# THE EFFECTIVENESS OF ALTERNATIVE STABILIZER FOR MUD CONCRETE TECHNOLOGY


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Doctor of Philosophy


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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

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**DECLARATION**

I here by declare that the thesis entitled "The effectiveness of alternative stabilizer for Mud Concrete Technology" submitted by me, for the award of the degree of *Doctor of Philosophy* to University of Moratuwa is a record of bonafide work carried out by me under the supervision of Prof.Rangika Halwatura.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Place: University of Moratuwa

Date: 30/11/2018 ......................................

**(Chameera Dussantha Udawattha)**

**CERTIFICATE**

This is to certify that the thesis entitled "The effectiveness of alternative stabilizer for Mud Concrete Technology" submitted by Chameera Udawattha, University of Moratuwa for the award of the degree of *Doctor of Philosophy*, is a record of bonafide work carried out by him under my supervision, as per the University of Moratuwa code of academic and research ethics.

The contents of this report have not been submitted and will not be submitted either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university. The thesis fulfills the requirements and regulations of the University and in my opinion meets the necessary standards for submission.

Place: University of Moratuwa

Date: 30/11/2018

**(Prof.Rangika Halwatura)**

## ABSTRACT

The building wall is our third skin. Edifice the third skin out of earth has been practiced since prehistoric era, because of the availability of soil as a raw material. Merely soil have many weakness including its geo technical properties of shrink swell, low density and high permeability. In order to convert geotechnical properties into engineering material, there should be a stabilizer. This study was conducted to study alternative stabilizer for earth based construction particular to mud concrete earth construction.

An inventory of potential alternative stabilizers were arose based on an immense literature survey, inspired from nature and from ancestral folk knowledge. Several mix designs were subjected to a strength development study. Overall engineering properties and total life cycle study was conducted according to engineering standards. The durability, cost, thermal performances, embodied energy and life-cycle cost were studied and compared with most available wall construction units. Finally, the impertinent technology was enhanced to use as residential scale technology for poor people in the country. The application and the manufacturing process was advocated among low income villagers to building their houses.

The study has found that natural polymers such as natural rubber latex, pines resin, dawul kurudu, and sugarcane bagasse can enhance the mechanical properties of a mud concrete block. Industrial waste such as fly ash, bottom ash, and rice husk ash can work as an alternative stabilizer. A more advanced technology of geopolymerizing mud concrete block was invented by this study. In the practical construction world, this novel wall material should be testified in front exiting wall material palette. Found that mud concrete block is a suitable solution to replace existing expensive wall construction technology. Finally, the manufacturing process was optimized into the plenteous production process to manufacture mud concrete block in mass scale. More than all, this thesis has given birth to an affordable wall construction technology for poor people in the country.



**Keywords:** *Earth building*, *soil stabilization*,*engineering properties*, *walling material*, *environmental fitness*, *life cycle analysis*.

## ACKNOWLEDGEMENT

*Once upon a time I was crossing the land of dust and fear*
*Looking for a land to seed without fear*
*Then **Dr.Narein Perera** showed me a river,*
*A river running through the land of dust and fear,*
*And he showed me a place and taught me how to seed a tree in the fastest gear,*

*Thank you for allowing me to plant a tree on your soils and let it breathe in your air,*
*And for bearing my dream topiary that provides you nothing but endeavor,*
*You provide rivers and streams for me and to nourish my saple,*
*You ruffle it with your whirly winds for that and much more,*
*Thank you for the pelts of sand and pours of fine, and thank you for erasing my dull*
*Leaves with your magical words,*
*Thank you my dear sir **Prof.Rangika Halwatura** for selflessly giving*
*All that you do have, although at ; times I dont deserve it,*
*There upon many others helped me with fertilizers and continuous supplies,*
*Praneeth Dilshan and Darshana Jayasinghe helped when I planted it.*
*And then Rasangi Lakmini, Himhansi Galkanda, Isuri Shanika Ariyarathne and Devinda*
*eranga water the plant.*
*Rizna Arooz, Kasun Nandapala, and Shakila Pathirana showed the*
*Way to grow it.*
*My big brother **Nadheera Udawattha** removed all the moss on the trunk*
*My younger brother **Sanjaya Udawattha** helped me to root down to the bed rock*
*I have a long way to go with this tree, and it becomes taller than Eifel tower because*
*Of my wife **Shanika and Baby Shaven.***
*It has many branches because **my father** never ever commanded to trim it.*
*Thank you, **my first Mother**, for opening my eyes with your elusive warnings,*
*you are unlucky to see I was growing this tree but another **mother** helped me to grown.*
*But I promise you all; I will grow more and more.*
*I will help others to grow their corn.*
*"Because some trees grow in to heaven"*

**Chameera Dussantha Udawattha**

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## List of Terms and Abbreviations

| | |
|---|---|
| **AWR** | Agard wood resin |
| **BOQ** | Bills of quantities |
| **BR** | Bael Resin |
| **CAB** | Hard soil block |
| **CC** | Cleaning Cost |
| **CP** | Cement slurry plaster |
| **CSEB** | Cement stabalized |
| **DK** | Dawul Kurudu |
| **DCS** | Dry Mean Compressive |
| **DMCS** | Dry Mean Compressive Strength |
| **EC** | Energy Cost |
| **EE** | Embedded energy |
| **FC** | Fixed Cost |
| **FSEB** | Fly Ash stabilized earth blocks |
| **GHG** | Green House Gas |
| **HCB** | Hollow cement Block |
| **IC** | Initial Cost |
| **JR** | Jack Resin |
| **LCC** | Life Cycle Cost |
| **LS** | Linear Shrinkage |
| **MC** | Maintenance Cost |
| **MCB** | Mud concrete Block |
| **NP** | Natural Polymer |
| **NRL** | Natural Rubber Latex |
| **NPV** | Net present values |
| **OC** | Overheads |
| **PR** | Pines Resin |
| **RE** | Refurbishment |
| **RES** | Residential Buildings |
| **RV** | Resale value |
| **SB** | Sugarcane Bagasse |
| **SI** | Suitability Index |
| **TSS** | Tensile splitting strenght |
| **UC** | Utilization Cost |
| **UCS** | Compressive Strength |
| **WAR** | Wood apple resin |

**CHAPTER 1**

# INTRODUCTION

Homo erectus came down from the tree and started walking toward planes. Homo sapiens is a civilized animal who wants to settle himself into a shelter. Still, homo sapiens was covered with skin. And then Homo sapiens managed to remove his hairy skin and started building the third skin. The building is our third skin. A skin protects us from all the environmental constraints. The construction of the third skin is called construction technology. Construction technology was optimized since the human kind started building their settlements. Earliest settlements used earth as the main building material. The best example is the Mesopotamian civilization. Mesopotamian civilization and Hindus valley civilization started to use earth as a building material. Because earth as a construction material is the most extravagantly usable material. Using earth materials to construct a wall has many benefits to the world because using earth can minimize environmental pollution. It has the lowest embodied energy and many eco-friendly qualities.

However, using earth/soil has many disadvantages in an urban context and may pose serious practical difficulties. Sri Lanka is a third world country; the country doesnt have the luxury of importing building materials. Not only the country is poor, but it also needs to build much affordable housing to accommodate the booming population. Therefore, as a nation the country should look into affordable building materials and yet eco-friendly enough to make no harm to the natural setting island, providing the suitable structural capacity to accommodate the urban context requirement in the country.

Therefore, the country's careful consideration has to be given to the suitability and adaptability of such methods and technologies, as most modern and highly sophisticated methods and technologies can create economically adverse conditions to the developing countries by draining their resources to procure sophisticated technology from developed countries. Hence, discoveries of Sri Lankan ancestors (wattle and daub) and improve it with modern technologies such as developed stabilizers would be a considerably advanced research problem.

## 1.1 Background

Mud concrete block is a new wall construction unit developed by the University of Moratuwa. The Mud-Concrete Block has also obtained a patent under Sri Lankan intellectual property act No.36 of 2003 (Halwathura, 2016). The developed technology is to use the earth as raw materials for building earth walling blocks. Mud concrete wall construction units composed with a fraction of soil and cement. The soil has been sorted as 4% cement (minimum), fine$\leq$10% ($\leq$sieve size 0.425mm), sand 5560% (sieve size 0.425mm$\leq$sand $\leq$4.75mm), gravel 3035% (sieve size 4.75mm$\leq$gravel$\leq$ 20mm) and water 18% to 20% from the dry mix. The precise gravel percentage regularizes the strength of the block and the wall. The manufacturing method of mud concrete block is shown in figure 1.1 on page 3. However, the author has conducted research and found that carbon footprint and embodied energy in mud concrete block is comparatively lower to other common wall construction materials such as brick and cement block. Thus, carbon footprint and embodied energy in mud concrete block is due to the addition of cement.

