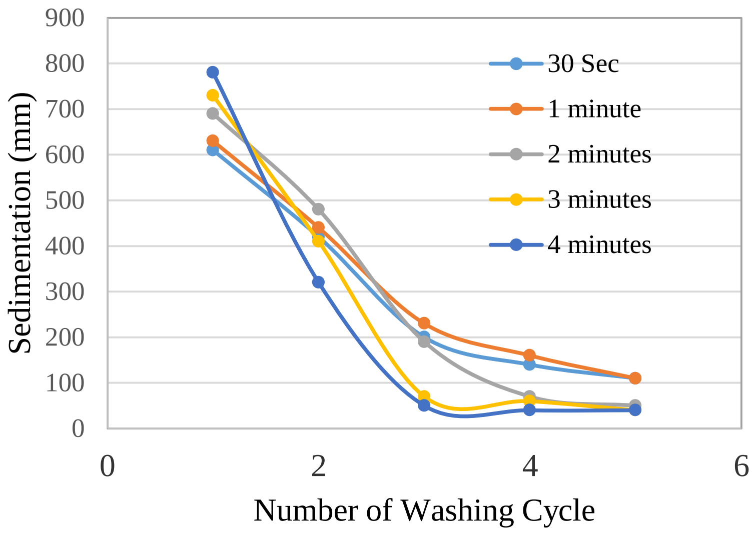


Figure 4-2: Change of Sedimentation with Time and Number of Washing Cycle

These results show that one-minute washing with five washing cycles gave the maximum sedimentation. However, with 4th and 5th washing, sedimentation amount was very small. That means the amount of finer content in the soil was very low after third washing. In this experiment, finer content in the gravel part was also important. It was necessary to keep at least 5% finer in the washed soil. Therefore, further analysis was done considering finer content in the gravel part too. To get a clear idea on this, cumulative sedimentation was analysed for different timing and washing. Table 4-4 shows the cumulative sedimentation for consecutive washings. According to the results, it can be seen that one-minute washing with five washing cycles gave the maximum yield. If only a single wash was considered, it is noted that sedimentation increases with washing time. When considering up to two cycles of washing, two minutes washing gives the maximum yield. For two and three cycles of washing, for both one minute and two minutes washing time, fairly equal amount of sedimentation can be seen. Therefore, considering the total time for washing, it was decided to continue the washing with one-minute washing time per wash. This should be cross-checked with the amount of finer in the washed soil after these washing. Then the exact conclusion could be reached to.

Table 4-4: Cumulative Sedimentation for Different Washing Time and Number of Washing

	Clay column height (mm)				
Time per wash (Minutes)	**1st wash**	**(1+2) wash**	**(1+2+3) wash**	**(1+2+3+4) wash**	**(1+2+3+4+5) wash**
0.5	610	1030	1230	1370	1480
1	630	1070	1300	1460	1570
2	690	1170	1360	1430	1480
3	730	1140	1210	1270	1310
4	780	1100	1150	1190	1230

Figure 4-3 shows clay sedimentation for five consecutive washing cycles. It is very explicit that with the number of washing, the sedimentation amount gets reduced. To decide on how many washing cycles are necessary to get the optimum yield of finer, as well as keeping the required finer content in the gravel part, the gravel part also was checked for finer percentage. Figure 4-4 shows gravel part of soil for three consecutive washing (a), (b) and (c). Then the finer content of these three samples was checked by performing the wet sieve analysis as per ASTM 117C. Table 4-5 shows the finer content of these three gravel parts.

Figure 4-3: Amount of Sedimentation after 30 Minutes for Different Washing

Figure 4-4: Gravel Part of Soil after Three Consecutive Washings

Table 4-5: Finer Content of Soil with Consecutive Washing

Soil Condition	**Finer content in the soil (%)**
Original Soil	28.20
After 1st wash (a)	13.76
After 2nd wash (b)	4.16
After 3rd wash (c)	1.34

Considering all these results it was decided to go for maximum 2 cycles of washing with one-minute washing to get the optimum yield. With this, finer percentage in the washed soil is near to 5%, but separated clay can be again added to the soil as necessary for CSEB production.

4.3. Properties of Materials

The main raw material for this research was soil with high clay and silt (finer). Initially, five soil types were tested for their physical properties. Table 4-6 shows the Atterberg limits and specific gravities of soils, while Table 4-7 shows the particle size distribution of soils. As explained in section 3.4. , S1 soil is industrially washed soil. The S4 and S5 soils are naturally available lateritic soils. The S2 and S3 soils were derived by washing the S4 and S5 soils, respectively, to reduce the finer content.

Table 4-6: Atterberg limits and Specific Gravity of Soils

Soil Type	Plastic limit	Liquid limit	Plasticity Index	Specific Gravity
S1	-	-	-	2.7
S2	32.45	23.09	9.36	2.9
S3	-	-	-	3.3
S4	45.25	29.55	17.2	2.3
S5	39.21	34.8	4.41	2.2

Table 4-7: Particle Size Distribution of Soils

Soil Type	0-0.075	0.075-2.0	2.0-6.0	6.0-12.0
S1	5	82	9	3
S2	19	28	20	33
S3	23	24	23	30
S4	40	30	10	25
S5	35	25	15	25

Soil blocks were stabilized with Portland cement. Fly ash was also used to mix with soil as a finer replacement.

4.4. Applicability of Particle Packing Concept

Grain size distributions of selected five soil types (S1 to S5) were explained in section 4.3. These gradings were compared with the theoretical packing concepts explained in section 2.11. Graphical representations of these grading and the theoretical concepts are shown in Figure 4-5. Considering the above represented soil types and optimization curves, the particle size distribution of soil types S2 and S3 are closer to the optimization curves. But their finer content is comparatively high (19% and 23% respectively).

It was necessary to select one suitable soil type out of these five (S1 to S5) or another type for further experiments. Therefore, selected five soil types were used for CSEB production with constant cement (6% used) content as the stabilizer. Table 4-8 gives the tested properties for cast CSEB. It shows that the blocks made with soil types, S2 and S3 have comparatively high dry and wet compressive strength among the selected soil types. However, other properties of blocks didn't have the highest values but were within the acceptable range. Blocks made with S1 soil type has a higher density and lower water absorption but low strength. Also, compared with the theoretical concepts, finer content should be less to have maximum packing. Among these soils, S1 has the lowest finer content. These results show that, when soil grading is near to the optimization curves as explained in theories, it can achieve comparatively a high performance in CSEB properties. The problem with S2 and S3 soils is the high amount of finer content. Therefore, it was decided to select S1 (with the lowest finer) soil for further testing by modifying its particle size distribution to fit into optimization curves. Even though there are four major theoretical concepts explained, for the experimental studies, mainly the power line was considered since its linear relationship makes the changing of grading distribution easier.

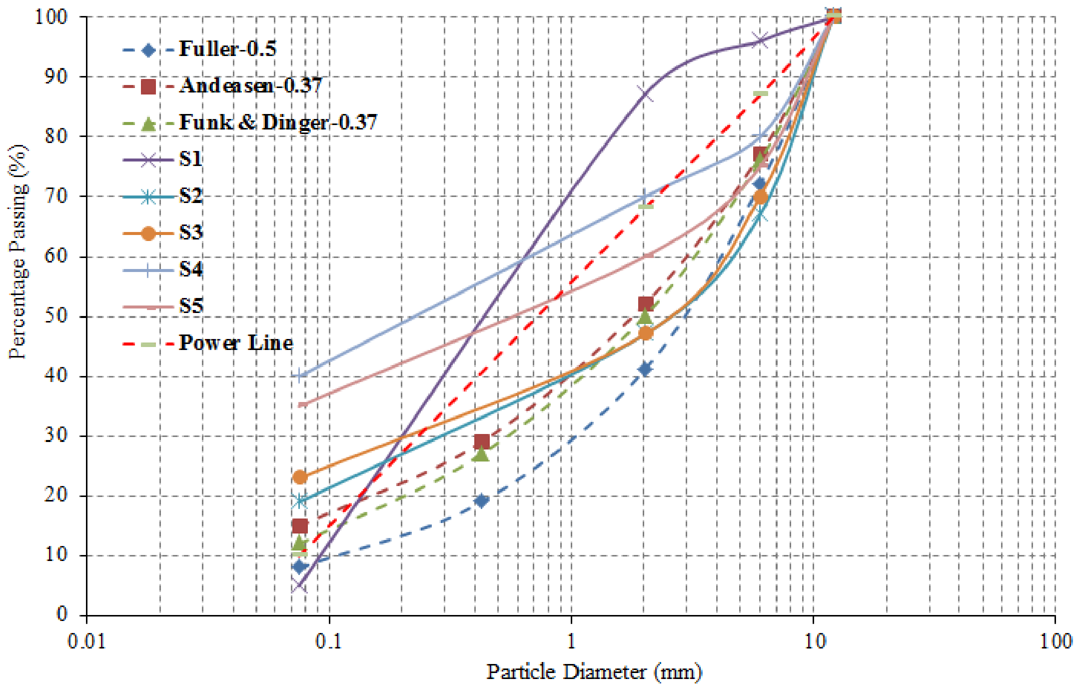


Figure 4-5: Comparison of Particle Distribution of Used soil with Theoretical Distribution

Table 4-8: Blocks Properties with Different Soil Gradings

Soil Type	Finer %	28 days Dry Com. Strength (MPa)	28 days Wet Com. Strength (MPa)	Dry Density (kg/m3)	Water Absorption (%)
S1	5	1.06	0.55	1956	9.5
S2	19	3.01	1.55	1854	12.9
S3	23	2.95	0.82	1778	19
S4	33	1.98	0.69	1713	18.5
S5	40	0.99	0.25	1481	31

4.5. Performance of CSEB with Reduced Clay and Silt

S1 soil was first used without any modification with varying cement content as the stabilizer. 20% of Quarry dust also was used to see any effect of it. Table 4-9 indicates the properties of CSEB with this condition. Figure 4-6 graphically represents the compressive strength behaviour of CSEB.

Table 4-9: Properties of CSEB with Varying Cement Content for S1 Soil

Cement %	7 days dry Com. Strength (MPa)	28 days dry Com. Strength (MPa)	28 days wet Com. Strength (MPa)	Dry Density (kg/m^3)	Water Absorption (%)
4	0.56	0.71	0.47	1820	10.0
6	0.85	1.06	0.55	1956	9.5
8	1.95	2.26	1.27	1956	10.2
10	3.96	4.49	3.42	1940	8.75

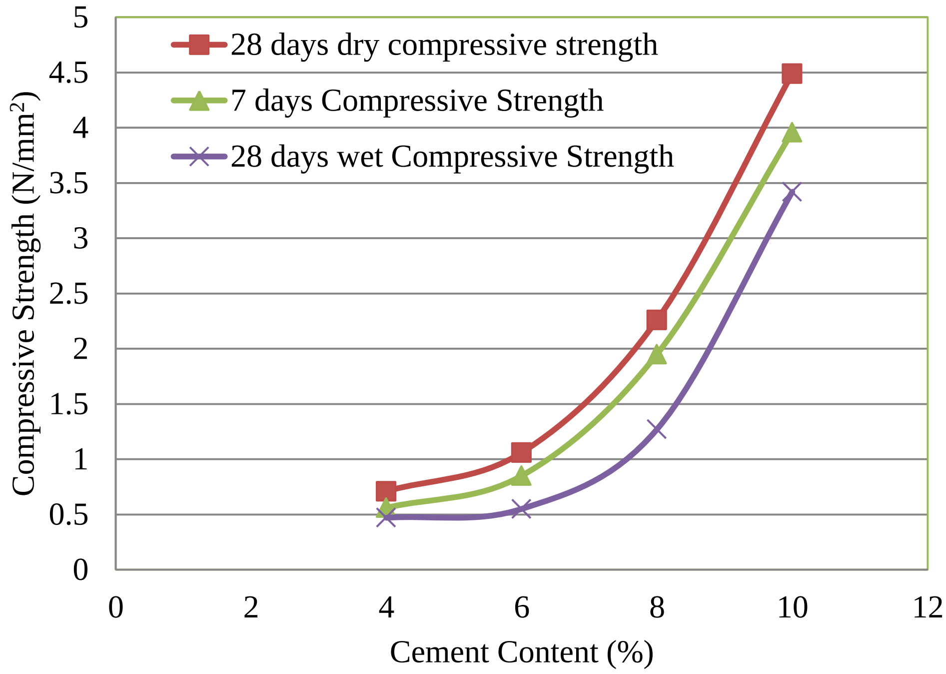


Figure 4-6: Compressive Strength Behaviour of CSEB with Varying Cement Content for S1 Soil

These results indicate that maximum 28 days dry compressive strength (4.49 N/mm^2) was achieved with 10% cement and it is in the category of Grade 2 CSEB as per SLS 1382 requirements [32]. Maximum wet compressive strength is 3.42 N/mm^2 and it is under Grade 1. Dry density and water absorption values also satisfy the SLS 1382 requirements. Compressive strengths with other lower cement contents are comparatively low.

4.5.1. Dry Compressive Strength of CSEB with Reduced Clay and Silt

Since the particle size distribution of S1 soil does not give high compressive strength, particle size distribution was modified by adding separated finer and other larger particles arising from the soil washing phase. Numerical calculation done to find the addition of finer and other particles, are explained below. Table 4-10 gives required soil grading and the available soil (S1) grading. Since the particles in the range of 0.075-2.0 mm was high, this modification could be done by adding particles in the other ranges. In this S1 soil, particle amount in the range of (0.075 – 2.0) *mm* is more than the required amount. Hence, except this range, particle amount of other three ranges were modified. Then, the remaining one will be automatically changed.

Table 4-10: Particle Size Distribution of S1 soil and Required Optimization Curve

Grading of	**0-075 *mm***	**0.075-2.0 *mm***	**2.0-6.0 mm**	**6.0-12.0 *mm***
Available (S1 soil)	5%	82%	9%	4%
Required (to fit into optimization curve)	5%	60%	20%	15%

Assume;

x= addition of finer content (0-0.075) *mm*

y= addition of amount of particle in the range of (2.0-6.0) *mm*

z= addition of amount of particle in the range of (6.0-12.0) *mm*

The calculation was done based on 10*kg* of S1 soil.

Amount of particle within 10 *kg* in different ranges for S1 soil and modified soil are as per Table 4-11. Then, considering the required percentages, Equations 4-1, 4-2 and 4-3 can be written. After solving these three equations simultaneously, the particle amount to be added could be found.

Table 4-11: Amount of Particles of S1 Soil and Modified S1 Soil per 10 *kg*

Grading of	**0-075 *mm***	**0.075-2.0 *mm***	**2.0-6.0 mm**	**6.0-12.0 *mm***
S1 Soil	500*g*	8500*g*	600*g*	400*g*
Modified Soil	500*g*	6000*g*	2000*g*	1500*g*

$$\frac{(500+x)}{(10000+x+y+z)}=0.05$$ ---------- Equation 4-1

$$\frac{(900+y)}{(10000+x+y+z)}=0.2$$ ---------- Equation 4-2

$$\frac{(400+z)}{(10000+x+y+z)}=0.15$$ ---------- Equation 4-3

By solving Equations 4-1, 4-2 and 4-3

x= 183.33g

y= 1833.0g

z= 1649.0g

Similar calculations were done for 7.5% and 10% finer content.

Figure 4-7 shows the particle size distribution for the modified soil and its comparison with optimization curves.

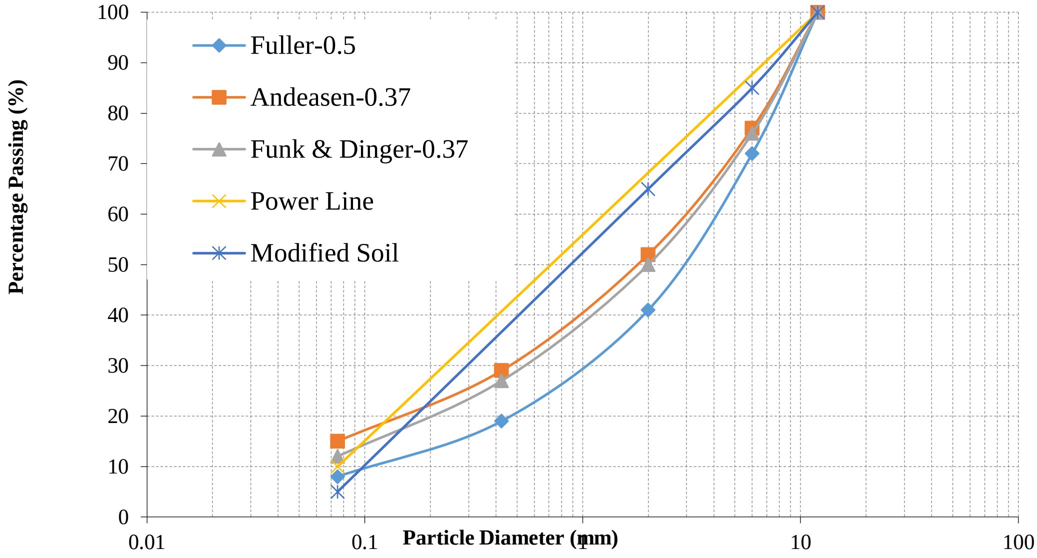


Figure 4-7: Particle Size Distribution of the Modified Soil in Comparison to Particle Packing Models

This modification was done for three different finer contents 5%, 7.5% and 10%. For each finer content, 4%, 6%, 8% and 10% cement stabilizations were used. 5% finer contained soil was used with 0% and 20% quarry dust for blocks production. With this, there were five different combinations of CSEB. Figure 4-8 shows 7 days dry compressive strength, while Figure 4-9 shows the 28 days dry compressive strength in comparison to the SLS 1382 Part I requirements.

Also, the relationship between the 7 days and 28 days compressive strength were checked for all the combinations. Table 4-12 gives that comparison. According to these results, it is clear that 4% cement usage as the stabilizer does not lead to considerable strength improvement after 7 days compared to other cement percentages. Also, with 10% cement, highest 7 days compressive strengths could be achieved.

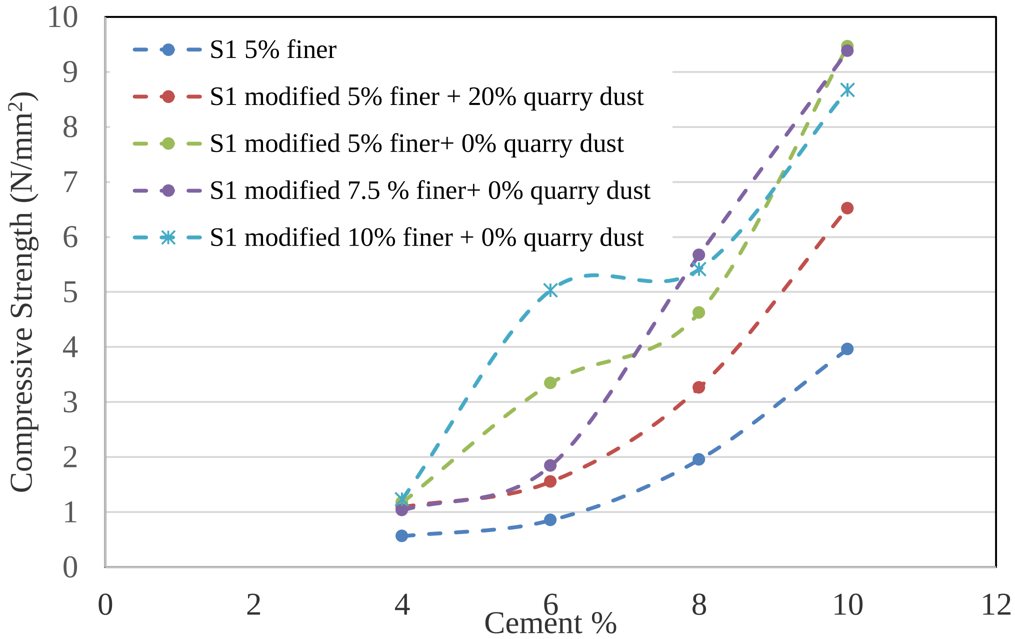


Figure 4-8: 7 days Dry Compressive Strengths of CSEB with Modified Soil

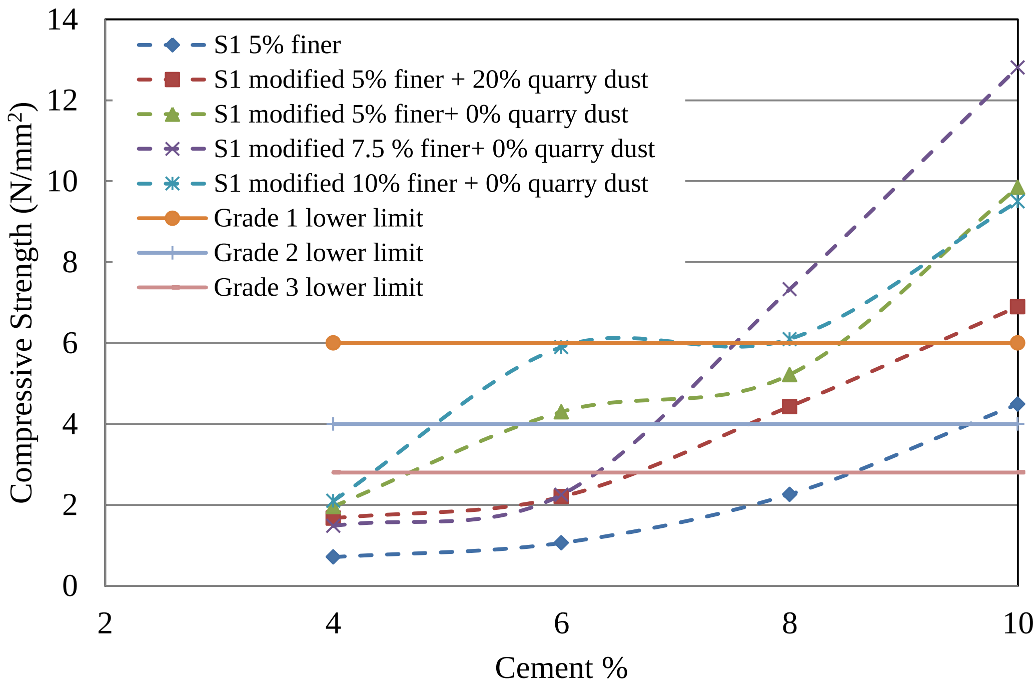


Figure 4-9: 28 days Dry Compressive Strengths of CSEB with Modified Soil

Table 4-12: Relationship between 7 days and 28 days Compressive Strengths (%)

Cement %	**S1 original 5% finer**	**S1 modified 5% finer + 20% quarry dust**	**S1 modified 5% finer+ 0% quarry dust**	**S1 modified 7.5 % finer+ 0% quarry dust**	**S1 modified 10 % finer+ 0% quarry dust**
4	79	65	60	70	59
6	80	70	78	82	85
8	86	74	89	77	76
10	88	94	96	73	91

According to the strength results shown in Figure 4-9, a higher compressive strength for all the finer content could be achieved with 10% cement stabilization. Use of quarry dust for the mixture did not have a significant influence for strength improvement compared to a mixture with no quarry dust. Also, it is clear that 4% cement content could not stabilize the blocks to achieve any of the Grades defined in SLS 1382. Therefore, for other testing, 4% stabilization was omitted. To get a more clear idea on strength values, Table 4-13 represents 28 days compressive strength values of blocks with comparison to the specified compressive strength values in SLS 1382.

Since these blocks were with very low silt and clay content, they were more likely to behave as cement blocks. By refereeing to SLS 855: Specifications for Cement blocks [137], the tested strength values can be compared with the strength requirements for cement blocks. All the blocks are suitable for single storey house construction (Minimum requirement is 1.2 N/mm^2) for all the mortar designation. Blocks with 7.5% finer with 8% cement stabilization are suitable up to five-storey buildings (Minimum requirement is 7.2 N/mm^2). For all the finer contents with 6% cement stabilization, blocks are suitable up to four-storey buildings.

Table 4-13: 28 days Dry Compressive Strengths Comparison with SLS 1382

	28-day Compressive Strength (N/mm^2)				
Cement %	**S1 original 5% finer**	**S1 modified 5% finer + 20% quarry dust**	**S1 modified 5% finer+ 0% quarry dust**	**S1 modified 7.5 % finer+ 0% quarry dust**	**S1 modified 10 % finer+ 0% quarry dust**
4	0.71	1.67	1.96	1.48	2.1
6	1.06	2.2	4.3	2.25	5.9
8	2.26	4.43	5.22	7.33	6.1
10	4.49	6.9	9.85	12.81	9.5

SLS 1382 Requirements	
Grade 1	>6
Grade 2	4.0 to 6.0
Grade 3	2.8 to 4.0

4.5.2. Wet Compressive Strength of CSEB with Reduced Clay and Silt

Wet compressive strength is usually used as a durability requirement measurement parameter. SLS 1382 defines the wet compressive strength values for different grades of blocks. Figure 4-10 represents the variation of wet compressive strengths with the cement content while Table 4-14 gives their numerical values to easily compare with the standard values.

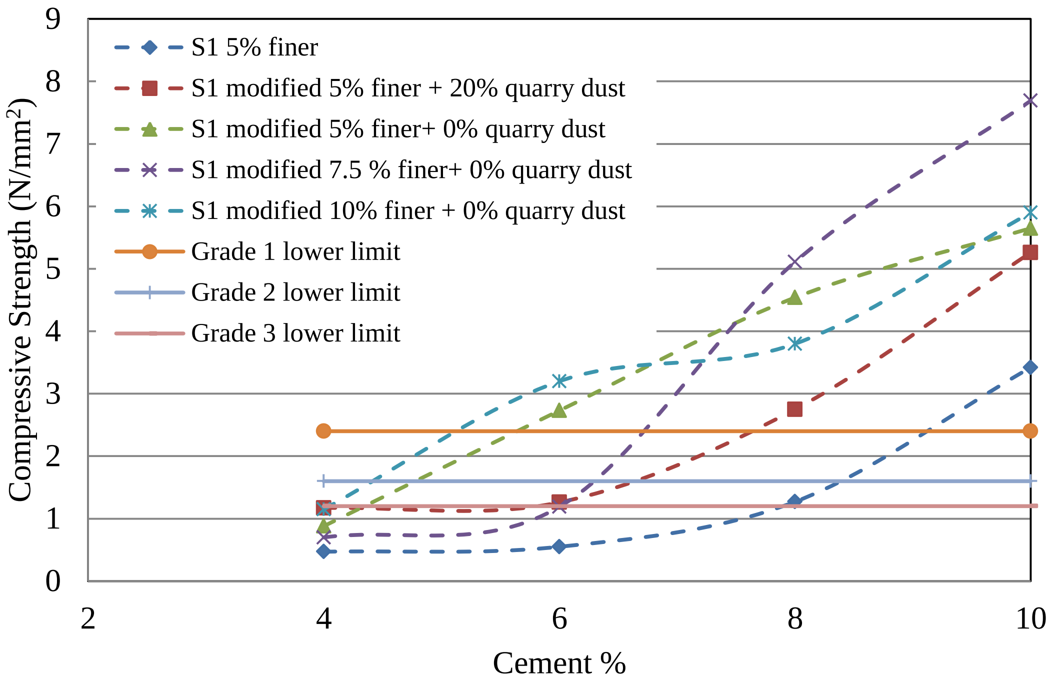


Figure 4-10: 28-day Wet Compressive Strengths of CSEB with Modified Soil

Table 4-14: -28 days Wet Compressive Strengths Comparison with SLS 1382

Cement %	28 days Compressive Strength (N/mm^2)				
	S1 original 5% finer	**S1 modified 5% finer + 20% quarry dust**	**S1 modified 5% finer+ 0% quarry dust**	**S1 modified 7.5 % finer+ 0% quarry dust**	**S1 modified 10 % finer+ 0% quarry dust**
4	0.47	1.17	0.88	0.7	1.15
6	0.55	1.26	2.73	1.20	3.2
8	1.27	2.75	4.54	5.11	3.8
10	3.42	5.26	5.65	7.69	5.9

SLS 1382 Requirements	
Grade 1	>2.4
Grade 2	1.6 to 2.4
Grade 3	1.2 to 1.6

According to the results, it could be seen that the 4% of cement usage did not give a guarantee to achieve the required strength as in SLS 1382. Use of 7.5% finer led to high wet compressive strength with 8% and 10% cement stabilization. The ratio of Wet/Dry compressive strength is also an indication of durability. For CSEB this ratio should be more than 0.4. Table 4-15 indicates those ratios.

Table 4-15: Wet/Dry Compressive Strength Ratio

Cement %	**S1 original 5% finer**	**S1 modified 5% finer + 20% quarry dust**	**S1 modified 5% finer+ 0% quarry dust**	**S1 modified 7.5 % finer+ 0% quarry dust**	**S1 modified 10 % finer+ 0% quarry dust**
4	0.66	0.70	0.45	0.47	0.55
6	0.52	0.57	0.63	0.53	0.54
8	0.56	0.62	0.87	0.70	0.67
10	0.76	0.76	0.57	0.60	0.62

These results show that irrespective of the cement and finer percentages, wet/dry compressive strength ratio is more than 0.4 for all the combinations.

4.5.3. Dry Densities and Water Absorption of CSEB with Reduced Clay and Silt

Tested blocks for dry density and water absorption gave the results as shown in Table 4-16. It clearly showed that, the water absorption ratio is having a greater improvement when optimizing the particle packing. The SLS 1382 defines the minimum value as 15%. Dry density values also showed that, all the blocks made with upgraded soil arrangement have more than 1800 kg/m^2. The SLS 1382 minimum value is 1750 kg/m^3

Table 4-16: Dry Densities and Water Absorption of CSEB with Modified Soil

Soil Type	Clay & Silt %	Cement %	Quarry dust %	Dry Density (kg/m^3)	Water absorption %
S1: washed soil to get 5% finer	5.0	4	20	1820	10.0
		6		1956	9.5
		8		1956	10.2
		10		1940	8.75
S1: modified to match the power line by adding larger particle	5.0	4	20	2009	8.43
		6		2009	9.2
		8		2009	7.7
		10		2023	5.1
S1: modified to match the power line by adding larger particle	5.0	4	0	1911	9.3
		6		2009	7.1
		8		2009	7.3
		10		2018	7.1
S1: modified to match the power line by adding larger particle	7.5	4	0	1890	11.3
		6		1961	10.1
		8		2009	7.5
		10		2055	6.8
S1: modified to match the power line by adding larger particle	10.0	4	0	1856	9.1
		6		1917	8.7
		8		1865	8.7
		10		1893	8.5

Figure 4-11 below shows the relationship of dry density to the 28 days dry compressive strength. According to that, it is difficult to predict a correlation between the density and the dry compressive strength on every occasion. There is a strong relationship only for the blocks with 7.5% finer. These increasing compressive strengths are related to the increasing cement content also. So, it can be noticed that for 7.5% finer, block dry density has a linear relationship to the dry compressive strength.

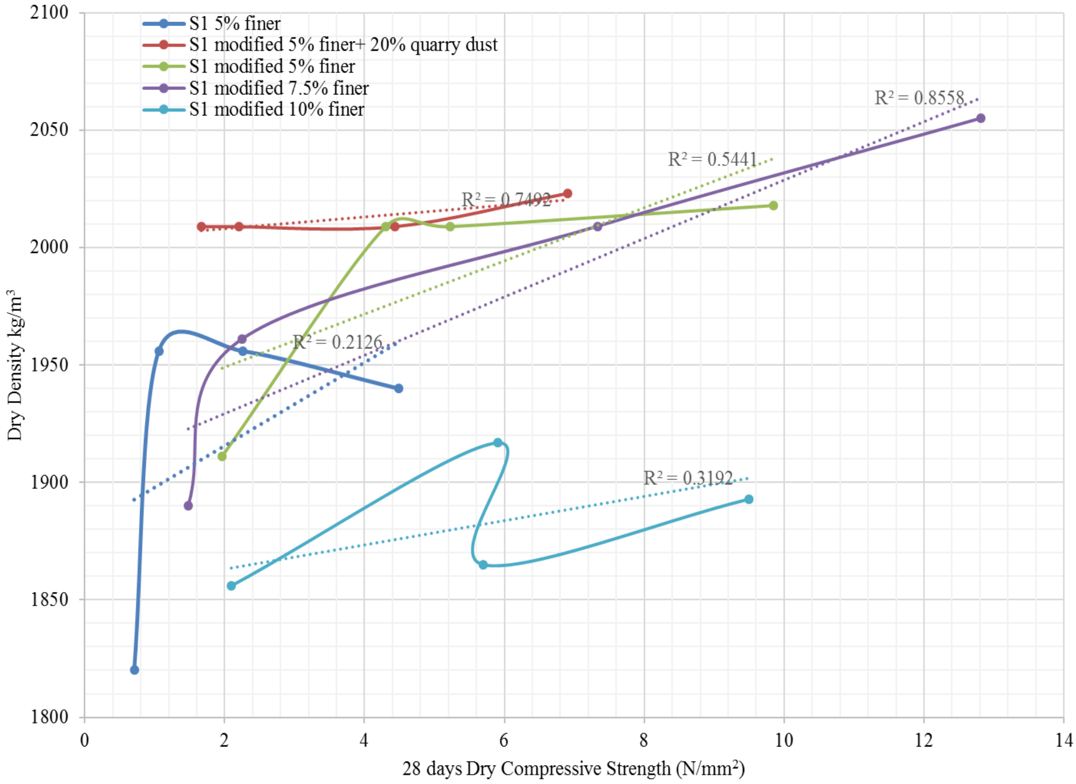


Figure 4-11: Relationship between Dry Density and 28 days Dry Compressive Strength

To get a more clear idea on the relationship between the dry density and the compressive strength, correlation coefficients were calculated and presented in Table 4-17. This also proved that the use of 7.5% finer led to a good relationship between the dry density and the compressive strength. Also, it is clear that when the compressive strength increases, the dry density increases too.

Table 4-17: Correlation between Dry Density and Dry Compressive Strength

Soil Used	**Correlation Coefficient between Dry Density and Dry Compressive Strength**
S1 5% finer	0.4611
S1 modified, 5% finer, 20% quarry dust	0.8655
S1 modified, 5% finer	0.7376
S1 modified, 7.5% finer	0.9251
S1 modified, 10% finer	0.5650

Similar to the above explanation, a relationship was established between the water absorption and the compressive strength. As shown in Figure 4-12, it is difficult to see a strong relationship between the compressive strength and the water absorption for all the finer content. For 7.5% and 10% finer content, the relationship is stronger than other finer contents. That means when the compressive strength increases, or in other words, when the cement content increases, the water absorption decreases.