Therefore, this study was conducted to investigate a substitute stabilizer for cement and broader concept to replace cement in the world. This study was initiated with a series of already used alternative stabilizer technologies followed by chemical and strength development studies. The study focused on Mud concrete wall construction technology development.

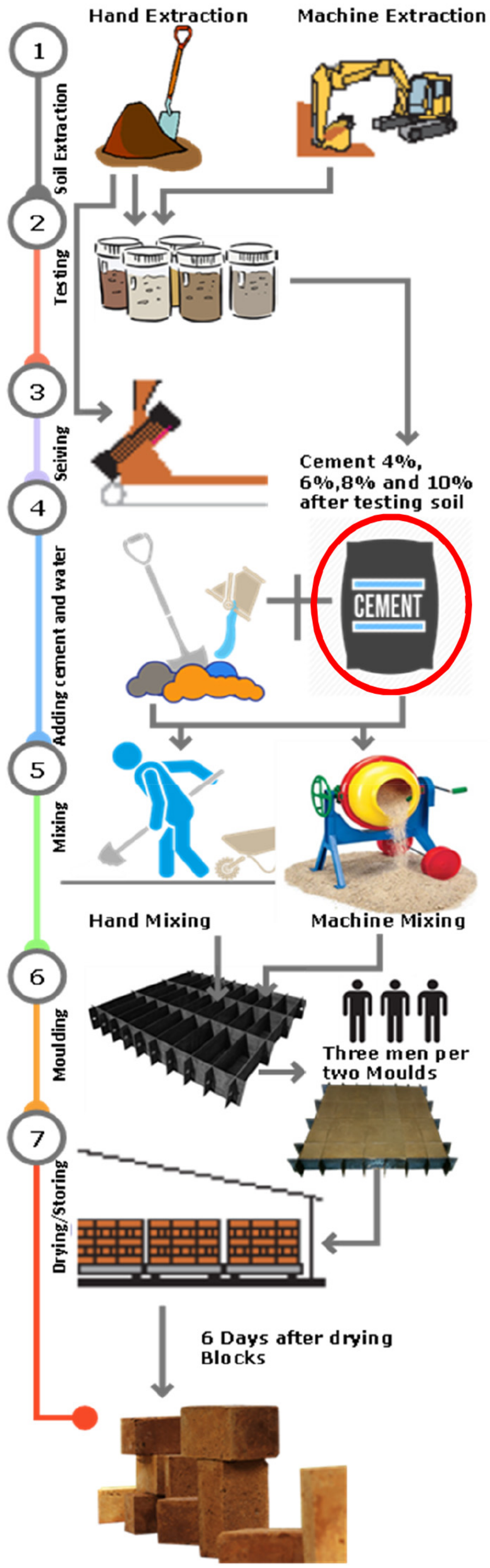



**Fig. 1.1** Mud concrete block manufacturing process

## 1.2 Rationale and research gap

### 1.2.1 Introduction to mud concrete

The idea of stabilizing is to create a bond between two particles. Cement as a stabilizer is used widely on earth due to the availability of raw materials and production method. However, the cement as a stabilizer has many drawbacks. Therefore, searching for an alternative for cement will help to improve not only the mud concrete technology but also the entire construction technology in the world. The earliest civilizations such as Egyptians habituated calcined gypsum; Greeks and Romans used heated limestone powders made by volcanic explosions to make mortar. Finally, Romans build continental scale civilizations by using cement to build bonds. It was Romans who found and named cement pozzolanic cement after the village Pozzuoli near Vesuvius a giant volcano found in Italy.

However, not all civilization had the fortune of using volcanic ash. Britains learn the technology from Romans and developed the technology to produce cement by crushing clay tile and systematically burned with lime to produce cement. It was Joseph Aspdin from the UK who got the first patent for the Portland cement in 1824. Since then Portland cement was developed into many variations to optimize and customized the stabilizing capacity.

The idea of stabilizing is to create a bond between two particles. Cement is such a stabilizer used widely on earth due to the availability of raw materials and production method. But the cement as a stabilizer has much weakness. Therefore, searching for an alternative for cement will help to improve not only the mud concrete technology but also improve entire construction technology in the world.

Construction technology is developing very fast to cater to the booming development in the country. The mother study explored the possibility of mixing mud and cement made the Mud concrete block. But when it comes to the actual scenario, comparatively low income people in the country are unable to afford cement. Hence, this study focused on overall sustainable development such as environmental sustainability, economic sustainability, and socio-cultural sustainability.

### 1.2.2 Searching answers from Nature

The interesting feature of this study is looking for a green alternative stabilizer. Nature is the grand material engineer, it can create abalone shells which are twice tougher than concrete, and silk stronger than steel. But the natural soil stabilization method cannot be executed in the human world. The 21st century is contoured with mass production. Therefore, the discovery of such a stabilizer needs to be scaled up with human production.

### 1.2.3 A search for an economically sustainable alternative stabilizer

This study focused on affordable construction technology. Therefore, every research design decision focused on a technology which is affordable for low income people in the country. Not only affordable in terms of the cost of the materials but also, affordable to use the technology. The technology should be come up with a barely minimum use of materials and equipment. Thus the study focused on developing an alternative technology with low cost in nature.

Further, the economies of scale and mass production were taken into consideration when the design problem was initiated. For example, the idea of optimizing the Mould into a simple technique to follow, So that it could be developed in the home and use by poor people in the country. General public those who work with their day to day equipment should be able to use these technologies to develop their houses and shelters.

### 1.2.4 A search of socio-economic suitability

The research design finally focused on the materials development which is suitable for the general public in the country. Special surveys were conducted in order to identify the requirements of the general public in terms of the color and size of the block. The mud concrete technology was finally optimized to mass scale development where the general craftsman can use the technology to develop their houses. The social appreciation and social acceptance were considered in greater scale to identify and optimize the best suitable technology.

### 1.2.5 A search for an affordable material

Finally, this thesis and the research is beneficial for poor people in the country. Cement is not an affordable material for all Sri Lankans. Therefore, some families are living in mud houses without proper strength and durability. As a result of that most of their social economic development is delayed. Thus the invention of novel walling materials can be a viable solution for them to build their own house by themselves and finally to construct a much affordable house from the earth itself. Therefore, the work described in this thesis focused on an affordable stabilizer to make affordable walling materials.

## 1.3 Objectives

This study was conducted to search for an alternative stabilizer for Mud concrete technology. Cement was the main stabilizer the research objective was becoming to find an alternative for cement. Then the theme objective was becoming handier and the research study was becoming a universal study to research and inventory alternatives for cement. The preparation of an inventory of possible alternative stabilizers was the first objective of this study. Considering the possibility of utilizing them in mud concrete block and studying the strength improvement was the second objective of this study. This is not only the compressive strength testing but also comparing it with the standard procedure test wall construction unit such as tensile splitting strength, density, water absorption, capillary action, surface roughness, durability standards etc. Finally, each and every stabilizer comes with different qualities sizes soon. Therefore, not all soil is suitable for different stabilizers. The final objective was to find out suitable soil mix proportion for each and every stabilizer and to understand the long-term usability, durability, and suitability for the Sri Lankan construction industry. The main objectives of this study as follows;

- To study the possible stabilizer for earth-based construction.
- To Study and compare the structural strength of different stabilizers for soil such as kiln ash, bottom ash and fly ash.
- To analyze the best particle mix; soil and discovered stabilizer, sand, gravel, with moisture.
- To analyze the sustainability index of new wall load bearing wall made of the discovered mixture and investigate the life-cycle cost and carbon footprint of Mud concrete block.
- To analyze the embodied of the mud block as a sustainable building material.
- To analyze the actual life cycle cost of the mud block as a sustainable material.
- To improve and suggest a methodology to develop the performances of the mud block.

## 1.4 The Methodology

This study never followed a linear research method to find out study the suitability of an alternative stabilizer for mud concrete and to alter its technology of mud concrete. The study was initiated on a series of literature, data from ancient inscriptions, folk knowledge and from bucket chemistry experiments *(see the Figure1.2 on page 12)*. However, to confirm the engineering qualities of developed stabilizer stabilized earth blocks, several standard procedures were followed. The summary of the research methodology is as follows.

1. A detail literature study was conducted to understand the earth-based construction technologies from past and present and then theses were categorised into different technological advancements.
   (a) An extended literature survey was conducted to understand the suitability of different stabilizers from earth-based construction. To supplement the literature survey, traveled around the country to find an alternative technology to stabilize soil to produce earth blocks. And studied ancient books to list out an inventory of possible stabilizers.
   (b) Instead of only a literature survey, the author conducted a nature study to understand how nature stable soil to make natural soil stabilization.
2. Prepared an inventory of possible stabilizer which can replace the cement in mud concrete technology.
3. Selected possible stabilizers were randomly mixed with soil by changing the proportions of the stabilizer to find the strength of the mud concrete block.
4. After testing the strength, the availability and workability were studied to develop it as a mud concrete block. Then the selected stabilizers were subjected to further studies to find the engineering property development and the best mix proportions to build mud concrete blocks.
5. After studying engineering properties of the previous experiment, suitable stabilizers were selected to make mud concrete blocks replacing cement.
6. The newly developed walling materials were manufactured in real scale and tested the mechanical and durability properties comparing other mostly available walling material palette.

7. Developed the size, shape and manufacturing method of the new walling materials and understand the usability of the walling block in real-world conditions.

8. Once the durability was tested, the novel walling materials were subjected to fungus growth and moss growth test to study the overall durability for practical use in the Sri Lankan context.

9. After studying the durability and usability in the Sri Lankan context, the novel walling materials were subjected to embodied energy and carbon footprint analysis.

10. The life cycle cost and total lifespan of the walling materials were studied from cradle to grave. And finally, the afterlife of the selected walling materials were studied comparing other most common walling materials in Sri Lanka and ranked to select the suitable walling materials and suitable stabilizer for Sri Lankan walls.

## 1.5 The main findings of this study

This study has several key findings which may contribute to national development. Some of the findings may offer solutions for the environmental issues in Sri Lanka. Some of the findings are reinventing Sri Lankan ancestors technologies. Most importantly some of the discoveries helped to create paths for several new research areas.

### 1.5.1 Patents out of this study are as follows

1. Fly Ash stabilized mud concrete block - Patent Number 19495.

2. Rubber stabilized earth blocks for load-bearing walls - Patent number 19379.

3. Geopolymerized self-compacting mud block - Patent number 19567.

Other than these patented stabilizers, this study has found that fly ash, bakery ash, bottom ash, rice husk burnt to ash, and even house fire ash can be chemically enhanced to use as an alternative stabilizer to make mud concrete blocks. Ancient Sri Lankan technologies such as natural polymers and fiber resin soil stabilization can be developed to certain extent to formulate and enhance the engineering properties of the mud concrete block. This study also found that natural polymers such as pines resin, natural rubber, Bael resin, Dawul Kurudu can be utilized as an alternative stabilizer for mud concrete blocks.

### 1.5.2 New research areas benefited by this study

This study has found a handful of stabilizers and most of them can be developed to a certain extent. Some of the findings opened up the path for new study areas and these are already been carried out under the same supervisor. This study also developed a novel method for calculating embodied energy and life-cycle cost of a wall construction material. The developed method is already published and used by many scholars. The idea of structural cooling phenomena happening inside a mud wall was thoroughly studied by this study. Interesting durability factors such as wind-driven rain (WDR) and bouncing drop rain (BDR) were examined by this study. Moss growth and mold growth are environmental constraints occurring in tropical walls. However, there are only a few studies and few standards methods were developed in the world to study the moss growth and mold growth. This study has developed a novel method for analyzing the moss growth and enhance the existing standard to evaluate the mold growth on wall surfaces.

1. Development of soil based wall finisher for tropics.
2. Mechanical properties of rubber stabilized mud concrete blocks.
3. Use of plastic waste as a filler material for mud concrete blocks.
4. Develop a mud based 3D printing material

### 1.5.3 This is a felicitous study

More than a passing acquaintance with new data and publishing articles, this study has developed an optimized method of manufacturing mud concrete blocks. The technology manufacturing has resulted in an industrial scale mud concrete production and job opportunities to manufacture mud concrete block in Sri Lanka.

## 1.6 Thesis layout

Soil stabilization is not a novel method to the world. Not only humans but also in the animal kingdom, there are many scenarios of soil stabilization. Nature is the grand materials engineer. It can create the abalone shells twice as toughest as our latest high tech ceramic and it can create silk stronger than steel. And also, our own ancestors are smarter than our modern world. Therefore, this study started with a inventory of possible stabilizers and then selected stabilizers were experimented alone with mud and soil to see the strength development as shown in the Figure1.2 on page 12.

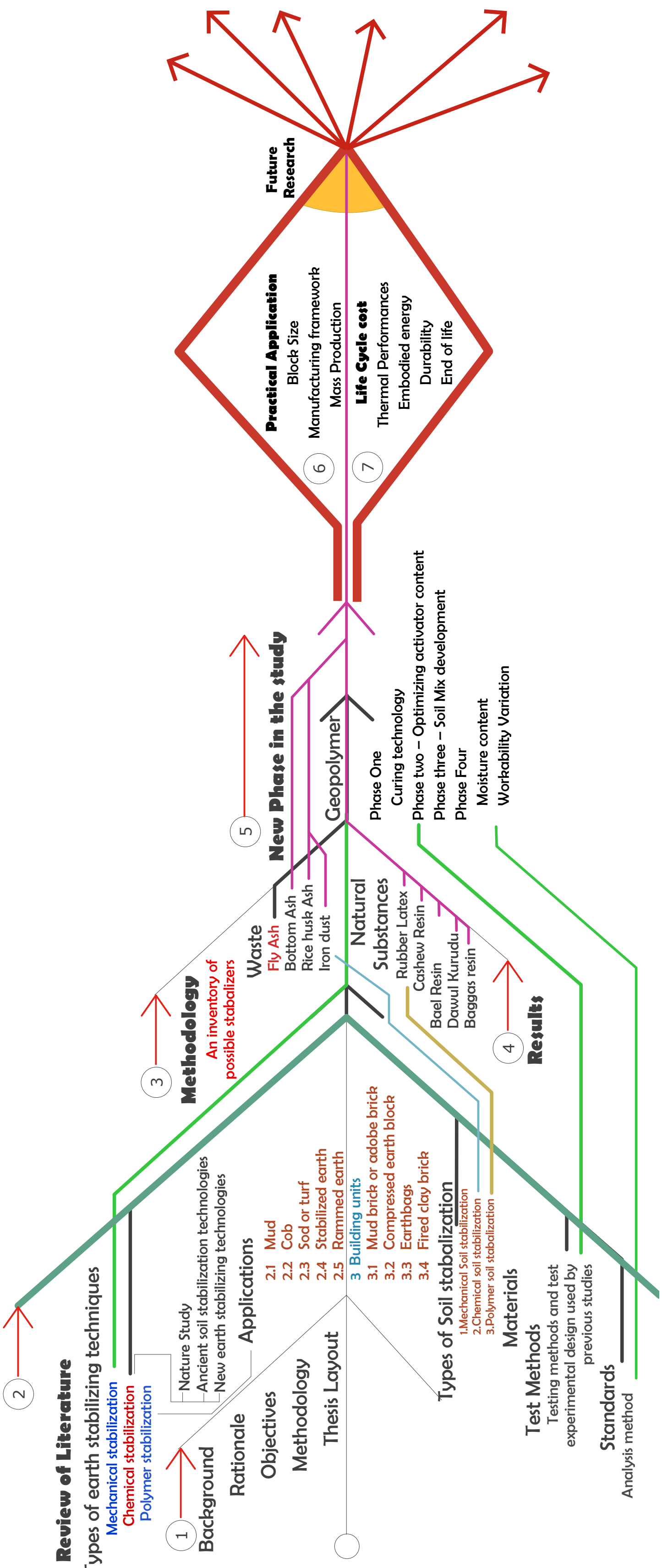



**Fig. 1.2** The layout of the Thesis

# CHAPTER 2

# REVIEW OF LITERATURE

## 2.1 General

Soil stabilization is not a novel thing to the world. There are many scenarios of soil stabilization even in the animal kingdom. Not only nature but also our ancestors used soil stabilizing technologies. They have been used zero cement technologies to stabilize the soil to create structures which were long last more than thousand years. Most of these technologies became folk science and abandoned after the end of the civilization. Therefore, instead of conducting a simple literature review of existing soil stabilizing technologies this study has subjected the literature into three sections namely.

1. Nature study
2. Ancient soil stabilizing technologies and
3. New earth stabilizing technologies.

However, in order to understand the soil stabilizing techniques, the stabilizers were divided into three sections considering their method of soil stabilizers such as mechanical soil stabilization, chemical soil stabilization, and polymeric soil stabilization.

### 2.1.1 Types of soil based constructions

The soil is a dynamic material that can be found in many parts of the world (Alpan, 1970). Its dynamic quality can be used to develop different types of walling materials.