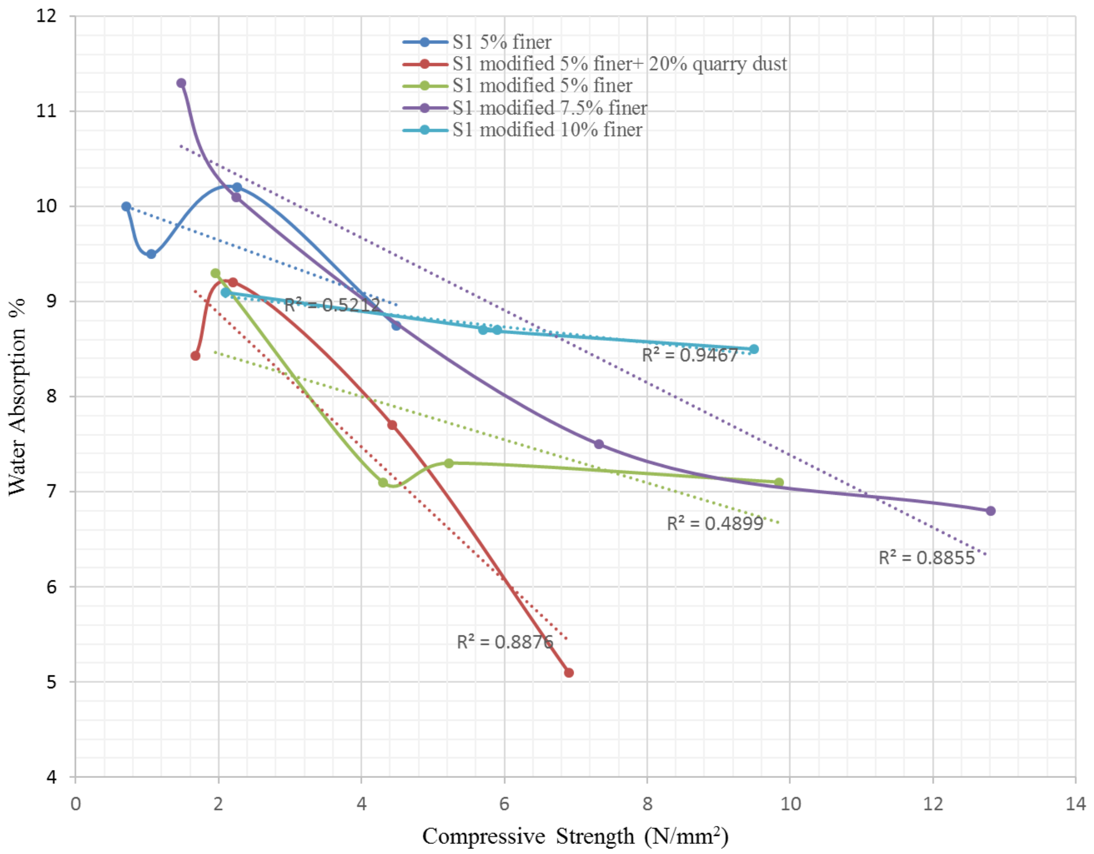


Figure 4-12: Relationship between Water Absorption and 28 days Dry Compressive Strength

Same information presented in Figure 4-12 was used to find the correlation between these two variables and presented in Table 4-18. According to the correlation coefficients, there is a strong decreasing tendency between these two variables for blocks with 7.5 % and 10% finer.

Table 4-18: Correlation between Water Absorption and Dry Compressive Strength

Soil Used	Correlation Coefficient between Water Absorption and Dry Compressive Strength
S1 5% finer	-0.7219
S1 modified, 5% finer, 20% quarry dust	-0.9421
S1 modified, 5% finer	-0.7000
S1 modified, 7.5% finer	-0.9410
S1 modified, 10% finer	-0.9730

4.5.4. Durability Characteristics of CSEB with Reduced Clay and Silt

According to the strengths, density and water absorption test results, it is obvious that the blocks made with 7.5% finer contained soil with 10% or 8% cement stabilization gave the most preferable block properties. Therefore, the accelerated erosion test was performed only for the blocks with 7.5% finer to see the erosion caused by rain. The test suggests to measure the pitting depth every 15 minutes. However, the pitting depth was hard to measure since it was too small. Figure 4-13(a) to (e) shows the surface appearance in different stages of the testing. According to that, there was no significant change in the block surface with spray testing. Thus, the CSEB block with selected finer and cement percentages can assure the requirement given in SLS 1382.

The scaled off factor was then calculated to get more ideas on durability. Two blocks were subjected to erosion test and both gave negligible values for the scaled off factor.

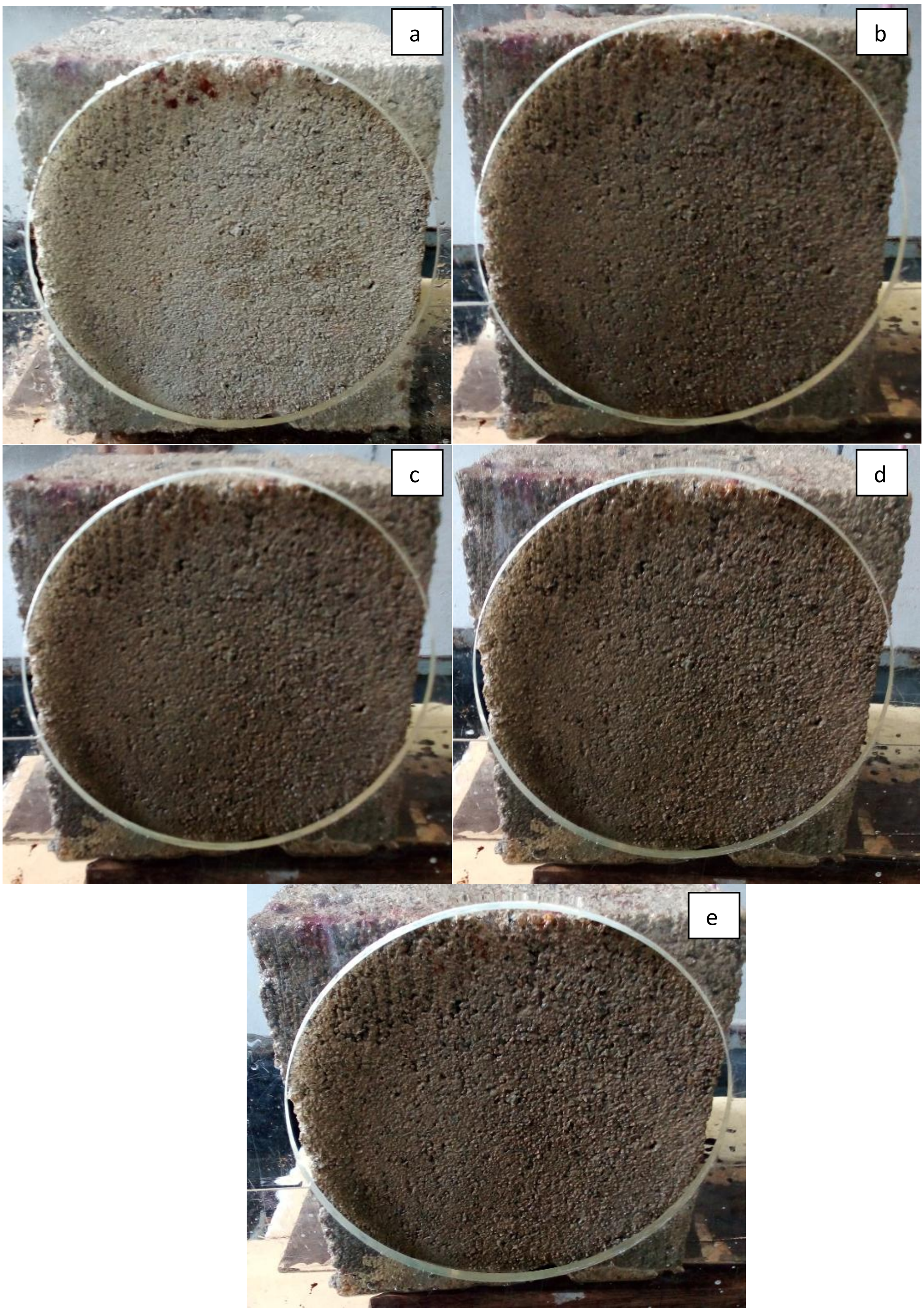


Figure 4-13: Erosion Test Results (a): Before testing, (b): After 15 minutes spray (c): After 30 minutes spray, (d): After 45 minutes spray, (e): After 1 hour spray

Wetting expansion and drying shrinkage were also tested only for the blocks made with the compositions. of selected materials. Table 4-19 indicates the test results. Wetting expansion or drying shrinkage is calculated as the difference between wet measurement and dry measurement is expressed as a percentage of the dry length. When compared to the requirements given in SLS 855, blocks produced with 7.5% finer and 7% cement are satisfied for drying shrinkage., The results obtained are very closer to the specified values for wetting expansion as well. SLS 1382 defines only the requirement of linear expansion and limiting value is 0.10 %. Therefore, test results clearly showed that the blocks made with 7.5% finer and 7% cement satisfied all the durability requirements given in SLS 855 and SLS 1382.

Table 4-19: Wetting Expansion and Drying Shrinkage of CSEB

	Wetting expansion		Drying shrinkage	
	Sample 1	Sample 2	Sample 1	Sample 2
First reading (mm)	9.305	8.503	9.349	8.544
Second reading (mm)	9.206	8.411	9.206	8.411
Dry Length (mm)	287 mm	287 mm	287 mm	287 mm
Final results	**0.034%**	**0.032%**	**0.049 %**	**0.046 %**
Specified value in SLS 855	0.03%		0.06%	

4.6. Performance of Industrial Scaled Blocks

Laboratory tests on CSEB revealed that use of 7.5% finer leads to maximum compressive strength for cement percentages of 10%, 8% and 6%. In the industry, normally used cement percentage is 7%. Therefore, it was decided to cast industrial scaled blocks with 7.5% finer and 7% cement. For each property, three blocks were tested and the average value was given as the result. Test results are shown in Table 4-20.

Table 4-20: Properties of Industrial Scaled Blocks

Block Property	Individual block result		Average Results
28 days dry compressive strength (N/mm^2)	Block 1	5.71	6.23
	Block 2	6.80	
	Block 3	6.26	
28 days wet compressive strength (N/mm^2)	Block 1	3.16	3.75
	Block 2	3.70	
	Block 3	4.38	
Dry density (kg/m^3)	Block 1	1890	1917
	Block 2	1945	
	Block 3	1915	
Water absorption (%)	Block 1	10.22	9.82
	Block 2	9.91	
	Block 3	9.32	

According to these test results, industrial scaled blocks satisfy the requirements of both Compressed Stabilized Earth Blocks and Cement Blocks as given in SLS 1382 and SLS 855 respectively.

4.7. Performance of CSEB with Fly Ash Replacement as Finer

The washed soil as explained earlier consisted of approximately 5% finer and the grading showed that it was a fine-grained soil. So, the gravel had to be added to fit the grading into the optimization curve. Then, the finer content was reduced hence separate finer could be added. As finer, fly ash was added to the mix and prepared CSEB were tested.

4.7.1. Properties of Used Fly ash (Particle size distribution, Specific gravity)

Fly ash used for the blocks were sieved through 0.425mm sieve and after that their particle size distribution is as shown in Figure 4-14. In this study, the purpose of using fly ash was to replace the finer particles. Other than that, its binding properties were not considered. The specific gravity of fly ash was 2.2 and it was less than that of used soil, resulting in less specific gravity for the soil-fly ash mix.

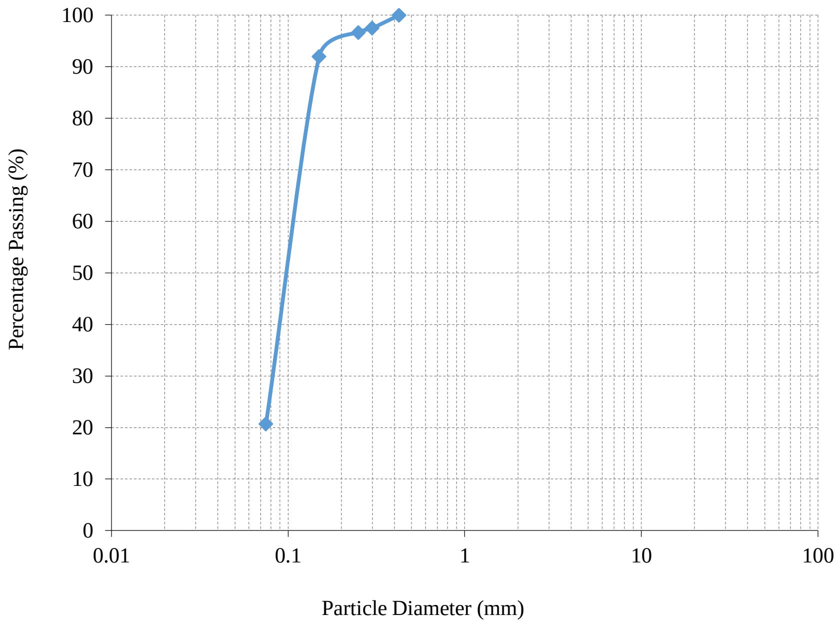


Figure 4-14: Particle Size Distribution of Fly Ash

4.7.2. Mix of Soil and Fly Ash

When mixing the soil and fly ash, the expected final particle size distribution is determined as per the power line. Thus, to match with the power line, other than the fly ash, different size larger particles were also added to the mixture. These larger particles were earlier extracted from the same soil. Then, the soil mixture has the particle size distribution as shown in Figure 4-15 and its comparison to the power line is also presented there.

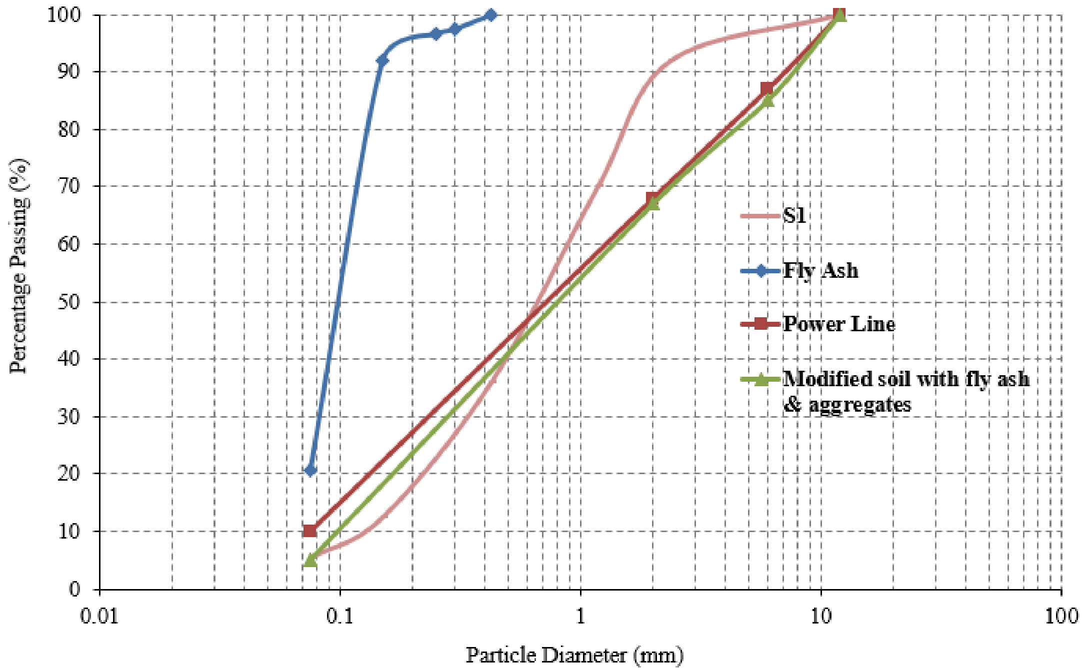


Figure 4-15: Comparison of Particle Size Distribution

4.7.3. Compressive Strength of CSEB with Fly Ash Replacement

As explained in section 3.5, finer content was changed to 5%, 7.5% and 10% by adding fly ash. Blocks were made for 6%, 8% and 10% cement stabilization. 7 days dry compressive strength, 28 days dry and wet compressive strengths of blocks made with fly ash as a finer are shown in Figure 4-16, Figure 4-17 and Figure 4-18 respectively.

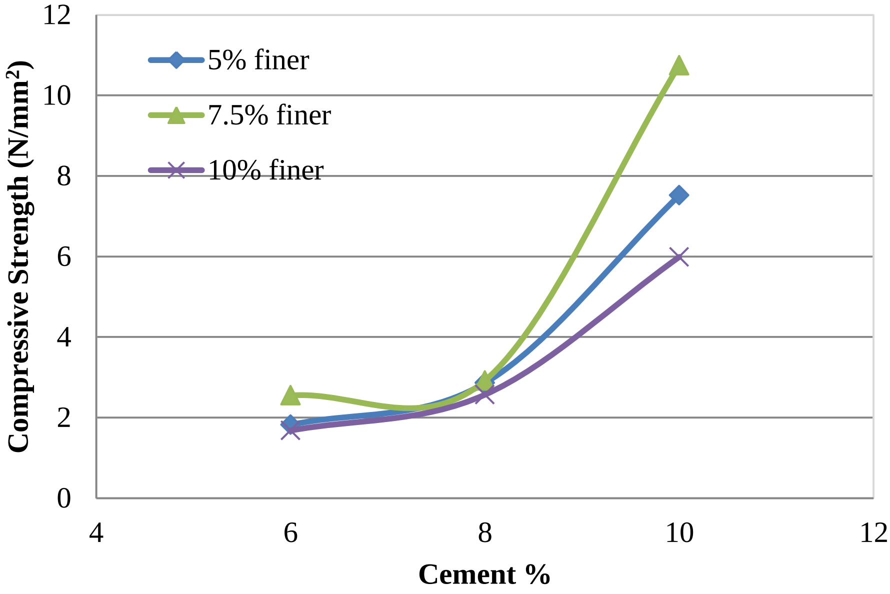


Figure 4-16: 7 Days Compressive Strength Results of Soil Blocks with Fly Ash

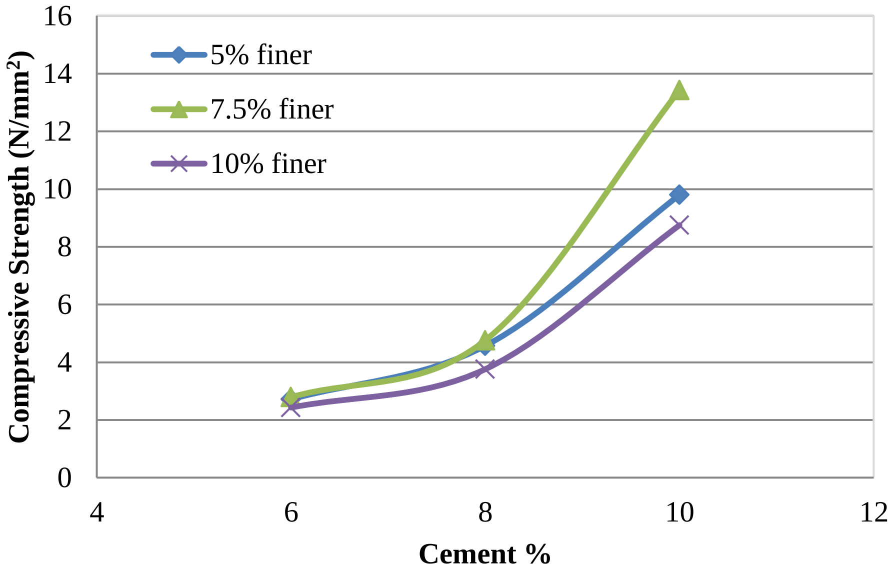


Figure 4-17: 28 Days Dry Compressive Strength Results of Soil Blocks with Fly Ash

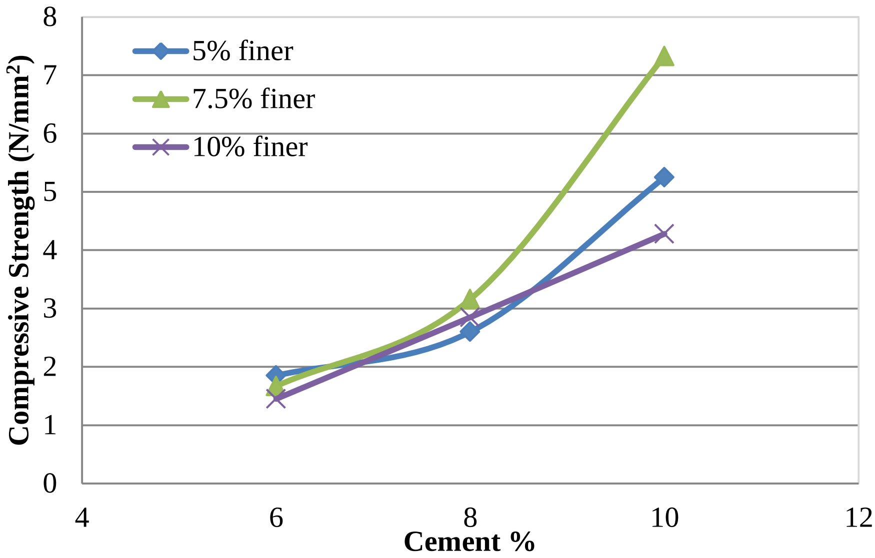


Figure 4-18: 28 Days Wet Compressive Strength Results of Soil Blocks with Fly Ash

Considering the compressive strength results of blocks with fly ash replacement, it was evident that when the cement content was 10%, high compressive strength could be achieved irrespective of the finer content. Among that, 7.5% finer with fly ash replacement has given high compressive strength compared to other finer contents.

4.7.4. Comparison with Soil Blocks

The study focused on two areas: CSEB made with silt & clay as finer and fly ash replacement as finer. The test results show that CSEB having silt & clay as finer gave more strength compared to CSEB with fly ash replacement. Figure 4-19 shows a comparison of 28 days compressive strength for these two cases. For this comparison, 4% cement stabilization was omitted since earlier results have shown that its influence was negligible.

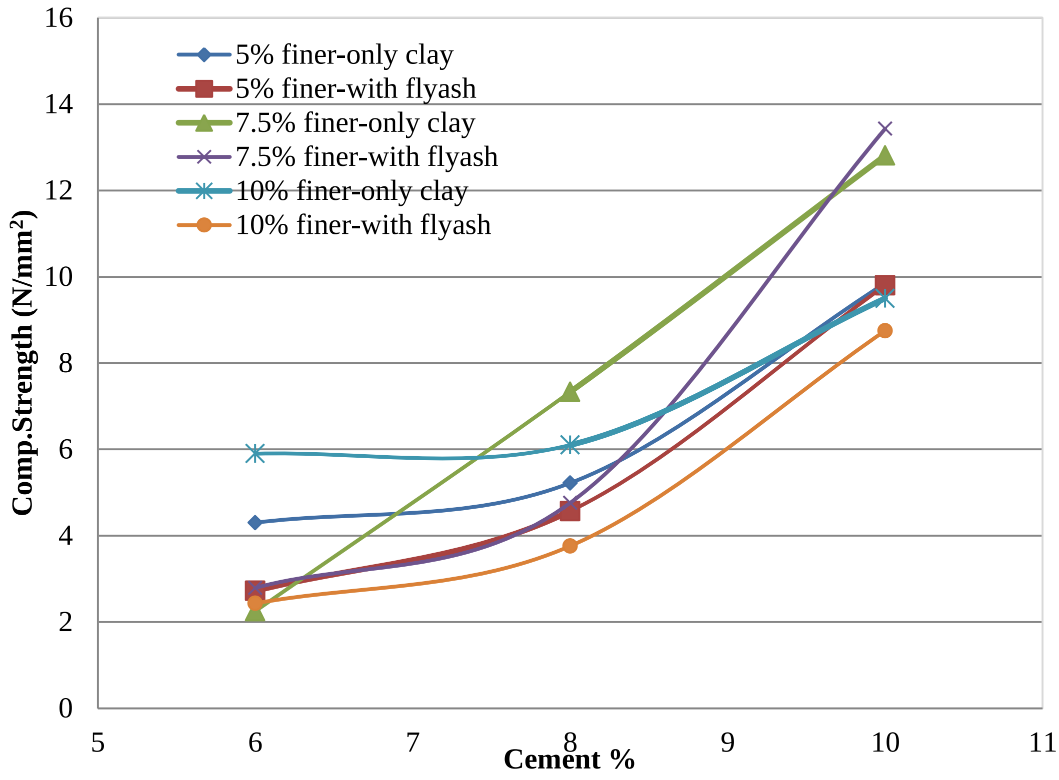


Figure 4-19: 28 Days Dry Compressive Strength of Blocks with Finer Replacement

When the finer content was 7.5% (for both cases of silt & clay as finer and fly ash replacement as finer), CSEB achieved high compressive strength for 8% and 10% cement content. When the cement content was 6%, it is difficult to arrive at a conclusion.

Table 4-21 shows the comparison of the compressive strengths of blocks made with silt & clay as finer and fly ash as finer. According to the values in the table, all the strength values are less for the blocks made with fly ash finer compared to that of clay & silt as finer. Table 4-22 shows the other properties of blocks.

Table 4-21: Comparison of Compressive Strengths when Fly Ash as a Finer and Silt & Clay as a Finer

5% finer replacement								
Cement %	**Dry Comp. Strength (N/mm^2)**				**Wet Comp. strength (N/mm^2)**		**Wet/Dry**	
	7 days		**28 days**					
6	1.82	3.34	2.72	4.3	1.85	2.73	0.6801	0.6349
8	2.86	4.62	4.57	5.22	2.6	4.54	0.5689	0.8697
10	7.52	9.46	9.8	9.85	5.25	5.65	0.5357	0.5736
7.5% finer replacement								
Cement %	**Dry Comp. Strength (N/mm^2)**				**Wet Comp. strength (N/mm^2)**		**Wet/Dry**	
	7 days		**28 days**					
6	2.55	1.84	2.79	2.25	1.67	1.19	0.5986	0.5289
8	2.92	5.67	4.76	7.33	3.16	5.11	0.6639	0.6971
10	10.75	9.38	13.43	12.81	7.33	7.69	0.5458	0.6003
10% finer replacement								
Cement %	**Dry Comp. Strength (N/mm^2)**				**Wet Comp. strength (N/mm^2)**		**Wet/Dry**	
	7 days		**28 days**					
6	1.68	5.03	2.43	5.9	1.45	3.2	0.5967	0.5424
8	2.57	5.41	3.76	6.1	2.85	3.8	0.758	0.6667
10	5.99	8.67	8.75	9.5	4.28	5.9	0.4891	0.6211

(white)	Fly ash as finer
(green)	Clay as finer

Table 4-22: Comparison of Dry Density and Water Absorption when Fly Ash as a Finer and Silt & Clay as a Finer

5% finer replacement				
Cement %	**Dry Density (kg/m^3)**		**Water absorption %**	
6	1968	2009	10.33	7.1
8	1903	2009	11.28	7.3
10	1949	2018	9.34	7.1
.5% finer replacement				
Cement %	**Dry Density (kg/m^3)**		**Water absorption %**	
6	1865	1961	11.4	10.1
8	1833	2009	12.4	7.5
10	2074	2055	6.32	6.8
10% finer replacement				
Cement %	**Dry Density (kg/m^3)**		**Water absorption %**	
6	1761	1917	13.89	8.7
8	1778	1865	13.77	8.7
10	1912	1893	11.54	8.5

(white)	Fly ash as finer
(green)	Clay as finer

Considering the properties other than the compressive strength, higher density and lower water absorption were achieved, when the CSEB are made with clay & silt as finer. But the blocks made with fly ash also reached the values specified in SLS 1382 as discussed in the following section.

4.7.5. Comparison with Standards

The test results were compared with SLS 1382: Specification for Cement Stabilized Earth Blocks and SLS 855: Specification for Cement blocks. According to the test results as shown in Table 4-23, when the cement content was 10% for all the selected finer contents, compressive strength values were above the limiting value for grade 1 CSEB (6.0 N/mm^2 and 2.4 N/mm^2 for dry and wet compressive strength respectively). For 5% and 7.5% finer, and 8% cement, compressive strength values reached to grade 2 CSEB (4.0 to 6.0 N/mm^2 for dry compressive strength and 1.6 to 2.4 N/mm^2 for wet compressive strength). Even with 6% cement, 7.5% finer could produce grade 3 CSEB (2.8 to 4.0 N/mm^2 for dry compressive strength and 1.2 to 1.6 N/mm^2 for wet compressive strength). Also, all the density and water absorption values (Table 4-24) were higher than the specified value (1750 kg/m^3 and 15% respectively) in SLS 1382 Part 1. Out of all the finer contents, 7.5% finer replacement led to the highest density and lowest water absorption when the cement replacement is 10%.

Table 4-23: Summary of Compressive Strength Results

Cement %	**5% finer with fly ash**			**7.5% finer with fly ash**			**10% finer with fly ash**		
	Dry	Wet	Wet/Dry	Dry	Wet	Wet/Dry	Dry	Wet	Wet/Dry
6	2.72	1.85	0.680	2.79	1.67	0.599	2.43	1.45	0.597
8	4.57	2.6	0.569	4.76	3.16	0.664	3.76	2.85	0.758
10	9.8	5.25	0.536	13.43	7.33	0.546	8.75	4.28	0.489

Table 4-24: Densities and Water Absorption Results

Cement %	**5% finer with fly ash**		**7.5% finer with fly ash**		**10% finer with fly ash**	
	Density (kg/m^3)	Water Absorption %	Density (kg/m^3)	Water Absorption %	Density (kg/m^3)	Water Absorption %
6	1968	10.33	1865	11.4	1761	13.89
8	1903	11.28	1833	12.4	1778	13.77
10	1949	9.34	2074	6.32	1912	11.54

4.8. Performance of Roof Tiles

Extracted finer mixed with fly ash was used for the production of roof tiles. The extracted finer was first checked with crack control test and it revealed that extracted clay alone does not give sufficient texture for the production of roof tiles.

Figure *4-20* (a) and (b) show sample casting for the crack control test and shrinkage behaviour after 24 hours.

Figure 4-20: (a) Sample Casting and (b) after 24 hours of Casting

Fly ash addition to clay supported the reduction of the shrinkage of clay. To find the correct percentage of fly ash, following fly ash percentages were added to the clay and crack control test gave the shrinkage behaviour as shown in Figure 4-21. It revealed that; 25% fly ash addition gave minimum shrinkage.

a. 10% of fly ash with extracted clay
b. 15% of fly ash with extracted clay
c. 20% of fly ash with extracted clay
d. 25% of fly ash with extracted clay
e. 30% of fly ash with extracted clay

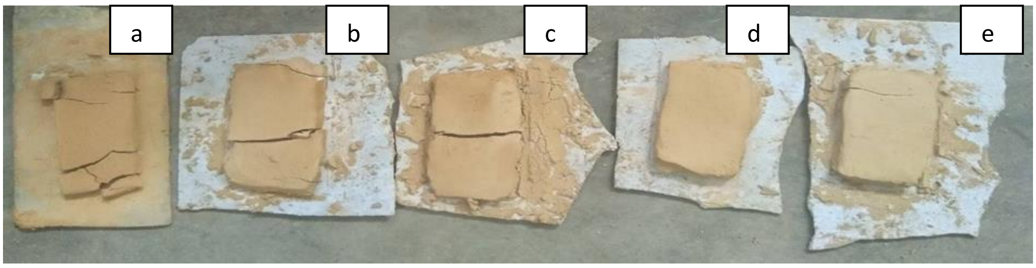


Figure 4-21: Crack Control Test with Fly Ash Addition

Fly ash was taken from Norechcholai LakVijaya Thermal Power Plant. The chemical analysis of fly ash (Table 4-25) shows it belongs to the class N fly ash as specified in ASTM C618. The test was performed at Geological Survey & Mines Bureau, Pitakotte, Sri Lanka. X-Ray Diffraction (XRD) test also proved that the prominent ingredients in fly ash are SiO_2 and Al_2O_3 (Figure 4-22).

Table 4-25: Chemical Analysis of Fly Ash

Constituents determined	**Contents %**	**Test Method**
Calcium as CaO	5.63	Acid Digestion and Atomic Absorption Spectrometry
Magnesium as MgO	1.59	
Iron as Fe_2O_3	3.35	
Aluminum as Al_2O_3	19.74	
Potassium as K2O	0.47	
Sodium as Na_2O	0.95	
Manganese as MnO	0.05	
Phosphorus as P_2O_5	1.89	Acid Digestion and UV/VIS
Titanium as TiO_2	1.98	
Silicon as SiO_2	47.48	Gravimetry
Loss on ignition	16.79	

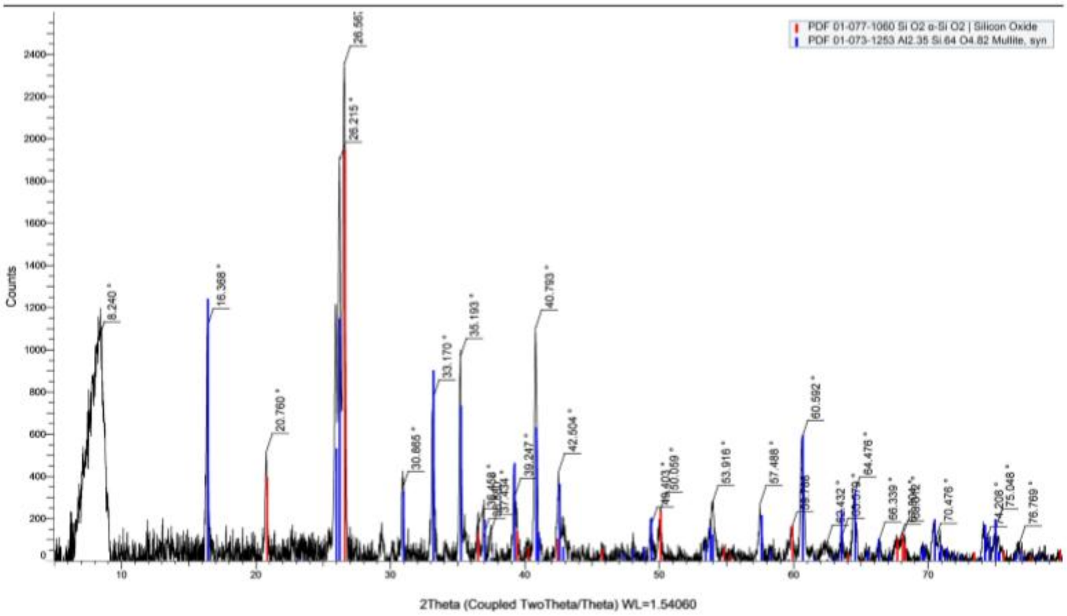


Figure 4-22: XRD Pattern on Fly Ash

To get a clear idea about the clay mix with fly ash, Atterberg Limit test was performed. Also, three clay samples taken from roof tile manufacturing companies were tested. Table 4-26 shows the Atterberg Limits and other necessary properties of clay mixed with fly ash.

Table 4-26: Properties of Clay mixed with Fly Ash

Sample Designation	Fly Ash Addition %	Liquid Limit LL	Plastic Limit PL	Plasticity Index PI	Specific Gravity SG	Linear Shrinkage LS
ECF00	0	44.91	29.47	15.44	2.51	5.241
ECF05	5	42.71	32.39	10.32	2.68	4.520
ECF10	10	39.41	35.66	3.75	2.63	5.850
ECF15	15	45.56	32.19	13.37	2.37	5.983
ECF20	20	41.64	34.2	7.44	2.16	3.806
ECF25	25	47.33	39.11	8.22	2.38	2.004
ECF30	30	38.93	29.61	9.32	2.41	3.960
ECF50	50	36.63	25.08	11.55	2.62	5.360
MC1	-	45.51	30.9	14.16	1.86	2.000
MC2	-	42.03	28.06	13.97	2.19	3.929
MC3	-	46.25	33.15	13.1	2.25	2.412

EC: Extracted clay, F: Fly ash, MC: Market Clay

According to the plasticity index values, all the clay and fly ash mix and market clay were within the low to medium plasticity range as defined by the soil mechanics theories as presented in the Table 4-27. Specific gravity values also did not make a clear sense. Therefore, shrinkage was considered as the governing criteria to select the appropriate mix with fly ash. The variation of linear shrinkage with fly ash content is represented graphically as in Figure 4-23 to get a clear idea.