The quality of different soil samples can be differentiated according to the particles size and the composition of the soil. Not only the quality of the soil available, However, also the availability of other raw materials affects the types of earth construction from one place to another (Nurul et al., 2010). For an example, most of the tropical countries like Sri Lanka use wattle and daub and hot arid countries use earth cut brick since they do not have enough water to build wattle and daub (Dissanayaka, 2016). However, other building materials such as availability of timber etc. may impact the type of earth structures (Pacheco-Torgal and Jalali, 2012).

### 2.1.2 Soil based construction in the world

Earth structures are a type of building made largely from soil and soil-related building components (Eires et al., 2013; Lima et al., 2012). The soil was most popular because of its availability on earth (Cesaretti et al., 2014; den Biggelaar, 1998; Villamizar et al., 2012). The soil has the plastic quality of deforming into many shapes and sizes even without undergoing many processes. Such qualities help to develop a soil based construction industry in the world and develop the industry in the local conditions as well (R. Arooz et al., 2015).

However, the soil has drawbacks, therefore, humankind invented different stabilizers to improve the quality of soil into construction materials (Latifi et al., 2015; J. Li et al., 2014). Even from the very beginning cradle of the civilization soil (earth may be combined with other materials, stabilizers, compressed and/or baked to add extra strength. Acquiring the strength and improving the strength of the soil was the only issue to resolve other than building out of the soil (Daniel T. Potts, n.d.). Because the soil was the most economical building materials for early man to use; it is the most affordable walling material for the world and may have a low environmental impact both during and after construction (Pacheco-Torgal and Jalali, 2012).

In order to gain more strength in the soil structures, early man used a straw and dried leaves (Christoforou et al., 2015). This was initially used in the Mesopotamian

**Fig. 2.1** Sun-baked straw combined brick from Mesopotamian civilization
source: http://www.biblearchaeology.org

civilizations where they used sun-baked bricks and the main stabilizer was straw *(see Figure2.1)*. The use of straw and soil called sod bricks and was called terrain in Spanish. The sod is a combination of a heavy mat of grassroots, which may be found in river bottomlands and grasslands. The European settlers on the North American Grasslands found that the sod walls are least likely to deteriorate due to harsh weather conditions. Sod walls were used for the walls of houses in Ireland. Scotland and Iceland, where some turf houses may still exist as a tradition of sod brick (Bahar et al., 2004; Illampas et al., 2014; Noble, 2007).

After the sod brick invention, mankind invented baked brick such as sun-baked brick and kiln-baked bricks. The main stabilizers of the sun-baked bricks and kiln baked bricks are mud(dust). Therefore, not all the types of soil are suitable for this manufacturing. However, there are many structures made of sun-baked bricks and kiln-baked brick on earth. Indus valley civilization is one of the most famous users of sun-baked bricks and kiln baked bricks (Benefits and Materials, 2009; M. Hammond, 1990).

Building out of bricks or blocks have much impedance. The construction of brick walls consumes time and labor. Therefore, human-kind invented in-situ wall and rammed earth. However, in-situ walls and rammed earth decay due to lack of stabilizers in the material (Maniatidis and Walker, 2003). Lime and other carbonate chemicals were used to strengthen the soil and used to building rammed earth and in-situ earth walls (Maniatidis and Walker, 2003; Pacheco-Torgal and Jalali, 2012). There have been many

**Fig. 2.2** World early civilization rammed earth building
Source : Visionary Journeys (Tian, 2011)

experiments using lime and many other stabilizers to develop the composition of soil based walls (Nagaraj et al., 2014). The famous wattle and daub walls made in European countries have the same materials combination of earth and lime. By adding lime to the soil they expected more lifespan, because carbonated soil structures have more impressive strength than just earth structures. Therefore, researches did experiments with different stabilizers such as cement and lime (Ciancio et al., 2014). Cement and lime consume a large amount of energy in their production stage, therefore the embedded energy of cement and lime are very expensive (Dias, 2013; Emmanuel et al., 2005; Monahan and Powell, 2011).

To improve the strength of soil based constructions scholar and researchers have invented to combine soil with cement and gypsum and improve the quality of earth-based construction (Hu et al., 2015). Romans are the first to invent a combination of soil and porcelain volcanic dust to develop a low-cost earth-based construction. Romans used volcanic dust (gypsum) and build roman concrete by using earth (H.Kosmatka and L.wilson, 2011; Lynne C. Lancaster, n.d.).


**Fig. 2.3** The wattle or warichchi walls

### 2.1.3 Soil-based constructions in Sri Lanka.

Sri Lanka has the worlds biggest brick building (Ranaweera, 2004). However, there were many experiments in the country to build earth structures. For an example, the first building *(the black building)* built after the incarnation of Mahinda Thero, there was a soil based structure and then fired using biomass (Ven. Mahanama Thera, 1912). After the dawn of the Sri Lankan civilization; Anuradhapura, Polonnaruwa, and many eras used fired bricks. The use of fired brick was famous in the upper-class families. However, not lower class families (Knox, 1681). Most of the lower class people used wattle and daub walls since they are prohibited to use lime. There are no stabilizers in wattle and daub walls (Figure2.3), therefore wattle and daub wall decay faster (Rohintan,Emmanuel, 2004). Hence our ancestors used lime as a weather insulator to reduce the decay in wattle and daub walls (Knox, 1681).

However, the majority built wattle and daub house because its affordable and availability of craftsmanship (V. T. L. Bogahawatte, 2009). Even after the independence, the trend of using mud and soil as walling material continues in some of the wet and dry areas in the country. Using earth /soil as a walling material has many weaknesses such as strength and durability. Thence, the ancient mud wall has been developed into a mud concrete wall by using cement as stabilizers (Sri Lankan Patent No 17616; (Halwathura, 2016). Cement is a very good stabilizer for soil (Bahar et al., 2004).

Wattle and daub have become the most popular affordable wall construction material in Sri Lanka. Even in modern day wattle and daub are very popular wall construction materials available all around the country (Emmanuel et al., 2005). This is due to the composition of Sri Lankan soil such as reddish brown latosolic soils (partially lateralized soils) addition; immature brown loams (clayey loams). Among the other important soil types are the alluvials that occur along the lower courses of rivers and the regosols (sandy soils) of the coastal tracts. The Sri Lankan soil has this greater strength and also it has been delayed for a million years. However, from every beginning in Sri Lankan civilization, lower class people were building their dwellings by using wattle and daub structures and the major stabilizer for the wattle and substructures are the dust contained in the soil itself (Cowan, 1998; Nicholson et al., 2000; Paula, 2006).

### 2.1.4 Modern developments in soil based constructions.

The development of soil based construction did not end due to the modernization of the humankind. Even after the 19th century, humankind observed the value of the earth based constructions. Most of the Architects and engineers have started promoting earth based constriction technologies as a low cost and yet sustainable walling materials to building structures in the world (Venkatarama Reddy and Prasanna Kumar, 2011). Thence many scholars were experimenting with different earth materials to build more sustainable and strong buildings out of earth (Bui et al., 2009; Donkor and Obonyo, 2015).

## 2.2 Soil stabilization

Soil stabilization is by definition is a modification of soil to enhance its physical properties. Stabilization can enhance the shear strength of soil (James and Kasinatha Pandian, 2014). Soil stabilization can improve shrink-swell properties of soil and improve the load-bearing capacity of the soil to support construction requirements. The idea of soil stabilization is to change the geotechnical properties of soil into engineer properties. The geotechnical properties of soil include such as shrink-swell properties, plasticity limit etc. (Carreon, 2006; Hossain et al., 2007; Lorenz et al., 2007; Rashid et al., 2017).

Soil can be improved to an engineering property such as compressive strength, tensile splitting strength, density improvement, low water absorption etc. There are three methods of soil stabilization. Most of these technologies are well defined and developed to stabilize soil for earth construction, paving construction and for road construction. Therefore, the know-how of soil stabilization has widely known all over the world (Amu et al., 2011; Geiman, 2005; James and Pandian, 2015).

## 2.3 Types of soil stabilization

There are three main types of soil stabilization such as

1. Mechanical soil stabilization
2. Chemical soil stabilization and
3. Polymeric soil stabilization.

### 2.3.1 Mechanical soil stabilization

Mechanical soil stabilization is, mechanically changing the property of the soil (usually by using compressing force), in order to improve its gradation, solidity, and other characteristics. Compaction is one of the common types of soil stabilization (Afrin, 2017). In this procedure, a heavyweight is discharged to the layer of soil repeatedly to prepare earth walls. The most common earth building application is the rammed earth. Rammed earth is constructed by using the mechanical soil stabilization technology. The ancient Sri Lankan transcripts say the soil in Ruwanmelisaye was rammed from six feet to one foot by using elephants. These are the oldest technologies of soil stabilization (Norman, 2015).