Table 4-27: Plasticity Types

Plasticity Index	Plasticity Type
0	Non plasticity
1-5	Slightly plasticity
5-10	Low plasticity
10-20	Medium plasticity
20-40	High plasticity
>40	Very high plasticity

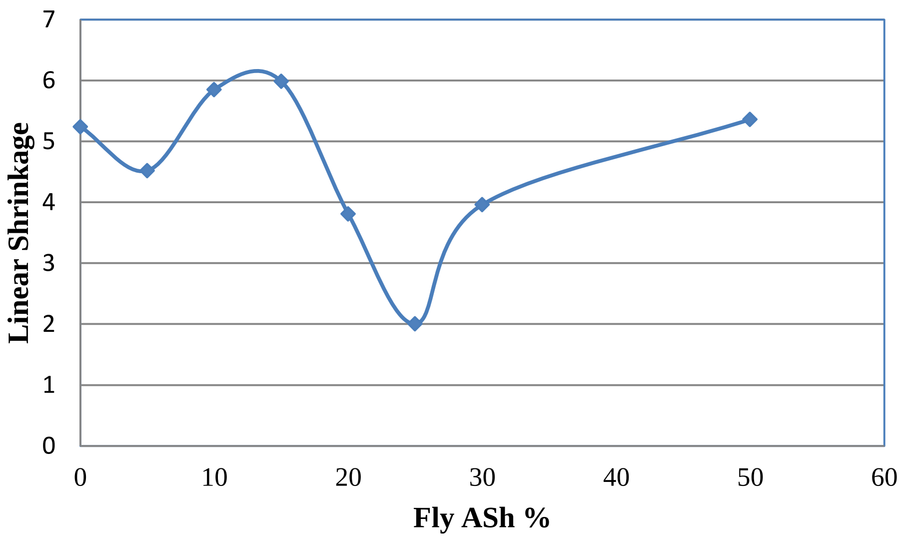


Figure 4-23: Variation of Linear Shrinkage with Fly Ash Content

The results show, 25% fly ash addition to clay gave the lowest linear shrinkage. Tested market clay MC1 exhibits the same linear shrinkage, while MC3 also exhibits lesser linear shrinkage. MC2 is having considerably high linear shrinkage and with 20% and 30% fly ash addition, that amount of shrinkage could be expected. Hence, the addition of 20% to 30% fly ash to the extracted clay would give sufficient properties to the clay to produce roof tiles.

Then the particle size distributions of fly ash, market clay, extracted clay mixed with 25% fly ash, were compared. This comparison is shown in Figure 4-24. From the figure, it is clear that the addition of 25% fly ash brings the particle size distribution near to the market clay.

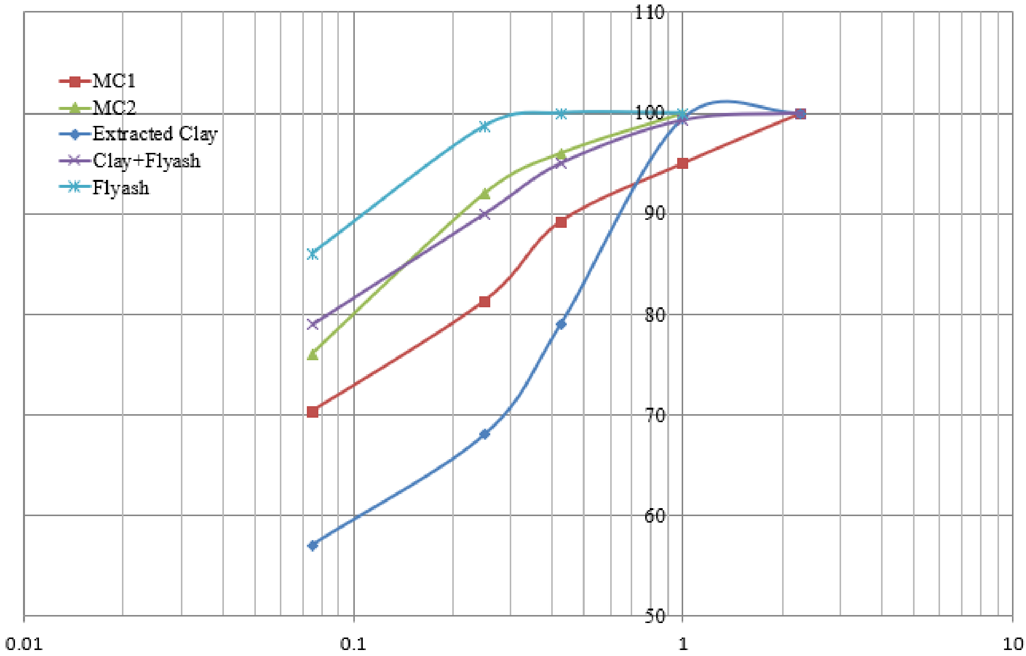


Figure 4-24: Comparison of Particle Size Distribution of Market Clay and Extracted Clay with 25% Fly Ash Addition

4.8.1. Test Results for Roof Tiles

Prepared roof tiles were tested for transverse braking strength, water absorption and permeability. The results were compared with market tiles too. Table 4-28 shows the results with a comparison of market roof tiles.

Table 4-28: Comparison of Market Roof Tiles and Extracted Clay Roof Tiles

Property	**Market Roof Tile**	**Extracted Clay Roof Tile**
Water Absorption	14.12%	17.22%
Permeability	Impermeable	Impermeable
Thermal Conductivity	0.64 W/mk	0.69 W/mk
Strength	1.03 kN	1.05 kN

These results show that the performance of roof tiles made with extracted clay have better performance compared to the available market rooftiles. Also, it satisfies the requirements given in SLS 2.

4.9. Performance of Clay Bricks

Clay bricks made with extracted finer with different composition of fly ash were tested for strength, durability and physical appearance as explained in section 3.14. According to the Atterberg test results indicated in Table 4-26 in section 4-7, 25% fly ash addition to extracted finer gave the lowest shrinkage. For other percentages also, shrinkage was not significantly large compared to some literature [123], [125]. Therefore, the bricks were made by adding fly ash up to 50%. The behaviour of clay and different percentages of fly ash were examined using SEM test. Figure 4-25 shows the microscopic structures for clay and fly ash mixes.

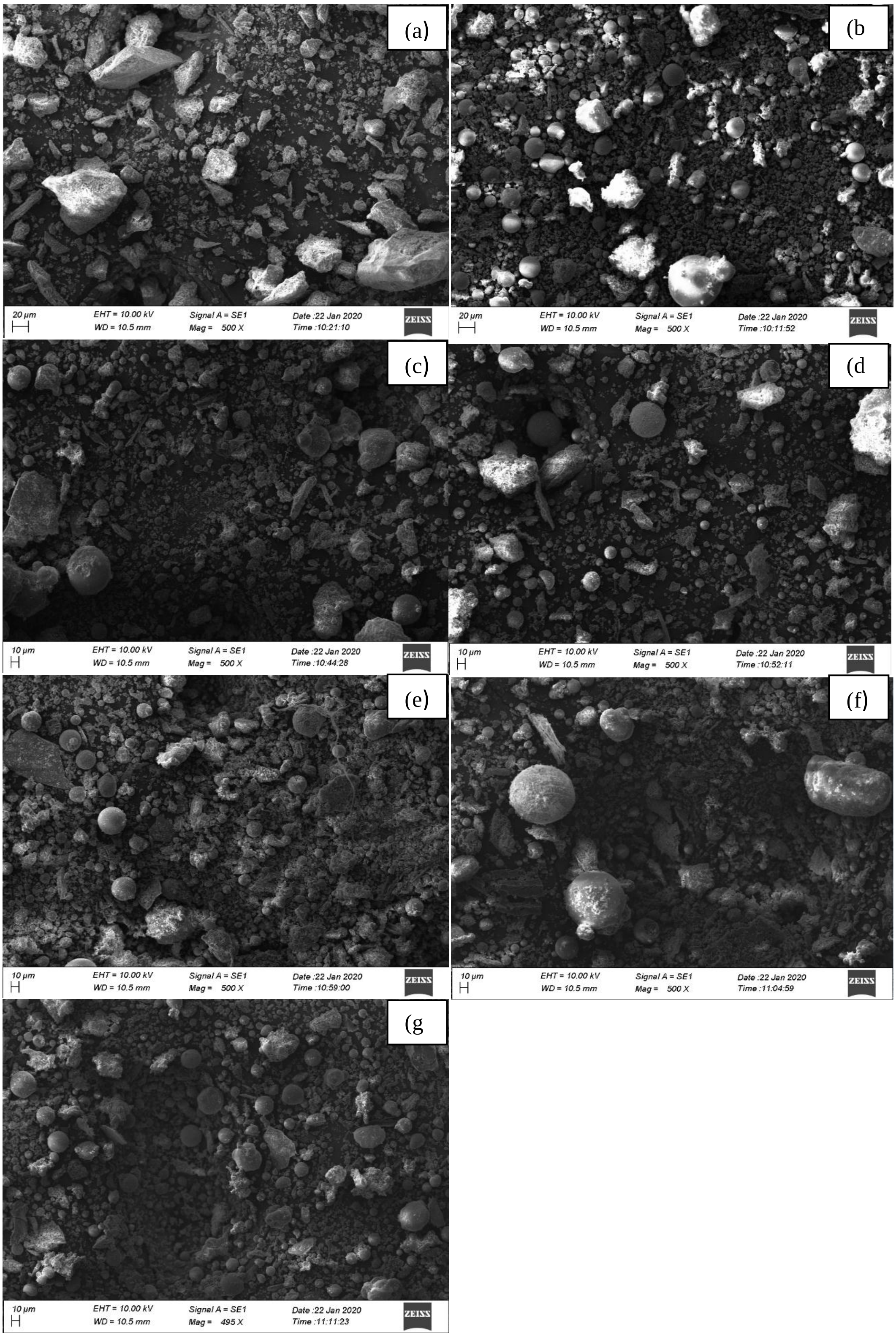


Figure 4-25: SEM images of clay (a), fly ash (b) and clay mix with fly ash 20% (c), 25% (d), 30% (e), 40% (f), 50% (g)

First, the prepared bricks were checked for the dimension variation after firing and Table 4-29 shows the dimension variation results. These variations were calculated based on the dimensions of the brick mould used (220 x 115 x 75) mm. Bricks were made with the clay available in the brick-making industry and fly ash addition also is done for the comparison purpose.

Table 4-29: Dimension Variation of Bricks

Brick specimen	**Fly ash %**	**Variation in length (%0**	**Variation in Width (%)**	**Variation in Height (%)**
ECB-F20	20	5.9	9.6	9.3
ECB-F25	25	4.5	8.7	9.3
ECB-F30	30	3.6	6.1	9.3
ECB-F40	40	3.2	4.3	7.1
ECB-F50	50	2.3	4.3	7.1
MCB-F00	0	11.82	18.26	21.33
MCB-F20	20	9.55	13.04	17.33
MCB-F25	25	8.18	9.57	16.00
MCB-F30	30	7.73	8.70	13.33
MCB-F40	40	2.73	6.09	10.67
MCB-F50	50	2.27	4.35	9.33
MCB-F60	60	1.36	4.35	6.66

ECB: Extracted Clay Bricks; MCB, Market Clay Bricks

These dimension variations are clearly visible in burnt bricks. Figure 4-26 shows few burnt bricks with different fly ash contents.

Figure 4-26: Burnt Bricks with Different Fly Ash Contents

These variations are presented in Figure 4-27 too.

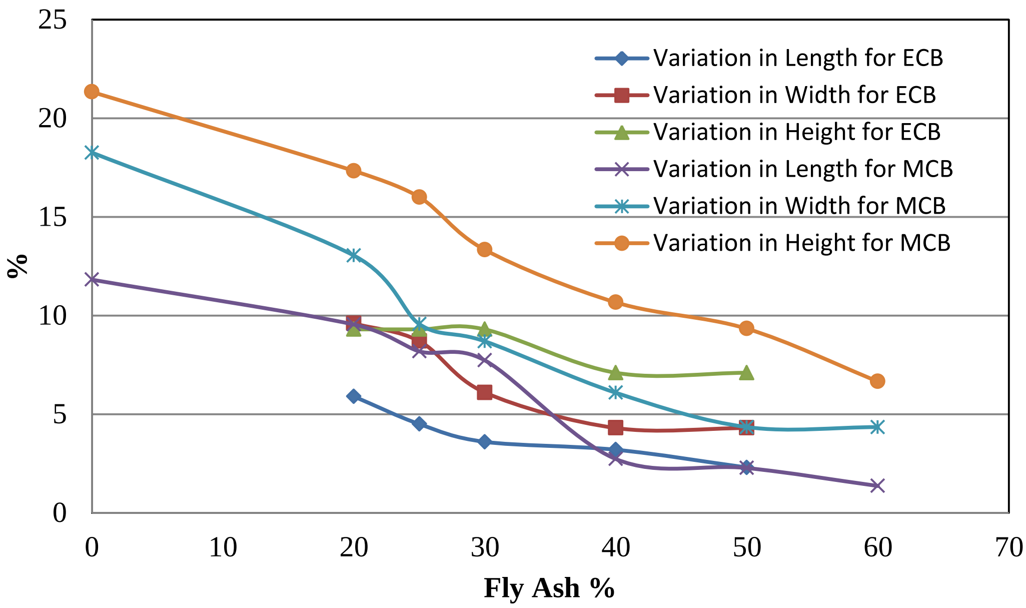


Figure 4-27: Dimension Variation of Burnt Bricks with Fly Ash

According to these dimension variations, it is clear that the fly ash addition helped to lower the shrinkage. So, the number of bricks needed to construct a unit wall area is reduced compared to a wall area built with normal bricks. Hence, these burnt bricks help to reduce the cost of wall construction.

Bricks were tested for compressive strength and flexural strength. Table 4-30 shows strength values of bricks for different fly ash percentages. The strengths of bricks were compared with randomly taken market bricks. Also, bricks made with clay taken from the brick-making industry and mixed with fly ash were considered for the comparison. These compressive strengths and flexural strengths variations are presented in Figure 4-28 and Figure 4-29 respectively.

Table 4-30: Compressive Strengths and Flexural Strengths of Bricks

Brick specimen	**Fly ash %**	**Compressive Strength (N/mm^2)**	**Flexural Strength (N/mm^2)**
ECB-F20	20	2.51	0.74
ECB-F25	25	3.99	1.25
ECB-F30	30	2.32	0.64
ECB-F40	40	1.52	0.59
ECB-F50	50	0.97	0
MB-1	-	3.85	1.51
MCB-F00	0	6.02	1.39
MCB-F20	20	4.02	1.06
MCB-F25	25	4.13	1.34
MCB-F30	30	2.42	1.3
MCB-F40	40	1.38	0.79
MCB-F50	50	2.17	0.68
MCB-F60	60	0.91	0.67

ECB: Extracted Clay Bricks, MB; Market Bricks, MCB: Market clay Bricks

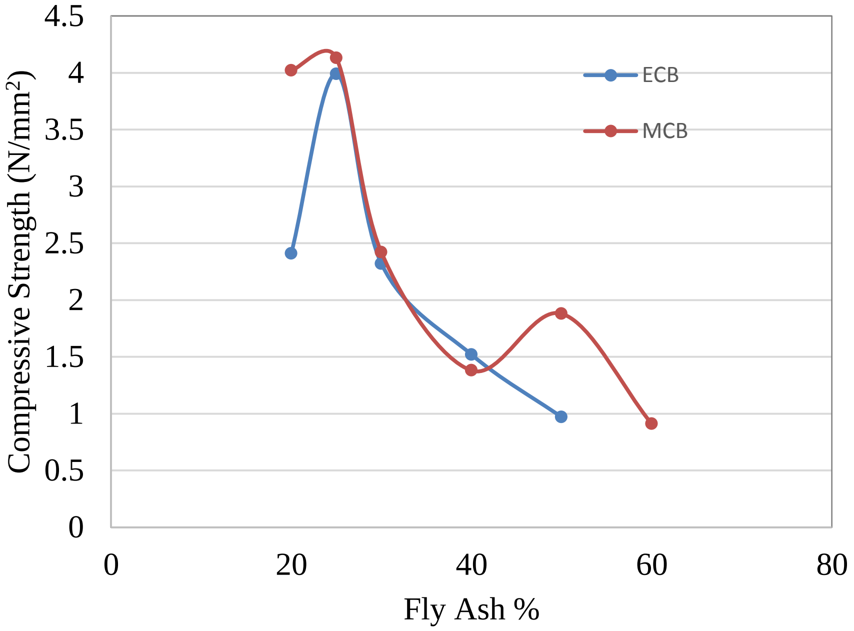


Figure 4-28: Compressive Strengths Variation of Burnt Bricks with Fly Ash %

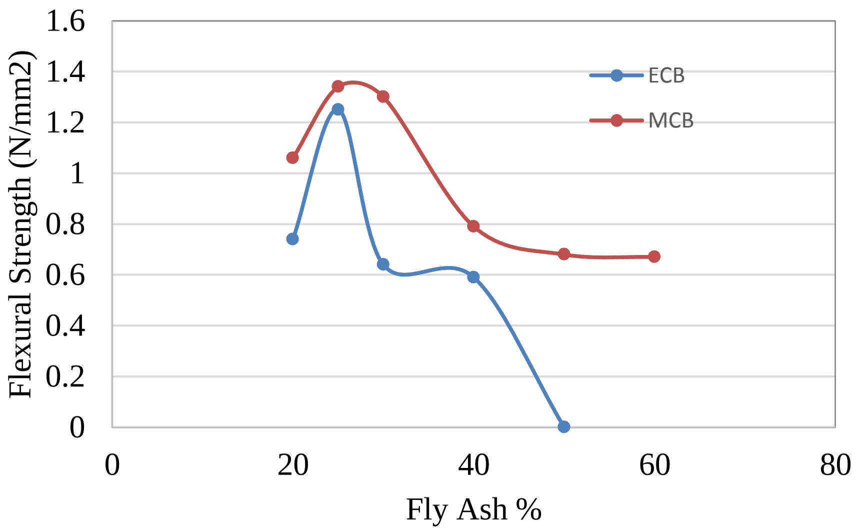


Figure 4-29: Flexural Strengths Variation of Burnt Bricks with Fly Ash %

According to the results of the strength of two bricks categories, 25% fly ash addition helped to achieve the maximum strengths for both compressive and flexural strengths.

For the above-mentioned brick specimens, dry density and water absorption were calculated and those are shown in Table 4-31. These dry density and water absorption variations are presented in Figure 4-30 and Figure 4-31 respectively.