There are many mechanically soil stabilized earth technologies in the world. The first technology is the rammed earth technology. The rammed earth technology is not a novel technology. It was first invented by Chinese to build dessert structures (Tian, 2011). And then it was developed as a walling material in African plains and European countries. The rammed earth technology was dispersed all over the world (Hall, 2007; Kapsalis and Symeonidis, 2009; Maniatidis and Walker, 2003; Pacheco-Torgal and Jalali, 2012; Padavic and Mulligan, 2002).

### 2.3.2 Chemical soil stabilization

The chemical soil stabilization relies on adding an additional chemical and mix with soil to react with soil. The chemical can enhance the physical soil properties (Saljnikov and Cakmak, 2016; Thomas, 2002). Cement is the most common chemical stabilizer for soil (Raj, 2005; Rujikiatkamjorn et al., 2005; Scott and Schoustra, 1968). The cementitious reaction refers to pozzolanic in nature (Brandt, 1994; Chengula, 2018; Malhotra and Mehta, 1996; Ramezanianpour, 2013). Pozzolanic chemical enhancements do not improve the tensile ability of the soil. Burning, and heating is also a type of chemical soil stabilization. The heating may improve the bonding ability between soil particles finally creating a brick out of the swell mud on earth. There are two types of chemical stabilization methods (Basha et al., 2005; Harris et al., 2006).

1. Heating and changing the chemical composition of the soil

2. Chemical stabilization by enhancing bonding links

The purpose of the chemical soil stabilization is to enhance the chemical properties of the soil. Cement is the most common soil stabilizer and lime is the oldest chemical soil stabilizer. Cement and lime change the chemical formation of the soil and then create a bond between soil particles. Portland cement and lime reacts with fine particles in the soil to produce engineering properties. The use of additional materials to interact with soil, then finally change the properties of soil is the purpose of chemical soil stabilization. The chemical soil stabilization is a natural phenomenon occurred in volcanic sites. The use of lava dust, ash, and smoke particles finally land on soil and the addition of rainwater creates hardy soil layers.

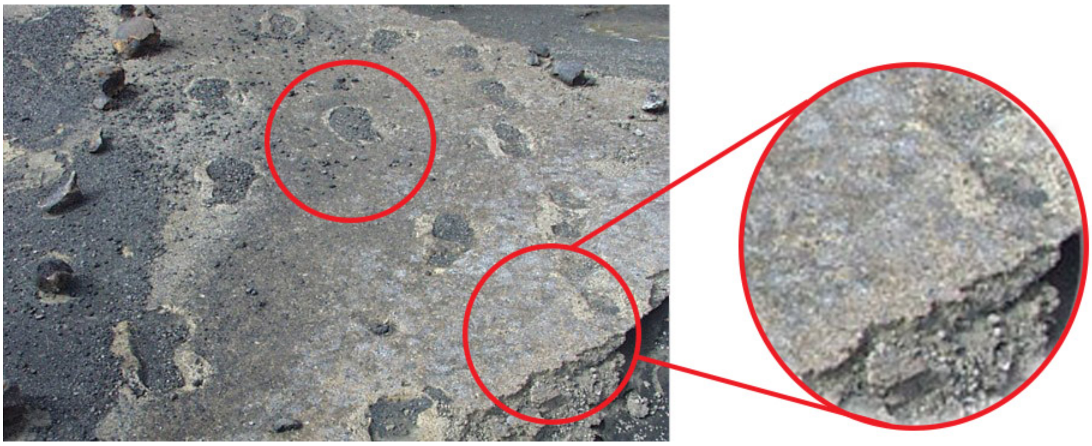


**Fig. 2.4** Volcanic ash landed on the surface of natural soil
source: www.sciencenews.org

In the human world, the most common method of chemically soil stabilization is the use of cement. The cement is an Egyptian invention. Cement as a stabilizer had a vital role in human civilization. The earliest civilizations such as Egyptians habituated calcined gypsum; Greeks and Romans used heated limestone powders made by volcanic explosions to make mortar. Finally, Romans build continental scale civilizations by using cement to build bonds. It was Romans who found and named cement pozzolanic cement after the village Pozzuoli near Vesuvius a giant volcano found in Italy. A volcanic ash stabilized soil layer is shown in see Figure2.4 on page 21, the enlarged image shows the soil strength gained due to the addition of natural volcanic ash. However, not all civilization had the fortune of using volcanic ash. Britains learn the technology from Romans and developed the technology to produce cement by crushing clay tile and systematically burning with lime to produce cement. It was Joseph Aspdin from the UK who got the first patent for the Portland cement in 1824. Since then Portland cement was developed into many variations to optimize and customized the stabilizing capacity.

### 2.3.3 Polymeric soil stabilization

The polymer is a longer bond created with the carbon-hydrogen bond. The bond itself is longer and stronger. However, polymeric soil stabilization was there in the animal

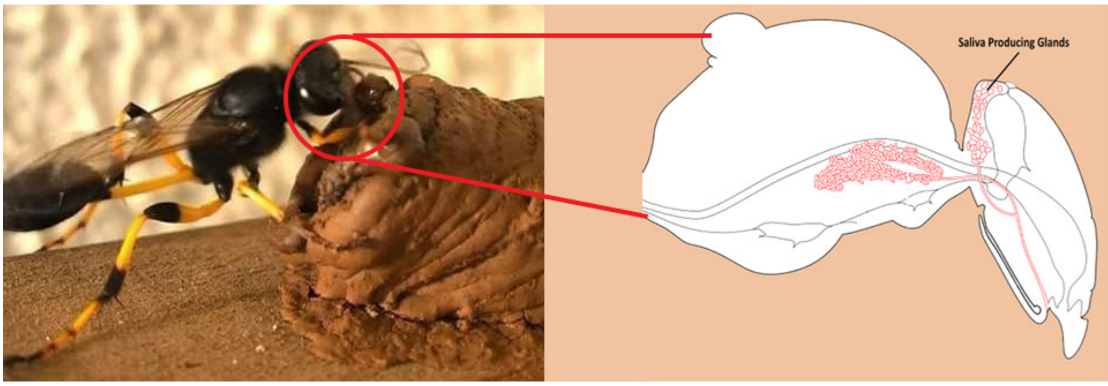



**Fig. 2.5** Mason bee stabilizing earth to build its nest
source: Wikipedia

world. The most common example is the Mason Bee Shown in Figure2.5. The mason bee uses, its saliva *(see figure 2.5* to stabilize earth and to build their nest. The saliva in the Mason-bee produces a small amount of natural polymer and they collect the finest clay from river banks. Since the soil particles are tiny and small, they are creating a stronger bond with mason bee saliva. At the very beginning of this study, the properties of the mason bee structure were studied as an inception for the experiment. However, further study should be conducted to understand the strength of Mason bee saliva to make stronger mud houses. Similarly, there is a list of birds who make mud based structures, such as cave swallow, barn swallow, purple martin, and flamingo (Figure2.6). The cave swallow, which lives in portions of Florida and Texas, builds a nest similar to the cliff swallow. These elaborate nests are sometimes covered and have a tunnel leading to them, which is made of mud. This bird collects patches of mud from the river banks and stacks them similarly like laying bricks on a construction wall. It brings wet mud patches before the rest getting dry.

In order to insulate the wall, it uses leaves and dry woods. Finally, the wall is touched by using their own feathers to improve the comfort of the nest. The most widely distributed swallow in the world, the barn swallow often build its mud nest in barns, sheds, garages, and outbuildings. The purple martin is the largest of the American swallows. It lives almost exclusively in birdhouses provided by people in the eastern U.S. In these boxes, it will make a nest of mud, grass, and twigs.

Interestingly, most of these birds are not using any type of stabilizing techniques to build their nests. Instead, they use optimum water content and soil composition to stabilize soil. On the other hand, they do not need high strength earth structures. The required durability of their homes is far less than human needs. However,

### 2.3.4 Fiber soil stabilization techniques.

Other than what was discussed in the previous section, there are methods and ways to improve the stabilization quality by using several materials such as fibers. The fiber soil strengthens also counted as a mechanical soil stabilization, because fibers do not change the chemical composition of the soil. Fibers do not directly stabilize the soil, However, it can develop or improve the quality of the stabilized earth block.

The oldest fiber stabilized earth blocks is the sod block invented by the Mesopotamians civilizations. The Mesopotamian civilization was based on Euphrates and Tigris river valleys. Those valleys were very famous as grasslands. When Mesopotamian civilization built their houses, they tend to mix mud with straws from grasses and build sod bricks. There have been many studies to improve the quality of fiber stabilization. Researches have experimented with banana fiber to improve the tensile quality of earth blocks (Annie Paul et al., 2008). The use of cow dung and straws are vernacular technology to stable the earth blocks (Abdalla et al., 2012; Silva et al., 2011).