Table 4-31: Density and Water Absorption of Bricks

Brick specimen	**Fly ash %**	**Dry Density (kg/m^3)**	**Water Absorption (%)**
ECB-F20	20	1230	33.93
ECB-F25	25	1183	33.28
ECB-F30	30	1156	37.19
ECB-F40	40	1083	39.87
ECB-F50	50	1059	42.14
MB	-	1891	13.11
MCB-F00	0	1453	32.77
MCB-F20	20	1332	33.87
MCB-F25	25	1243	33.81
MCB-F30	30	1234	34.81
MCB-F40	40	1146	36.88
MCB-F50	50	1088	39.07
MCB-F60	60	1019	41.23

ECB: Extracted Clay Bricks, MB; Market Bricks, MCB: Market clay Bricks

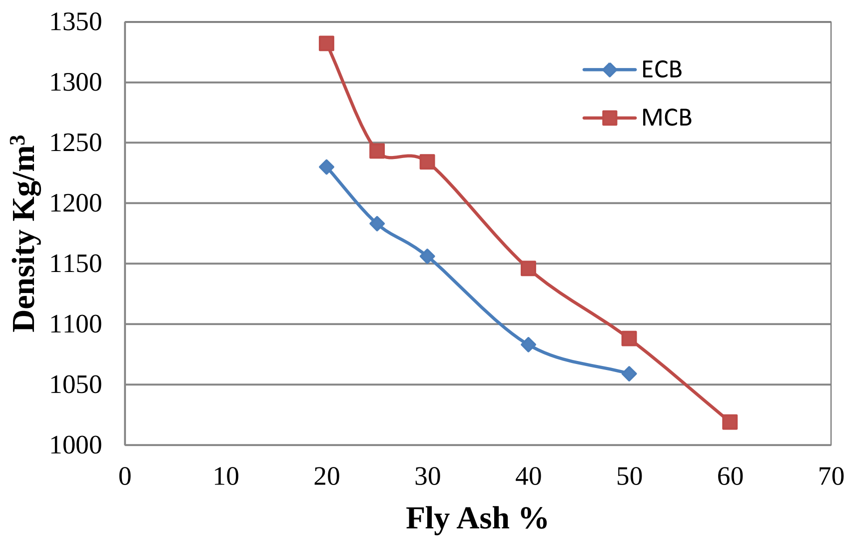


Figure 4-30: Density Variation of Burnt Bricks with Different Fly Ash %

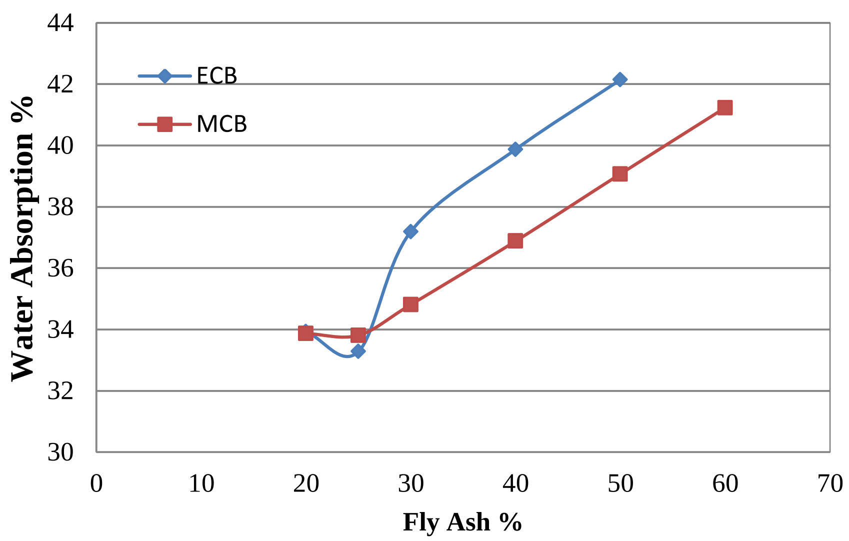


Figure 4-31: Water Absorption Variation of Burnt Bricks with Different Fly Ash %

According to the above test results, the most dominant feature is the reduction of density with fly ash addition. This will be a good feature in masonry construction since the handling of light-weight bricks requires less labour ending with unit rate reduction for masonry work. Considering the water absorption ratio, 25% of fly ash addition helps the lowest water absorption even though it is high compared to the bricks available in the market. Finally, it can be concluded that the addition of 25% of fly ash would give the optimum results for the properties of burnt-bricks. Efflorescence test also was conducted for the bricks made with 25% fly ash addition. Results show that the bricks did not show any type of efflorescence.

Wire-cut bricks (Figure 4-32) made with 25% fly ash addition to extracted clay were tested for relevant properties and those are shown in Table 4-32.

Figure 4-32: Wire-Cut Bricks made with Extracted Clay and Fly ash

Table 4-32: Properties of Wire-cut Bricks

Property	Result	SLS 39 Requirement
Dry Compressive Strength	10.64 N/mm^2	10 N/mm^2
Flexural Strength	2.09 N/mm^2	-
Density	1708 kg/m^3	-
Water Absorption	16.25 %	18%
Efflorescence	Slight	Slight

4.10. Summary

The chapter discussed the analysis results related to the properties of products namely CSEB, roof tiles and brunt-bricks. All the results were presented in the form of tables or figures to illustrate the results more clearly.   The results were discussed in detail with comparison to the available relevant standards. Also, results were reviewed with respect to the literature in the absence of standards. Next chapter will discuss the cost analysis of soil-based products considered in this study.

CHAPTER 5 : COST ANALYSIS OF PRODUCTS

5.1. General Introduction

The previous chapter discussed the results obtained related to the products of this study namely CSEB, roof tiles and burnt-bricks. Those results were presented using charts, figures and tables. Also, results were compared with the available standards. This chapter aims to analyse the cost of the product which were discussed in earlier chapters. That is unit cost of a CSEB, unit cost of a roof tile and unit cost of a burnt brick. The procedure of calculating these unit costs is well defined. The difference in calculating these costs is due to the raw materials used. The main raw material was soil and was separated for gravel and finer by washing. Therefore, the work norm for soil washing was first established. For this, 1-hour work of soil washing was considered and the procedure is explained below.

5.2. Cost Calculation for Soil Washing

<u>Resource used- per hour</u>

2 unskilled labours

20 soil buckets (20 *l* each)

30 water buckets (20 *l* each)

Concrete mixer

Electricity

Containers to put clay slurry for settlement

Space to put gravel for drying

<u>Calculations</u>

20 soil buckets= 0.40 m^3

Yield of gravel arising from 0.40 m3 after washing = 0.22 m^3

Yield of finer arising from 0.40 m3 after washing = 0.16 m^3

About 0.02m^3 is a loss

Based on this, 1 cube (2.83 m^3) will produce

Gravel = 1.556 m^3

Finer = 1.132 m^3

Labour requirement for 1 cube = 2.83/ (0.40*8)

= 0.9 days (for 2 labour)

Water requirement =40/0.40*2.83

=5660*l*

Out of this water, 60% can be reused.

Cost of 1 cube of soil washing

1 cube of soil = Rs. 2500.00

Labour cost = 0.90*2*1500.00

= Rs. 2700.00

Cost of water =5660/1000* 0.4*70

(Cost of one unit of water is Rs. 70.00-taken from National Water Supply and Drainage Board)

=Rs. 160.00

Total cost = Rs. 5200.00

This cost is to produce 1.556 m^3 of gravel and 1.132 m^3 of finer. Therefore, cost for gravel and finer can be mentioned as;

Cost of 1.556 m3 gravel = Rs. 3010.00

Cost of 1 cube of gravel =Rs. 5474.00

Specific gravity of gravel	= 2.7
Therefore,1 cube of gravel	= 2.83 m^3 x 2700 kg/m^3
	= 7641 kg
Cost of 1 kg of gravel	= 5474/7641
	= Rs. 0.72

Cost of 1.132 m3 of finer	= Rs. 2189.00
Cost of 1 cube of finer	= Rs. 5474.00
Specific gravity of finer	= 2.51
Therefore, 1 cube of finer	= 2.83 m^3 x 2510 kg/m^3
	= 7103 kg
Cost of 1 kg of finer	= 5474/7103
	= Rs.0.77

5.3. Cost Calculation for CSEB Production

Cost of CSEB was calculated considering the block size of (150 x 150 x 150) *mm*. Later it was converted to the size of (350 x 175 x 100) *mm* which is the commonly available block size in the market. Table 5-1 shows the unit cost of resources used.

Table 5-1: Unit Cost of Resources Used for CSEB

Material	**Cost (Rs)**
Cement (Per Kg)	20.00
Soil (Per Kg)	0.72
Clay (Per Kg)	0.77
Labour (Per block)	8.00

Cost of CSEB was calculated for different percentages of cement and finer. The testing results revealed that the average dry weight of a block was 7.0 kg. So, the requirements of materials were considered based on one block weight. Then this cost was converted to the standard size of a block and labour cost was added. Table 5-2 to Table 5-4 show the cost of CSEB for 10%, 8% and 6% cement respectively.

Table 5-2: Cost Analysis of CSEB with 10% Cement

Finer (%)	**Soil (Kg)**	**Cost for soil (Rs)**	**Finer replacement (Kg)**	**Cost of Finer (Rs)**	**Cement (Kg)**	**Cost of cement (Rs)**	**Total (Rs)**
10	6.3	4.47	0.7	0.54	0.7	14	19.01
7.5	6.475	4.60	0.525	0.40	0.7	14	19.00
5	6.65	4.72	0.35	0.27	0.7	14	18.99

Finer (%)	**Cost of materials for 1 block, Size (150*150*150) *mm***	**Cost of materials for 1 block, Size (350*105*165) *mm***	**Add for labor cost**	**Cost of a block (Rs.)**
10	19.01	34.16	8.00	42.16
7.5	19.00	34.14	8.00	42.14
5	18.99	34.12	8.00	42.12

Table 5-3: Cost Analysis of CSEB with 8% Cement

Finer (%)	**Soil (Kg)**	**Cost for soil (Rs)**	**Finer replacement (Kg)**	**Cost of Finer (Rs)**	**Cement (Kg)**	**Cost of cement (Rs)**	**Total (Rs)**
10	6.3	4.47	0.7	0.54	0.56	11.20	16.21
7.5	6.475	4.60	0.525	0.40	0.56	11.20	16.20
5	6.65	4.72	0.35	0.27	0.56	11.20	16.99

Finer (%)	**Cost of materials for 1 block, Size (150*150*150) *mm***	**Cost of materials for 1 block, Size (350*175*100) *mm***	**Add for labor cost**	**Cost of a block (Rs.)**
10	16.21	29.13	8.00	37.13
7.5	16.20	29.11	8.00	37.11
5	16.99	29.09	8.00	37.09

Table 5-4: Cost Analysis of CSEB with 6% Cement

<table>
<tr><th>Finer (%)</th><th>Soil (Kg)</th><th>Cost for soil (Rs)</th><th>Finer replacement (Kg)</th><th>Cost of Finer (Rs)</th><th>Cement (Kg)</th><th>Cost of cement (Rs)</th><th>Total (Rs)</th></tr>
<tr><td>10</td><td>6.3</td><td>4.47</td><td>0.7</td><td>0.54</td><td>0.42</td><td>8.40</td><td>13.41</td></tr>
<tr><td>7.5</td><td>6.475</td><td>4.60</td><td>0.525</td><td>0.40</td><td>0.42</td><td>8.40</td><td>13.40</td></tr>
<tr><td>5</td><td>6.65</td><td>4.72</td><td>0.35</td><td>0.27</td><td>0.42</td><td>8.40</td><td>13.39</td></tr>
<tr><td colspan="8"></td></tr>
<tr><th>Finer (%)</th><th colspan="2">Cost of materials for 1 block, Size (150*150*150) mm</th><th colspan="2">Cost of materials for 1 block, Size (350*105*165) mm</th><th>Add for labor cost</th><th colspan="2">Cost of a block (Rs.)</th></tr>
<tr><td>10</td><td colspan="2">13.41</td><td colspan="2">24.10</td><td>8.00</td><td colspan="2">32.10</td></tr>
<tr><td>7.5</td><td colspan="2">13.40</td><td colspan="2">24.08</td><td>8.00</td><td colspan="2">32.08</td></tr>
<tr><td>5</td><td colspan="2">13.39</td><td colspan="2">24.06</td><td>8.00</td><td colspan="2">32.06</td></tr>
</table>

5.4. Cost Calculation for CSEB with fly ash

Cost calculation of CSEB with fly ash differs from the CSEB with clay addition based on the fly ash cost. Usually fly ash can be taken from the LakVijaya Thermal Power Plant free of charge and only the transport cost is to be considered. The information taken from local suppliers revealed that the transport cost varies from Rs. 10,000.00 to Rs. 12,000.00 from Puttalam to Colombo. So, the average cost of Rs. 11,000.00 was considered for this calculation.

Transport cost of 1 cube (2.83 m^3) = Rs. 11,000.00

Specific gravity of fly ash = 2.2

1 cube of fly ash = 6226kg

Cost of 1 kg of fly ash = Rs. 1.77

So, cost of CSEB with fly ash addition can be calculated as indicated in Table 5-5 to Table 5-7 for 6%, 8% and 10% cement stabilization.

Table 5-5: Cost Analysis of CSEB with Fly Ash for 10% Cement

Finer (%)	**Soil (Kg)**	**Cost for soil (Rs)**	**Fly ash replacement (Kg)**	**Cost of Fly ash (Rs)**	**Cement (Kg)**	**Cost of cement (Rs)**	**Total (Rs)**
10	6.3	4.47	0.7	1.24	0.7	14.00	19.71
7.5	6.475	4.60	0.525	0.93	0.7	14.00	19.53
5	6.65	4.72	0.35	0.62	0.7	14.00	19.34

Finer (%)	**Cost of materials for 1 block, Size (150*150*150) *mm***	**Cost of materials for 1 block, Size (350*175*100) *mm***	**Add for labor cost**	**Cost of a block (Rs.)**
10	19.71	35.41	8.00	43.41
7.5	19.53	35.09	8.00	43.09
5	19.34	34.75	8.00	42.75

Table 5-6: Cost Analysis of CSEB with Fly Ash for 8% Cement

Finer (%)	**Soil (Kg)**	**Cost for soil (Rs)**	**Fly ash replacement (Kg)**	**Cost of Fly ash (Rs)**	**Cement (Kg)**	**Cost of cement (Rs)**	**Total (Rs)**
10	6.3	4.47	0.7	1.24	0.56	11.20	16.91
7.5	6.475	4.60	0.525	0.93	0.56	11.20	16.73
5	6.65	4.72	0.35	0.62	0.56	11.20	16.54

Finer (%)	**Cost of materials for 1 block, Size (150*150*150) *mm***	**Cost of materials for 1 block, Size (350*175*100) *mm***	**Add for labor cost**	**Cost of a block (Rs.)**
10	16.91	30.38	8.00	38.38
7.5	16.73	30.06	8.00	38.06
5	16.54	29.72	8.00	37.72

Table 5-7: Cost Analysis of CSEB with Fly Ash for 6% Cement

Finer (%)	**Soil (Kg)**	**Cost for soil (Rs)**	**Fly ash replacement (Kg)**	**Cost of Fly ash (Rs)**	**Cement (Kg)**	**Cost of cement (Rs)**	**Total (Rs)**
10	6.3	4.47	0.7	1.24	0.42	8.40	14.11
7.5	6.475	4.60	0.525	0.93	0.42	8.40	13.93
5	6.65	4.72	0.35	0.62	0.42	8.40	13.74
Finer (%)	**Cost of materials for 1 block, Size (150*150*150) *mm***		**Cost of materials for 1 block, Size (350*175*100) *mm***		**Add for labor cost**	**Cost of a block (Rs.)**	
10	14.11		25.36		8.00	33.36	
7.5	13.93		25.33		8.00	33.33	
5	13.74		24.69		8.00	32.69	

Considering the above cost calculation, summary of cost of the blocks is as per Table 5-8. Cost of blocks made with 7% cement was calculated as an average of cost of blocks with 6% and 8% cement. Average selling cost of a cement sand block in the industry is around Rs.42.00. According to this information it can be concluded as these soil blocks with 7.5% finer and 7% cement are cost effective.

Table 5-8: Summary of Cost Calculation for Soil Blocks

Cement %	Unit cost of a block with reduced clay & Silt (Rs.)	Unit cost of a block with fly ash (Rs.)
10	42.50	43.00
8	37.40	38.00
6	32.30	32.50
7	34.85	35.25

5.5. Cost Calculation for Burnt Bricks

Cost of burnt bricks was calculated considering the cost information in Table 5-9. Firing cost was taken from previous researches. The average weight of a brick was revealed as 1.800*kg.* Labour cost per brick is usually Rs. 5.00., The total cost of a burnt-brick could be calculated, considering 25% overhead to account for drying bricks, preparation for kiln and baking etc. When considering the bricks made with 25% fly ash addition, the cost of a brick is around Rs.8.55 which is significantly lower than the cost of bricks available in the market.

Table 5-9: Cost of Burnt Bricks with Extracted Clay

Brick specimen	**Fly ash %**	**Clay amount (*kg*)**	**Cost of Clay (Rs.)**	**Fly ash amount (*kg*)**	**Cost of Fly ash (Rs.)**	**Cost of Materials (Rs.)**	**Total (Rs.)**
EC-F20	20	1.44	1.11	0.36	0.64	1.76	6.76
EC-F25	25	1.35	1.04	0.45	0.80	1.84	6.84
EC-F30	30	1.26	0.97	0.54	0.96	1.93	6.93
EC-F40	40	1.08	0.84	0.72	1.27	2.11	7.11
EC-F50	50	0.90	0.70	0.90	1.59	2.29	7.29

5.6. Cost Calculation for Roof tiles

The weight of prepared roof tiles was 2.772 kg. SLS: 2: 1975 says that the weight should not be more than 2.7 kg. There is a small mass increment in the prepared tiles. With further investigation, this could be addressed to reduce the tile mass. Extracted clay density was 2510 kg. So, the volume of one tile is 1.1044 x 10^{-3} m^3.

For one tile

Clay weight = 2.079 kg

Fly ash weight = 0.693 kg

Cost of clay = 2.079 x 0.77 = Rs. 1.60

Cost of fly ash = 1.77 x 0.693 = Rs.1.23

Data taken from tile factories

For 500 tiles; electric cost is Rs. 350.00 and the cost for 5 labours is Rs. 7500.00

Firing cost for 3500 tiles is Rs. 4500.00

So, making cost of one tile	= (7500+350)/500 = Rs. 15.70	
Firing cost of one tile	= 4500/3500	= Rs. 1.30
Total cost of one tile	= 1.60+1.23+15.70+1.30	
	= Rs. 19.80	

The production cost of roof tiles with extracted clay was compared with the production cost of market roof tiles. Normally the tiles available in the market have the mass of nearly 3.0 kg. The density of clay is 1860 kg/m^3. So, the volume of one tile is about 1.62×10^{-3} m^3.

Cost of clay	=Rs. 2900.00 for m^3
Material cost of one tile	= 2900 x 0.00162 = Rs. 4.70
Total cost of one tile	= 4.70 + 15.7 + 1.3
	=Rs 21.70

When compared with the Market roof tiles, the new product saves the production cost by 8.75 %.

5.7. Summary

This chapter explained the cost calculation process for the soil-based products considered in this study. Soil-based production started with soil washing. First, work norm was established for soil washing to get the cost of separated finer particles and coarse particles. The cost information was taken as practiced in the construction industry, for the production of other soil-based products. Next chapter will conclude all the processes and results obtained in this study.

CHAPTER 6 : CONCLUSIONS AND FUTURE WORKS

6.1. General Introduction

The study focused on reducing clay and silt in soils by washing process, utilization of washed soils to produce CSEB and the use of removed clay and silt of soils for the production of building materials, mainly clay roof tiles and burnt clay bricks. Optimizing the strength parameters of washed soils by use of particles packing theories, recycling and optimizing the use of water and the use fly ash to produce clay roof tiles and bricks too investigated. The study established that CSEB can be produced with improved strength and durability by the use of soil washing process. Further, up to 60% of water can be re-cycled in the washing process. The removed clay and silt together with fly ash can improve the properties of clay roof tiles and burnt clay bricks. The cost calculations established that the building products of washing soils will be more economical.

6.2. Conclusions

The literature search established that past attempts to improve the strength and durability of CSEB had been investigated by lowering clay and silt content through the use of materials such as sand or by mixing different soils and by use of high content of stabilizers such as cement. The published research had clearly established that strength and durability increase with lower content of clay and silt. The literature search confirmed that past studies was not explored the possibility of lowering of clay and silt of soils by washing process for the production of CSEB. The washing processes have been mainly for the removal of clay in sand for construction work. Further, investigations on the influence of other larger particle sizes have not been extensively performed.

The clay and silt content in the soil was lowered through soil washing. The concrete mixer was used for the washing of soils during the experimental study due to the requirement of recovering clay and silt of the wash and to use low water content.

This established that improved washing process of the mechanics of concrete mixer can be used to remove clay and silt of soils.

Use of high-water content for washing is unavoidable. However, water can be re-used with the use of alum as a coagulant agent. Soil washing helped in two ways; to lower the silt and clay content in the soil and to use separated silt and clay for roof tiles and burnt bricks production. Considering the methods suggested by many researchers to reduce to the clay and silt content in the soil, this soil washing method is perceived as a novel method. The study proves the feasibility of soil washing using a selected soil, suggesting the whole process. Due to the high varieties in soils taken from different places, the same results derived through this study cannot be directly applied. However, the suggested process can be used to find the time for sedimentation, the reusability level of water and the yield of finer.

The first experimental study was focused on washed soils which contain more than 90% of particles larger than clay and silt. To take the whole structure of the particle size distribution into account, the study focused on re-arranging the particle size distribution of the soil to match the optimization curves. Through this, the first objective of the research study (to develop a process to reduce clay and silt from a given soil to produced CSEB) was achieved. Five soil types with different soil grading were first used to check the effect of soil grading on CSEB properties. It shows, that if the soil grading is near the optimization curve, CSEB gains more desirable improvement. Use of washed soil for CSEB production needed rearrangement of soil grading. This rearrangement was done in accordance with particle packing theories. CSEBs produced with this rearranged soil showed improvements in their block properties. For this study, the soil was rearranged for three different clay and silt contents: 5%, 7.5% and 10%. The results show that high compressive strength can be achieved with 7.5% clay and silt content and 8% and 10% cement contents. Most of the compressive strengths are acceptable for Grade I blocks, as per SLS 1382. The dry density and water absorption ratio are also higher than the values specified in SLS 1382.

The study focused on using fly ash as finer instead of silt and clay. The blocks made with fly ash addition showed that 10% cement stabilized blocks, achieved high value for dry and wet compressive strengths and those satisfied the Grade 1 requirements as mentioned in SLS 1382, part II. Also, 8% of cement stabilized blocks achieved the compressive strength values in the Grade 2 blocks range for all the fly ash addition. Even with 6% cement stabilization, 7.5 % fly ash addition gave a compressive strength in Grade 3 range. All the blocks, irrespective of the cement content and fly ash content, have the densities and water absorption values satisfying the SLS 1382 requirements. As a whole, the addition of fly ash as a part of finer resulted in the improvement of properties of CSEB. Since the produced blocks are with very low silt and clay content, these blocks are similar to cement blocks too. Therefore, the values of tested properties were compared with SLS 855 and the block properties were satisfied as per SLS 855. The durability of produced CSEB was tested using accelerated erosion test, wetting expansion and drying shrinkage. All the durability requirements as mentioned in SLS 1382 and SLS 855 were satisfied by the produced CSEB. According to the results obtained considering both strength and durability requirements, the study showed that the washed soil can be used effectively for CSEB production which satisfies the relevant standards. It covers the third objective of the study which is “To determine the properties of soil blocks produced from soil with reduced clay and silt”.

Industrial scaled blocks were made for the selected 7.5% finer and 7% cement stabilization. According to test results, industrial scaled blocks satisfy the requirements of both Compressed Stabilized Earth Blocks and Cement Blocks as given in SLS 1382 and SLS 855 respectively.

The study revealed that the use of separated silt and clay could be used for the production of roof tiles and burnt bricks. Since the properties of extracted soil did not show the sufficient texture and linear shrinkage to produce both the products, bricks and roof tiles, fly ash was added. Fly ash is an industrial waste hence, use of it for these production leads to manage the disposing of fly ash. Results show that addition of 25% fly ash to the extracted clay gives optimum properties to both products. The properties of tested roof tiles and burnt bricks satisfy the requirements given in SLS 2 and SLS 39 respectively. Production of wire-cut bricks also proves that the use of extracted clay with fly ash mixing is a sustainable solution for building materials. According to these results, use of extracted clay for soil-based production can be recommended and it covers the achievement of the second objective of this study.

As the fourth objective of the study, production cost of CSEB, burnt bricks and roof tiles were considered. The cost analysis of blocks also showed that the production cost of a block which is similar to an industry available block is around Rs. 35.00. Considering the average selling price of a block, around 20% profit can be secured from a block. Significant cost reduction with the production of roof tiles and bricks can also be secured.

Finally, it can be concluded that the soil washing process can be used to separate finer particles and coarse particles to produce sustainable building materials as an innovative integrated approach. With this process waste and abundant soil can be utilized effectively by minimizing the adverse effect to the environmental.

6.3. Recommendation for further studies

The experimental study used a concrete mixer for washing process which proved the application of mechanical process for washing, separation of clay and silt and re-cycling of water. This area requires further investigation in the future to identify the best mechanical process and to optimise the use of water.

Soil is very common material and available in large quantities with different ranges of clay and silt, sand and gravel. The study used soils mainly consists of clay and silt in the range of 25% to 40%. This type of soil is used in the construction industry for road and other constructions. However, soils are available outside this range both lower clay and silt and higher clay and silt. The lower range is being used on commercial basis to produce wash sand but washed part of clay and silt is not extracted. Therefore, investigations require to recover clay and silt from soils both higher and lower ranges of this study.

The present study mainly focused on reducing the clay and silt from a soil by soil washing and upgrading the particle size distribution using different range particles separated from the same soil. To change this particle size distribution, it is possible to use different range particles from another source. As an example, crushed construction waste with different sizes or bottom ash can be used.

The production of CSEB requires the use vibrating type machines while generally CSEB use pressed type (often hydraulic) machines. The experimental study used common vibrating type machines used for cement: sand blocks. Therefore, further investigations are required to establish the best machine or the modification required for common cement: sand block making machines to produce best CSEB with lower clay and silt.

For the production of burnt bricks, it is suggested to use open kiln for firing for every mix of fly ash with extracted clay. Wire-cut bricks also can be produced with all the fly ash percentages. Mixing of extracted clay with industry available clay for burnt bricks and roof tile production can be further researched.

REFERENCES

[1] F. Pacheco-Torgal and S. Jalali, “Earth construction: Lessons from the past for future eco-efficient construction,” *Constr. Build. Mater.*, vol. 29, pp. 512–519, 2012.

[2] D. Silveira, H. Varum, A. Costa, T. Martins, H. Pereira, and J. Almeida, “Mechanical properties of adobe bricks in ancient constructions,” *Constr. Build. Mater.*, vol. 28, no. 1, pp. 36–44, 2012.

[3] J. C. Morel, A. Mesbah, M. Oggero, and P. Walker, “Building houses with local materials: Means to drastically reduce the environmental impact of construction,” *Build. Environ.*, vol. 36, no. 10, pp. 1119–1126, 2001.

[4] D. Allinson and M. Hall, “Hygrothermal analysis of a stabilised rammed earth test building in the UK,” *Energy Build.*, vol. 42, no. 6, pp. 845–852, 2010.

[5] F. McGregor, A. Heath, E. Fodde, and A. Shea, “Conditions affecting the moisture buffering measurement performed on compressed earth blocks,” *Build. Environ.*, vol. 75, pp. 11–18, 2014.

[6] J. E. Aubert, P. Maillard, J. C. Morel, and M. Al Rafii, “Towards a simple compressive strength test for earth bricks?,” *Mater. Struct. Constr.*, vol. 49, no. 5, pp. 1641–1654, 2016.

[7] P. J. Walker, “Strength, durability and shrinkage characteristics of cement stabilised soil blocks,” *Cem. Concr. Compos.*, vol. 17, no. 4, pp. 301–310, 1995.

[8] A. L. Murmu and A. Patel, “Towards sustainable bricks production : An overview,” *Constr. Build. Mater.*, vol. 165, pp. 112–125, 2018.

[9] M. Khemissa and A. Mahamedi, “Cement and lime mixture stabilization of an expansive overconsolidated clay,” *Appl. Clay Sci.*, vol. 95, pp. 104–110, 2014.

[10] K. Swapna and K. Giridhar, “Experimental Investigation of Soil Stabilization by using Coir Fiber, Fly Ash and CaCl 2,” vol. 0904, no. 04, pp. 563–568, 2017.

[11] A. M. A. Riza, F.V., Rahman, I.A. and Zaidi, “Possibility of lime as a stabilizer in compressed earth brick (CEB),” *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 1(6), pp. 582-585., 2011.

[12] E. A. Adam and P. J. Jones, “Thermophysical properties of stabilised soil building blocks,” *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, vol. 32, no. 7, pp. 324–325, 1995.

[13] L. K. Aggarwal, “Bagasse-Reinforced Cement Composites,” *Cem. Concr. Compos.*, vol. 17, pp. 101–112, 1995.

[14] D. Maskell, A. Heath, and P. Walker, “Inorganic stabilisation methods for extruded earth masonry units,” *Constr. Build. Mater.*, vol. 71, pp. 602–609, 2014.

[15] J. D. Sitton and B. A. Story, “Estimating Soil Classification Via Quantitative and Qualitative Field Testing for Use in Constructing Compressed Earth Blocks,” in *Procedia Engineering*, 2016.

[16] R. A. Silva, E. Soares, D. V Oliveira, T. Miranda, N. M. Cristelo, and D. Leitão, “Mechanical characterisation of dry-stack masonry made of CEBs stabilised with alkaline activation,” *Constr. Build. Mater.*, vol. 75, pp. 349–358, 2015.

[17] K. Heathcote, “Earthwall construction Compressive strength of cement stabilized pressed earth blocks,” *Build. Res. Inf.*, vol. 19, no. 2, pp. 101–105, 1991.

[18] M. Segetin, K. Jayaraman, and X. Xu, “Harakeke reinforcement of soil-cement building materials: Manufacturability and properties,” *Build. Environ.*, vol. 42, no. 8, pp. 3066–3079, 2007.

[19] Department of Census and Statiistics Ministry of National Policies and Economic Affairs, “Survey on Construction Industries,Final Report,” 2015.

[20] A. Guettala, H. Houari, B. Mezghiche, and R. Chebili, “DURABILITY OF LIME STABILIZED EARTH BLOCKS,” pp. 61–66, 2002.

[21] Perera. A. Jayasinghe C, “Stabilized Soil Block Technology for Sri Lanka,”

in *Research for Industry, Engineering Research Unit, University of Moratuwa, Sri Lanka*, 1999, pp. 147–160.

[22] S. N. Malkanthi and Perera A.A.D.A.J., "Durability of Compressed Stabilized Earth Blocks with Reduced Clay and Silt," in *IOP Conference Series: Materials Science and Engineering*, 2018, vol. 431, no. 8.

[23] B. V. Venkatarama Reddy and K. S. Jagadish, "Embodied energy of common and alternative building materials and technologies," *Energy Build.*, 2003.

[24] M. C. J. Delgado and I. C. Guerrero, "Earth building in Spain," *Constr. Build. Mater.*, vol. 20, no. 9, pp. 679–690, 2006.

[25] C. Jayasinghe, "Comparative Performance of Burnt Clay Bricks and Compressed Stabilized Earth Bricks and Blocks," *Eng. J. Inst. Eng. Sri Lanka*, vol. 40, no. 2, p. 33, 2007.

[26] I. Alam, A. Naseer, and A. A. Shah, "Economical stabilization of clay for earth buildings construction in rainy and flood prone areas," *Constr. Build. Mater.*, vol. 77, pp. 154–159, 2015.

[27] Rizna Azoor, .Rangika Halwathura and. Chameera Udawattha, "Manufacturing framework and Cost optimization for Building Mud concrete Blocks (MCB)," *Mobilization Mod. Technol. Sustain. Dev. Asia*, p. 112, 2016.

[28] F. R. Arooz and R. U. Halwatura, "Case Studies in Construction Materials Mud-concrete block (MCB): mix design & durability characteristics," *Case Stud. Constr. Mater.*, vol. 8, no. June 2017, pp. 39–50, 2018.

[29] S. Sheweka, "Using mud bricks as a temporary solution for GaZa reconstruction," *Energy Procedia*, vol. 6, pp. 236–240, 2011.

[30] "Compressed Earth Blocks." [Online]. Available: https://en.wikipedia.org/wiki/compressed earth block.

[31] "Compressed Stabilised Earth Block." [Online]. Available: http://www.earth-auroville.com/compressed_stabilised_earth_block_en.php. [Accessed: 19-Jul-2019].

[32] Sri Lanka Standard Institution, “SPECIFICATION FOR COMPRESSED STABILIZED EARTH BLOCKS:Part 1 Requirements,” Colombo, 2010.

[33] Sri Lanka Standard Institution, “SPECIFICATION FOR COMPRESSED STABILIZED EARTH BLOCKS:Part 2 Test Methods,” Colombo, 2010.

[34] Sri Lanka Standard Institution, “SPECIFICATION FOR COMPRESSED EARTH BLOCKS:Part3 Guidelines on Production,Design andConstruction,” Colombo.

[35] H. D. Shrestha, “Standard Norms and Specification for CSEB Block.”

[36] V. Rigassi and CRATerre-EAG, *COMPRESSED EARTH BLOCKS: MANUAL OF PRODUCTION Volume I. Manual of production A Publication of the Deutsches Zentrum für Entwicklungstechnologien -GATE in: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH in coordination with BASIN -1985*, vol. I. 1985.

[37] D. J. Harris, “A quantitative approach to the assessment of the environmental impact of building materials,” *Build. Environ.*, 1999.

[38] A. Mujahid, A. Zaidi, F. V. Riza, and I. A. Rahman, “Preliminary Study of Compressed Stabilized Earth Brick (CSEB),” *Aust. J. Basic Appl. Sci.*, vol. 5, no. 9, pp. 6–12, 2011.

[39] C. Jayasinghe, A. Perera, and S. West, “The Application of Hand Moulded Stabilised Earth Blocks for Rural Houses in Sri Lanka,” *Proceeding EARTBUILD 2005 Conf. Univ. Sydney*, pp. 178-187 BT-Proceedings of Earth Build 2005, Int, 2005.

[40] H. B. Nagaraj, M. V Sravan, T. G. Arun, and K. S. Jagadish, “Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks,” *Int. J. Sustain. Built Environ.*, vol. 3, no. 1, pp. 54–61, 2014.

[41] C. Udawattha and R. Halwatura, “Embodied energy of mud concrete block (MCB) versus brick and cement blocks,” *Energy Build.*, vol. 126, pp. 28–35, 2016.

[42] C. Udawattha and R. Halwatura, “Advances in Building Energy Research

Thermal performance and structural cooling analysis of brick , cement block , and mud concrete block,” *Adv. Build. Energy Res.*, vol. 0, no. 0, pp. 1–14, 2016.

[43] C. Jayasinghe, “Embodied energy of alternative building materials and their impact on life cycle cost parameters,” pp. 1–20.

[44] “Compressed Stabilized Earth Blocks.” [Online]. Available: https://houseconmin.gov.lk/compressed-stabilized-earth-blocks/. [Accessed: 12-Jul-2019].

[45] C. Jayasinghe, “Characteristics of Different Masonry Units Manufactured with Stabilized Earth,” *Int. Symp. Earthen Struct. Indian Inst. Sci. Bangalore*, pp. 252–258, 2007.

[46] Perera A.A.D.A.J. and Jayasinghe C, “Strength characteristics and structural design methods for compressed earth block walls,” *Mason. Int.*, vol. 16(1), pp. 34–38, 2003.