(a) Cave Swallow (b) barn Swallow (c)Purple martin

**Fig. 2.6** Earth builders from bird kingdom
source: Wikipedia

Traditional Tswana Houses were made by using earth blocks and plastered by using cow dung mixture (Nurul et al., 2010). The idea was to introduce additional bonding to the mortar. Roma et al. (2008) mixed vegetable fibers with earth mixture to produce tiles (Roma et al., 2008). Cai and Hejazi in 2012 experimented with synthetic fibers such as polypropylene fibers to develop the tensile quality of earth fills. However, both experiments could not achieve the required standard strength of 2N/mm$^2$(Annie Paul et al., 2008).

The research team of this thesis Udawattha and Halwatura (2016c) experimented with bamboo straws to develop the tensile quality of in-situ cast earth walls. However, it was a failure and bamboo straws did not combine with earthen materials and finally started cracking even without a load. There were many experiments were being to explicate the tensile ability of earth construction by using waste bio fibers, millet waste, straw natural fibers etc. (Bal et al., 2012; Illampas et al., 2014; Yetgin et al., 2008).

Compressed Stabilized Earth Block (CSEB) is the recent introduction of new earth walling material (Nagaraj et al., 2014). The idea was to compress earth in a mold by heavy machinery (Deboucha and Hashim, 2011). Since the manufacturing process itself is compressing the earth, they are good at compression loads (Joseph and Tretsiakova-McNally, 2010)). Therefore, Donkor and Villamizar in 2015 tried to improve the tensile quality of CECB block by adding cassava feels and polypropylene fibers. The issue with fiber reinforcing is fiber balling while mixing or fibers are not combining properly with earth block mixture (Hejazi et al., 2012)). Therefore, studies were conducted to improve the tensile quality of the earth blocks by adding natural polymers, because natural polymers can mix with earth mixture easier than natural fibers (Galán-Marín et al., 2010; Juarez et al., 2007).

Natural fiber soil stabilization is a better method of improving the tensile quality of the earth construction (Thakur et al., 2011). Sri Lankan ancestors used animal fibers to the stabilize soil. The use of flax, hemp fibers, and squirrel hairs also a method of fiber soil stabilization. According to these sources, natural fibers can be used as the stabilizing material, because natural fibers also have natural polymers inside the fibers. However, some fibers are used as reinforcement for concrete walls (Ardanuy et al., 2015). Using natural fibers in cementations mixtures is an alternative. However, scholars those who use fibers to stable soil complaint that fibers are difficult to mix with soil. Fibers tend to make "balling effect" within the mixture of the clay and soil (Donkor and Obonyo, 2015). Therefore, the required tensile quality of fiber stabilization will not be effective.

## 2.4 Ancient soil stabilizing technologies

The need for man-made house started since the farming age (20,000 BC) (Abdalla et al., 2012). Since then humankind started to stabilize soil to build their third skin. The most primitive soil stabilizing techniques were the use of raw earth mixed with water and air-dried or sun-dried. This technology is called adobe construction. The concept of adobe construction is to use earth in raw and utilize the mix into clay mixture to stabilize soil (Pacheco-Torgal and Jalali, 2012).

### 2.4.1 Adobe

Adobe is a simple soil block. First, mix soil with water and then sun-dried until it gets to get the optimum strength. However, the adobe has a weakness of bearing tensile forces. And adobe bricks tend to crack in the drying period. In order to reduce this cracking Sumerians invented an earth technology called sod bricks.

### 2.4.2 Sod Bricks

Sumerians were the first to start manufacturing mud sod blocks in mass scale in the early Bronze Age. They mixed mud collected from the valleys of the Tigris and Euphrates mixed with straw from plains and sun-dried. Their invention was the sod bricks (Begum et al., 2014). Sod bricks were not fired and they are very primitive to use. Once they sun dried them properly, used mud mortar to make brick walls. In order to gain more strength in the soil structures, Sumerians used a straw and dried leaves (Christoforou et al., 2015). This was initially used the in the Mesopotamian civilizations where they used sun-baked bricks and the main stabilizer was straw. They collected straw from the river valleys and combined with mud and made sod bricks. Sod brick technology does not refer to any stabilization method. Instead, the fiber in the sod brick helps to make cross-links between clay particles and finally creates a better strength brick (Reddy, 1994).

However, sod brick technology has the weakness of mixing with straw. Straw is a fiber type of material where which does not straightaway mix with soil. As a result of this, the straw tends to make bolls and are not mixed with soil in the production of the sod bricks. As a result of this, our ancestors managed to create a cob wall (Pinto et al., 2012). Use of straw and soil called sod bricks, called terrain in Spanish, the sod is that combination of a heavy mat of grassroots, which may be found in river bottomlands and grasslands. This was popular in Mesopotamian civilization since the entire civilization was based on grasslands. Not only early civilizations but also European settlers on the North American Grasslands found that the sod walls are least likely to deteriorate due to harsh weather conditions. And sod walls were once all-encompassing used for the walls of houses in Ireland, Scotland, and Iceland, where some turf houses may still exist as a tradition of sod brick (Daniel T. Potts, n.d.; Raddin, 1964).

### 2.4.3 The cob wall

The cob wall technology is to separate the straw from the brick and make a straw wall and then plaster with mud in order to make a confinement strength. In addition to the strength, there is an insulation effect. Nonetheless, this technology was spread into the European context where the collection of straws were encouraged during the paddy collection period and then make walls of straws and finally plastered or confined with clay. Similar to the sod bricks, cob wall technology does not use any stabilizing technology. Similar to the sod bricks cob walls has the similar weakness of mixing fibers and clay. The clay and straw mixture gains the strength for a small period and then it starts cracking from the straw joint itself. In order to rectify this, the ancestors invented the technology of wattle and daub technology (Peris Mora, 2007; Pinto et al., 2012).

### 2.4.4 Wattle and daub

The idea of wattle and daub is to make a wooden structure and filled with adobe mixture without using any stabilizer. This is a very common technology used in Sri Lanka (Dissanayaka, 2016; housing programme 2011, 2011). In most cases, timber structure was made by using timber types of bamboo. However, wattle and daub walls have this weakness of timber decay inside the clay wall. Sometimes insects were used to eat and destroy the timber structure and finally accounts for the destruction of the wall. In order to rectify these issues ancient ancestors have explored more advanced earth technologies such as rammed earth and fired brick technologies (Minke, 2001).

### 2.4.5 Rammed Earth technology

Wattle and daub also replaced with another technology named rammed earth technology. The idea of rammed earth is to compress the earth to stabilize the soil. The compression stabilization is the stabilization technology used to the stabilize soil in rammed earth technology (Maniatidis and Walker, 2003; Pacheco-Torgal and Jalali, 2012). The rammed earth was made by laying damp earth between formwork and mold and compacted by ramming; wall construction formwork (Jayasinghe and Kamaladasa, 2007).

This technology was first introduced by Chinese and then many Aryan civilizations used the rammed earth technology. The oldest existing rammed earth structure counted into more than 6000 years. The watchtower shown in the image is a rammed earth construction in the Han dynasty (202BC) from the province of Gansu shown in Figure 2.2 on page 16. This is the oldest rammed earth structure in the world. Not only this watch tower, the longest man-made structure in the world, the great wall was also made

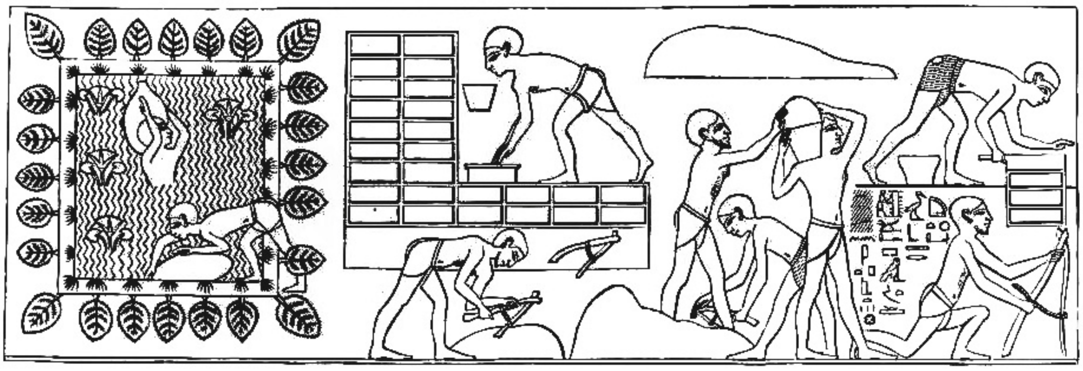


**Fig. 2.7** Egyptian brick manufacturing site
Source : Nicholson et al. (2000)

out of the rammed earth technology (Rael, 2009).

In the great wall, the bearing structure was first made by using larger stones and then filled with rammed earth technology (Arizzi et al., 2015). Not only China many parts of the world used rammed earth technology. However, the rammed earth has the weakness of withholding to weather decay. In order to reduce this, Egyptians used lime stabilized rammed earth technology. Then again people used chemicals stable the rammed earth technology. However, the rammed earth seems very large construction. The thickness of the rammed earth wall should be higher in order to get the strength and durability (Bui et al., 2009).

### 2.4.6 Fired Brick

The fired brick technology was first developed by Hindus valley civilization. First, they collected clay from the Ganga valley and then mixed with some amount of sand. After the Hindus valley civilization Egyptian civilization has used the more same technology. Following this many civilizations have used the brick technology. Not only this large civilization. However, but also in Sri Lanka fired brick technology was used. Sri Lankans made the world largest brick structure in the 1st century AD in Anuradhapura called Jethawanaramaya (V. V. Bogahawatte, 1993).

Fired brick also refers to soil stabilization. The technology of making fired brick is to change the chemical composition of the soil mixture to make bricks. When adobe bricks were fired to a larger temperature, the iron particles tend to melt and bind among other soil particles and create a bond. However, the brick technology was then developed into several advanced technologies like engineering bricks and wire cute bricks. The fired brick technology was developed with many advanced technologies and still used in the world.

Even though there are scripts of Egyptian brick manufacturing plants *(see Figure 2.7)* they do not share the information about their great pyramid construction. However, there is a hypothesis of making Giza pyramid bricks by hybridizing two technologies of mechanical stabilization and chemical stabilization. They used the technology of rammed earth to stabilize make larger scale blocks and they used the technology of lime to the stable soil. This was first documented by the Prof. Joshep (Davidovits, 2008a). He showed the concept of chemical advanced rammed earth blocks used in the Giza pyramids. Some scholars claim that Egyptians alkaline activated soil mixture to make fake stones. Prof. Joseph Davidovits was the composer of this idea. He claimed that pyramids were made of fake stones created by Egyptians. He developed the concept of geopolymer in 1975 (Davidovits, 2005, 2008b). He has documented this new hypothesis in the book "Why the pharaohs built the Pyramids with fake stones". Not only Egyptians However, but also Chinese civilizations used this technology (Davidovits and Morris, 1988; Provis and van Deventer, 2013).

### 2.4.7 Lime stabilized earth blocks

In a small town in the Chinese civilization, people used to make a fire in the village center and then mixed lime collected from the river beds and then mixed with clay in order to make soil blocks (Needham et al., 1996). This was not documented properly the Romans invented the materials concept of cement. The lime accounts into chemical stabilization. The chemical stabilization can improve the particle bonds in the block. This does not need fixing However, it needed some types of compaction. Some researchers claimed that the biggest man-made the structure of Giza pyramid is made of lime stabilized earth blocks. They omitted fired clay bricks because it's very difficult to make larger scale bricks. They can make larger scale bricks it very difficult to bake inside the bricks. However, prof.Joshep has made some salutation and had done some porotypes to show how the Egyptians made lime stabilized earth block to take Giza pyramids. First, they make a wooden structure size of the bricks and then they poured a soil and lime mixture into the mold. Finally, it was rammed in order to make a high strengthen compressed earth blocks. The lime stabilization is the pre-technology used before the invention of cement. After the lime block, the advanced technology was to make earth structured stabilized by using cement (Davidovits, 2005, 2008a,b; Davidovits and Morris, 1988).

Cement as stabilizer had a vital role in human civilization. The earliest civilizations such as Egyptians habituated calcined gypsum; Greeks and Romans used heated limestone powders made by volcanic explosions to make mortar. Finally, Romans build continental scale civilizations by using cement to build bonds. It was Romans who found and named cement pozzolanic cement after the village Pozzuoli near Vesuvius a giant volcano found in Italy. However, not all civilization had the fortune of using volcanic ash. Britains learn the technology from Romans and developed the technology to produce cement by crushing clay tile and systematically burned with lime to produce cement. It was Joseph Aspdin from the UK who got the first patent for the Portland cement in 1824 (Davis, 1904, 1924, 2015; Per and Tongbo, 2017).

### 2.4.8 Roman lime, volcanic ash stabilization technology

Romans invented to use volcanic ash to make cement-like materials. They mixed volcanic ash lime and soil to make earth structure roadways etc. There is roman which has been deluged under the Mediterranean Sea since the first century AD. The mixture of this concrete is similar to modern-day concrete. The volcanic ash triggers a chemical reaction in which lime molecules react with ash to make a bond between the whole mixtures. The roman lime and volcanic ash stabilized structures were under the ocean to chemical attacks. Roman civilization introduced the concrete. They mixed made concrete out of volcanic ash, lime, and volcanic rocks. They triggered the combination of seawater, lime and volcanic ash to build dockyard structures. Interesting some of this structures still standing on earth since 2nd century AD. However, volcanic ash is very rare materials on earth. And they are coming out at a huge cost (Hu et al., 2015).

#### 2.4.9 Cement stabilized earth blocks

After the invention of cement, many civilizations try to make structures stabilized by using cement. The first cement stabilized earth structure is the Hadrian wall in Britain. The Hadrian structure is rammed earth and stone wall in the United Kingdom. And the many people have developed the technology of soil stabilization by using cement. And today its a very common walling material called CSEB (Cement stabilized earth blocks) (Jayasinghe, 2011). The cement stabilized earth blocks are referring to the chemical earth stabilization. The use of cement shall make the chemical composition of the soil and finally create a stronger bond in the earth block (Maïni, 2010; Nagaraj et al., 2014; Nematchoua et al., 2015).

## 2.5 Ancient soil stabilizing technologies from Sri Lanka

Sri Lankans were building monumental building buildings without using a single drop of cement. The Sigiriya fortress is a good example of a castle built without using cement. However, after the 1st century, BC Sri Lankans learned the way of building brick structures. The Kalopasadaya is a good example of soil stabilization. According to Mahawamsa, after the arrival of Mahinda thero, the king Devanampiyatissa built a building for Buddhist monks within one day. The technology states that they build mud wall structures and fired entire building at once to make it fast. Which means the building was built by using rammed earth and then fired to get the requires strength. The firing can change the soil chemical composition to create a stronger bond in the soil structure of the building (Ven. Mahanama Thera, 1912).

In addition to Kalopasadaya, there are many Atuwa articles written inscription about the technology which they used to build walls. The Sigiriya fortress the mirror wall was built by using fired brick and then plastered by using natural polymer to stabilize the mixture. According to the archeologist, the mixture was composed with Bael polymer, animal hair (from squirrels) and lime from Matale. And also the Sigiriya frescos were painted on a plaster made of natural components such as Beal resin and wood apple fibers etc. However, since then, Sri Lankan ancestors used to make monumental building by using lime as the main stabilizer. They mixed soil with lime to make the bond and stable the soil on the road etc. The use of lime itself has many weaknesses. The biggest weakness is that the lime stabilizer soil mixture does not have any tensile strength. When conducting the literature survey, this study found that people from Matale and Uva Paranagama (ancient villages produce lime from paddy fields) mix lime and Dawul kurudu to make a much better lime paint and paint Pagodas (Geiger and Rickmers, 1992).

Knox (1681) stated that use of lime as a stabilizer for temples and other buildings instead of wattle and daub. " The palace is walled about with a clay wall, and thatched, to prevent the clay being melted by the rains, which are great and violent. Within this wall it is all full of houses, most of which are low and thatched; However, some are two stories high, and tiled very handsomely".

## 2.6 New earth stabilizing technologies.

Even though our ancestors managed to develop a series of earth construction technologies, many of the researchers tried to develop a better earth construction technology. Most of these researches were trying to develop ancient earth construction technology into advanced earth construction technology. Because most of these scholars refer to the earth itself as the most suitable materials on earth to make buildings. There are three different soil stabilization techniques. Therefore, the trending soil stabilization techniques shall be discussed according to above-mentioned soil stabilization methods

(Afrin, 2017).

### 2.6.1 Mechanical soil stabilization for walling purpose

After the invention of rammed earth, many scholars try to develop alternative methods of soil stabilization by using mechanical stabilization. Most of these scholars were focused on developing much better-rammed earth technology. There were many studies to develop the rammed earth mixture to optimize the best soil design to develop the durability and strength of the rammed earth construction. And then there are many studies to improve compacting technology (Maniatidis and Walker, 2003; Padavic and Mulligan, 2002).