[47] H. B. Nagaraj, A. Rajesh, and M. V Sravan, “Influence of soil gradation , proportion and combination of admixtures on the properties and durability of CSEBs,” *Constr. Build. Mater.*, vol. 110, pp. 135–144, 2016.

[48] R. Fitzmaurice, “Manual on Stabilized Soil Construction for Housing,” *United Nations Tech. Assist. Program. NewY ork*, 1958.

[49] B. V. Venkatarama Reddy and M. S. Latha, “Influence of soil grading on the characteristics of cement stabilised soil compacts,” *Mater. Struct. Constr.*, vol. 47, no. 10, pp. 1633–1645, 2014.

[50] C. Jayasinghe, “Stablized soil block technology for Sri Lanka,” *Proc. Annu. Symp. Eng. Res. Unit, Univ. Moratuwa, Sri Lanka*, pp. 147–160, 1999.

[51] B. V. Venkatarama Reddy and P. Prasanna Kumar, “Cement stabilised rammed earth. Part A: Compaction characteristics and physical properties of compacted cement stabilised soils,” *Mater. Struct. Constr.*, vol. 44, no. 3, pp. 681–693, 2011.

[52] B. V. Venkatarama Reddy and P. Prasanna Kumar, “Cement stabilised

rammed earth. Part B: Compressive strength and stress-strain characteristics," *Mater. Struct. Constr.*, vol. 44, no. 3, pp. 695–707, 2011.

[53] M. C. N. Villamizar, V. S. Araque, C. A. R. Reyes, and R. S. Silva, "Effect of the addition of coal-ash and cassava peels on the engineering properties of compressed earth blocks," *Constr. Build. Mater.*, vol. 36, pp. 276–286, 2012.

[54] R. Alavéz-Ramírez, P. Montes-García, J. Martínez-Reyes, D. C. Altamirano-Juárez, and Y. Gochi-Ponce, "The use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks," *Constr. Build. Mater.*, vol. 34, pp. 296–305, 2012.

[55] S. Guettala, "Properties of the Compressed-Stabilized Earth Brick Containing Cork Granules Journal of Earth Science and Climatic Properties of the Compressed-Stabilized Earth Brick Containing Cork Granules," vol. 9, no. May, 2016.

[56] J. C. Morel, A. Pkla, and P. Walker, "Compressive strength testing of compressed earth blocks," *Constr. Build. Mater.*, vol. 21, no. 2, pp. 303–309, 2007.

[57] B. V. Venkatarama. Reddy. and K. S. N. R. K.S. Jagadish, *Alternative Building Materials and Technologies*. New Delhi: New Age International (P) Limited, 2007.

[58] H. Danso, D. B. Martinson, M. Ali, and J. B. Williams, "Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres," *Constr. Build. Mater.*, vol. 101, pp. 797–809, 2015.

[59] J. C. Smith and C. Augarde, "Optimum water content tests for earthen construction materials," *Proc. Inst. Civ. Eng. - Constr. Mater.*, vol. 167, no. 2, pp. 114–123, 2013.

[60] S. H.Patil, "Research on Inter Locking Stabilised Soil Bricks (I.S.S.B.) a Literature Survey," *Int. J. Res. Eng. Technol.*, vol. 05, no. 03, pp. 375–378, 2016.

[61] F. G. Bell, *Engineering Treatment of Soils; Soil Stabilization*. E and EN

SPON, London, UK, 1993.

[62] A. A. D. A. J. Perera. C. Jayasinghe, “Hand Moulded Cement Stabilized Soil Blocks as a Walling Material,” no. June, 2016.

[63] A. Y. B. Anifowose, “Stabilisation of lateritic soils as a raw material for building blocks,” *Bull. Eng. Geol. Environ.*, vol. 58, no. 2, pp. 151–157, 2000.

[64] P. S. S. Razvi, D. Nannaware, S. Bankar, A. Yadav, H. Shaikh, and C. Engineering, “STUDY ON STABILIZATION OF SOIL USING BURNT BRICK,” pp. 2757–2770, 2018.

[65] İ. Türkmen, E. Ekinci, F. Kantarcı, and T. Sarıcı, “The mechanical and physical properties of unfired earth bricks stabilized with gypsum and Elazığ Ferrochrome slag,” *Int. J. Sustain. Built Environ.*, vol. 6, no. 2, pp. 565–573, 2017.

[66] H. Danso, B. Martinson, M. Ali, and C. Mant, “Performance characteristics of enhanced soil blanks: a quantitative review - Supplementary tables,” *Build. Environ.*, pp. 1–11, 2014.

[67] B. S. Waziri, Z. A. Lawan, and M. Mala, “Properties of Compressed Stabilized Earth Blocks (CSEB) For Low- Cost Housing Construction: A Preliminary Investigation,” *Int. J. Sustain. Constr. Eng. Technol.*, vol. 4, no. 2, pp. 2180–3242, 2013.

[68] R. Bahar, M. Benazzoug, and S. Kenai, “Performance of compacted cement-stabilised soil,” *Cem. Concr. Compos.*, vol. 26, no. 7, pp. 811–820, 2004.

[69] F. McGregor, A. Heath, E. Fodde, and A. Shea, “Conditions affecting the moisture buffering measurement performed on compressed earth blocks,” *Build. Environ.*, 2014.

[70] American Society of Testing Materials, “ASTM D559, Wetting and Drying Compacted Soil-Cement Mixtures,” 1989.

[71] John Atkinson, “Based on part of the Geotechnical reference package,” City University, London.

[72] B. V. V. Reddy and S. S. Lokras, “Steam-cured stabilised soil blocks for masonry construction,” *Energy Build.*, 1998.

[73] “BSI Standards Publication Guide to durability of buildings and building elements , products and Components,” 2015.

[74] K. P. Arandara and C. Jayasinghe, “Identification of Durability Problems in Earth Buildings,” *Eng. J. Inst. Eng. Sri Lanka*, vol. XXXX, no. 04, pp. 14–21, 2007.

[75] A. R. Shahiar. & B. B. M. S. Islam, M. I. Hossain, M.A. Islam, “Construction of Earthen house using CSEB: Bangladesh Perspective,” in *3rd International Conference on Advances in Civil Engineering, CUET, Chittagong, Bangladesh*.

[76] K. K. G. K. D. Kariyawasam and C. Jayasinghe, “Cement stabilized rammed earth as a sustainable construction material,” *Constr. Build. Mater.*, vol. 105, pp. 519–527, 2016.

[77] E. Obonyo, J. Exelbirt, and M. Baskaran, “Durability of Compressed Earth Bricks: Assessing Erosion Resistance Using the Modified Spray Testing,” pp. 3639–3649, 2010.

[78] S. A. A. M. Fennis and J. C. Walraven, “Using particle packing technology for sustainable concrete mixture design,” *Heron*, vol. 57, no. 2, pp. 73–101, 2012.

[79] M. Mangulkar and S. Jamkar, “Review of Particle Packing Theories Used For Concrete Mix Proportioning,” *Int. J. Sci. Eng. Res.*, vol. 4, no. 5, pp. 143–148, 2013.

[80] M. Santhanam, “Particle packing theories and their application in concrete mixture proportioning : A review,” no. November, 2017.

[81] V. Wong, K. Wai Chan, and A. Kwok Hung Kwan, “Applying Theories of Particle Packing and Rheology to Concrete for Sustainable Development,” *Organ. Technol. Manag. Constr. An Int. J.*, vol. 5, no. 2, pp. 844–851, 2013.

[82] H. A. C. K. Hettiarachchi and W. K. Mampearachchi, “Validity of aggregate

packing models in mixture design of interlocking concrete block pavers (ICBP),” *Road Mater. Pavement Des.*, vol. 0, no. 0, pp. 1–13, 2017.

[83] T. C. Power, *The Properties of Fresh Concrete*. New York: Willey, 1968.

[84] Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation Government of India New Delhi, “TECHNO ECONOMIC FEASIBILITY REPORT ON FLYASH BRICKS.”

[85] “Fly Ash, Building & Construction Material.” [Online]. Available: http://cementationindia.com/fly-ash.html. [Accessed: 11-Jul-2019].

[86] A. A. Landman, “Aspects of solid-state chemistry of fly ash and ultramarine pigments,” no. December, 2004.

[87] G. P. Makusa, “State of the Art Review Soil Stabilization Methods and Materials,” *J. STATE ART Rev.*, pp. 1–30, 2012.

[88] A. A. Sofi, T. A. Sheikh, R. A. Wani, and A. Manzoor, “Cement stabilized earth blocks (CSEB): An economic and eco- friendly building material .,” *IOSR J. Mech. Civ. Eng.*, vol. 13, no. 6, pp. 6–11, 2016.

[89] American Society of Testing Materials, “ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use,” 2014.

[90] Aakash Suresh Pawar, “Engineering Properties of Clay Bricks With Use of Fly Ash,” *Int. J. Res. Eng. Technol.*, vol. 03, no. 21, pp. 75–80, 2015.

[91] A. Nataatmadja, “Development of low-cost fly ash bricks,” no. August, pp. 831–843, 2015.

[92] S. Karthik, E. Ashok, P. Gowtham, G. Elango, D. Gokul, and S. Thangaraj, “Soil Stabilization By Using Fly Ash,” vol. 10, no. 6, pp. 20–26, 2014.

[93] C. Egenti, J. M. Khatib, and D. A. Oloke, “High Carbon Fly ash and Soil in Shelled Compressed Earth Masonry Units,” no. December, 2015.

[94] T. S. Shetty, K. B. Rao, and B. J. Pai, “A Feasibility Study on the Compressive Strength of Flyash and Lime Stabilized Laterite Soil Blocks,” *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 5, no. 9 (Spl), pp. 73–80, 2016.

[95] F. G. Bell, “GEOLOGY Lime stabilization of clay minerals and soils,” vol. 42, pp. 223–237, 1996.

[96] L. Miqueleiz *et al.*, “The use of stabilised Spanish clay soil for sustainable construction materials,” *Eng. Geol.*, vol. 133–134, pp. 9–15, 2012.

[97] A. A. Raheem, D. Ph, O. A. Bello, B. Tech, O. A. Makinde, and B. Tech, “A Comparative Study of Cement and Lime Stabilized Lateritic Interlocking Blocks A Comparative Study of Cement and Lime Stabilized Lateritic Interlocking Blocks .,” no. November, 2015.

[98] A. . Ngowi, “Improving the traditional earth construction: a case study of Botswana,” *Constr. Build. Mater.*, vol. 5(6), pp. 4–7, 1997.

[99] E. G. Akpokodje, “The stabilization of some arid zone soils with cement and lime,” *Q. J. Eng. Geol. Hydrogeol.*, vol. 18, no. 2, pp. 173–180, 1985.

[100] O. Izemmouren and S. Guettala, “Mechanical Properties and Durability of Lime and Natural Pozzolana Stabilized Steam-Cured Compressed Earth Block Bricks,” *Geotech. Geol. Eng.*, vol. 33, no. 5, pp. 1321–1333, 2015.

[101] J. A. Bogas, M. Silva, and G. Gomes, “Unstabilized and stabilized compressed earth blocks with partial incorporation of recycled aggregates of recycled aggregates,” *Int. J. Archit. Herit.*, vol. 00, no. 00, pp. 1–16, 2018.

[102] U. S. Environmental Protection Agency, “A Citizen ’ s Guide to Soil Washing,” pp. 1–4, 1996.

[103] D. A. Genrich, “Isolation and characterization of sand- , silt- , and clay-size fractions of soils,” 1972.

[104] M. A. Y. June, “THE SEPARATION OF CLAY MINERALS BY CONTINUOUS PARTICLES ELECTROPHORESIS,” vol. 54, no. 1966, pp. 937–942, 1969.

[105] M. J. Mann and E. Groenendijk, “First full-scale soil washing project in the USA,” *Environ. Prog.*, vol. 15, no. 2, pp. 108–111, 1996.

[106] L. D. Baver, *Soil Physics*, 3rd ed. New York : Wiley, 1956.

[107] Kata L. Reshel and James M. Ebeling World Aquatic Society, “Screening and Evaluation of Alum and Polymer Combinations as Coagulation / Flocculation Aids to Treat Effluents from Intensive Aquaculture Systems,” vol. 37, no. 2, pp. 191–199, 2006.

[108] M. A. Al, M. Y. Al Ani, and A. M. S. Shihab, “Journal of Environmental Science and Health . Part A : Economical evaluation of using polymers with alum for turbidity removal in water treatment,” vol. 1204, no. June, 2016.

[109] S. Chapter, C. Coagulant, and F. P. Fundamentals, “Coagulation and Flocculation,” pp. 1–6.

[110] M. A. P. Reali, “THE USE OF POLYMER AS FLOTATION AID IN WATER TREATMENT,” vol. 4, no. 2, pp. 159–164.

[111] M. Dondi, G. Guarini, M. Raimondo, and C. Zanelli, “Recycling PC-TV waste glass in clay bricks and roof tiles,” vol. 29, pp. 1945–1951, 2009.

[112] I. Demir and M. Orhan, “Reuse of waste bricks in the production line,” vol. 1323, no. November, 2017.

[113] R. R. Menezes, H. S. Ferreira, G. A. Neves, H. D. L. Lira, and H. C. Ferreira, “Use of granite sawing wastes in the production of ceramic bricks and tiles,” vol. 25, pp. 1149–1158, 2005.

[114] A. Olgun, Y. Erdogan, Y. Ayhan, and B. Zeybek, “Development of ceramic tiles from coal fly ash and tincal ore waste,” vol. 31, pp. 153–158, 2005.

[115] S. Kurama, A. Kara, and H. Kurama, “Investigation of borax waste behaviour in tile production,” vol. 27, pp. 1715–1720, 2007.

[116] A. E. Lavat, M. A. Trezza, and M. Poggi, “Characterization of ceramic roof tile wastes as pozzolanic admixture,” *Waste Manag.*, vol. 29, no. 5, pp. 1666–1674, 2009.

[117] G. T. Factory, “Manufacturing and Characterization of Roof Tiles a Mixture of Tile Waste and Coal Fly Ash Kiremit Atığı ve Kömür Uçucu Külü Karışımından Çatı Kiremiti Üretimi ve Karakterizasyonu,” pp. 1–6, 2017.

[118] D. Ingunza, M. Del Pilar, and L. Andressa, “Use of Sewage Sludge as Raw Material in the Manufacture of Roofs,” no. Cmes, pp. 31–33, 2015.

[119] R. Gaggino, M. J. Positieri, P. Irico, J. Kreiker, R. Arguello, and M. P. A. Sánchez, “Ecological Roofing Tiles Made with Rubber and Plastic Wastes,” *Adv. Mater. Res.*, vol. 844, pp. 458–461, 2013.

[120] F. P. E. Kallas, O. R. K. Montedo, and M. D. de M. Innocentini, “Use of Nickel Slag as Raw Material for Roof Tiles Production,” *Mater. Sci. Forum*, vol. 912, pp. 212–217, 2018.

[121] J. Sutas, A. Mana, and L. Pitak, “Effect of Rice Husk and Rice Husk Ash to Properties of Bricks,” *Procedia Eng.*, vol. 32, pp. 1061–1067, 2012.

[122] G. H. M. J. S. De Silva and M. L. C. Surangi, “Effect of waste rice husk ash on structural , thermal and run-off properties of clay roof tiles,” *Constr. Build. Mater.*, vol. 154, pp. 251–257, 2017.

[123] G. H. M. J. S. De Silva and B. V. A. Perera, “E ff ect of waste rice husk ash (RHA) on structural , thermal and acoustic properties of fi red clay bricks,” *J. Build. Eng.*, vol. 18, no. September 2017, pp. 252–259, 2018.

[124] G. H. M. J. S. De Silva and M. P. D. P. Mallwattha, “Strength , durability , thermal and run-off properties of fired clay roof tiles incorporated with ceramic sludge,” *Constr. Build. Mater.*, vol. 179, pp. 390–399, 2018.

[125] M. A. Rahman, “Properties of clay-sand-rice husk ash mixed bricks,” *Internatlona/ J. Cem. Compos. Light. Concr.*, vol. 9, no. 2, pp. 105–108, 1987.

[126] D. Tonnayopas and P. Tekasakul, “Effects of Rice Husk Ash on Characteristics of Lightweight Clay Brick,” in *Technology and Innovation for Sustainable Development Conference (TISD2008), Faculty of Engineering, Khon Kaen University, Thailand*, 2014, no. January 2008.

[127] S. Adikari. GLM Ariyadasa, SSK Muthurathne, “Investigating the Physical , Mechanical and Thermal Properties of Common Roofing Materials in Sri Lanka,” no. December, 2015.

[128] Bureau of Ceylon, *SLS 2: Specification for clay roofing tiles*. Colombo, 1975.

[129] "How Bricks Are Categorized." [Online]. Available: https://www.thebalancesmb.com/bricks-types-uses-and-advantages-844819. [Accessed: 19-Jul-2019].

[130] N. Phonphuak and P. Chindaprasirt, *Types of waste, properties, and durability of pore-forming waste-based fired masonry bricks*. Elsevier Ltd, 2014.

[131] J. Ingham, "Bricks, terracotta and other ceramics," *Geomaterials Under Microsc.*, pp. 163–170, 2013.

[132] F. M. Fernandes, *Clay bricks*. Elsevier, 2018.

[133] Bureau of Ceylon, *SLS 39: SPECIFICATION FOR COMMON BURNT CLAY BUILDING BRICKS*. Colombo, 1978.

[134] American Society of Testing Materials, "ASTM C117 Standard Test Method for Materials Finer than 75- μ m (No . 200) Sieve in Mineral," *ASTM Stand. Guid.*, vol. 04, no. 200, pp. 1–4, 2003.

[135] American Society of Testing Materials, *ASTM D4318 Standard Test Methods for Liquid Limit. Plastic Limit, and Plasticity Index of Soils*. 2010.

[136] B. V. V. Reddy, Stabilised soil blocks for structural masonry in earth construction. Woodhead Publishing Limited, 2012.

[137] Sri Lanka Standard Institution, "SPECIFICATION FOR CEMENT BLOCKS: Part 1- Requirements," Colombo, 1989.