### 2.6.2 Chemical soil stabilization

Chemical soil stabilization is an advanced method of restructuring the geotechnical property into engineering property. The use of the chemical can enhance the engineering properties of the soil block. The best example of chemically stabilized earth block is the cement stabilized earth blocks. There are many versions of cement stabilized earth blocks. Instead of making simple adobe block stabilized with cement, scholars tried to make compressed cement stabilized earth blocks. Cristelo et al. (2012) stated that chemicals can enhance the engineering properties of the soil. Fouchal et al. (2015) also stated that clayey soil has the bad geotechnical property and this can be enhanced by using chemicals. He suggests that the technology of alkaline activation can create bonds between larger particles (Samal et al., 2015).

### 2.6.3 Polymeric soil stabilization

The simple explanation for this is to make cross-links between two soil particles. In this method no need to change the chemical composition of the soil. Chang and Cho (2012) stated that the polymer makes a network of links between soil particles. The use of synthetic polymers to the stable soil is widely used in road construction and waterproof construction. Whereas they use a large amount of synthetic carbon-based polymers to stable the top layer of the soil. The most common synthetic polymers are made of petroleum. Some are water-based and some of these polymers are to mix with alternative chemicals. Few studies were conducted to use natural polymers as soil stabilizers. Because its very difficult to mass produce natural polymers. The biggest naturally producing polymer is natural rubber. There were several attempts to develop natural rubber as a stabilizer for concrete and earth constructions. Lambert and Rinaudo (1985) experimented in 1985 to see the possibility of using Xanthan gum as an alternative stabilizer for soil. Chang et al. (2015) also extended the Xanthan gum study in 2015 and found that Xanthan gum has the capability of making soil bonds.Chang et al. (2015) also developed a new biopolymer to stable soil (Chang et al., 2012).

## 2.7 Inventory of possible alternative stabilizers

After conducting a detail literature study, an inventory of possible stabilizer was selected for further study. The inventory was based on two principals; availability of raw materials and the cost of the stabilizer and practical mixing possibility of the following stabilizer. The inventory also comprised of several industrial ashes. The fly ash from coal power generation plant is one such material. Because fly ash produced in large quantities in Sri Lanka. And bottom ash too. Rice husk ash also could be found in large quantities in Sri Lanka. More than all developing industrial waste as an alternative stabilizer can be a win-win study for the country. Based on several studies the inventory of alternative stabilizer was composed of many materials such as Natural Polymers Rubber Latex, Pines Gum, Lignin, Molasses, Hydrophilic polymer and industrial Waste such as Fly Ash, Bottom Ash, Rice Husk Ash, and sludge.

Nevertheless, the selection of such alternative stabilizer for mud concrete block needs a critical analysis. The first study should be the availability of raw materials. And then the workability, the manufacturing process cost etc. The available source, previous studies properties, and production method were studied to understand the possibility of using following as alternative stabilizers. Studying compressive strength and engineering properties is an expensive process. Therefore, only a selected number of alternative stabilizer were subjected to further study. Most of them were selected due to the availability of raw materials in Sri Lanka and conceiving local industrial development. The inventory of possible alternative stabilizers and stabilizing technologies are shown in Appendix A on page 203.

## 2.8 Summary

A detailed literature survey was conducted to understand exiting earth wall technologies. The available stabilizers for earth-based technologies. Then the literature survey was acquitted to study possible alternative stabilizer for the mud concrete technology. The author had traveled crossed country to find an inventory of possibility of using Sri Lankan ancestral knowledge to the stable soil to make earth walling block Historical study and ancient technology inscriptions were studied to find possible stabilizer for mud concrete block.

A nature study was conducted to find possible solutions from the natural world. In addition, industrial waste inventory was developed to see any possibilities of ameliorating industrial waste to the stabilize soil *(see Figure2.8 on page 36)*.

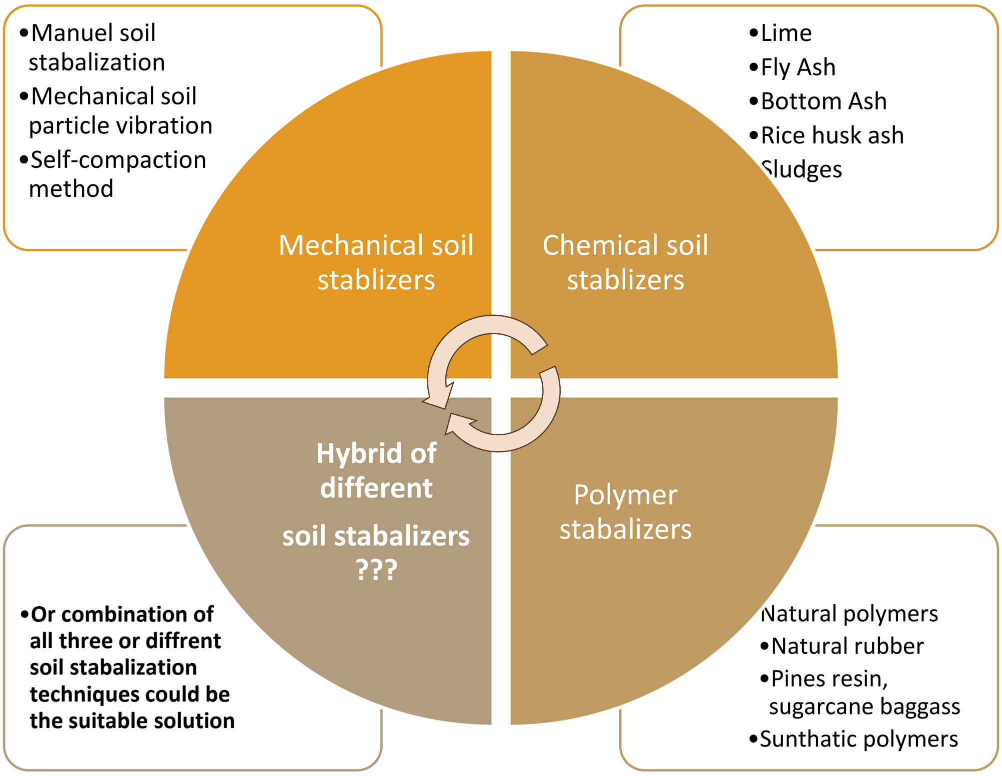



**Fig. 2.8** Summary of possible alternative stabilizers

CHAPTER 3

# RESEARCH METHODOLOGY

## 3.1 General

Studying possibilities of alternative stabilizers was purely a bucket chemistry and series of blind mixes. Following these standard methods were used and developed to acquire selected stabilizers. Finally, thorough and more technical methods were used to analyze and understand the best mix proportions, soil mix design to develop mud concrete block. Once the optimum mix was developed and finalized to manufacture mud concrete block, the production method was optimized. The life cycle cost and embodied energy content were calculated by using the systemic procedure. The research method started with an inventory of suitable stabilizers mentioned in the literature review. Most of the stabilizers were not invented but developed to stabilize mud concrete block. Therefore, the basic method was to understand the exiting stabilizing pallet in the world. For that three different types of stabilizers were taken into analysis and identified their pros and cons by using literature and field survey. Then the study focused on several stabilizers that can be developed to make eco-friendly mud concrete technology. The basis for the selection of many suitable stabilizers is the availability of resources. For an example suitable stabilizers like Agarwood resin, wood apple resin etc. are rare substances and hardly found in mass quantities. Such a stabilizer is not practical in real-world production. Therefore, that kind of stabilizers were omitted from the further study. Alternative stabilizer like sludge and house ashes are not composed of singular materials. Those stabilizers are composed of different kinds of chemicals. Therefore, these are very difficult to study and finalize the chemical quality. In order to start the initial experiment, selected stabilizers were mixed with soil and created a paste to identify the workability and mixability of selected alternative stabilizers. There are plenty of natural fibers found in literature, however, and those are very difficult to mix with soil. When they are mixed with soil they make a balling effect and not mixing with the soil as one single mix.

This study was based on a series of blind mixes based on the original mud concrete block mixtures. After that, out of the blind mixes, a set of soil stabilizing technologies were selected for further studies. All three types of soil stabilizing technologies were further studied. Then they were subjected to deeper analysis and chemical experiments to develop an alternative stabilizer. Subsequently to the development of those stabilizers, they were subjected to life cycle cost and durability analysis to understand the long-term effect of those stabilizers. Following this carbon footprint and embodied the energy and the life-cycle cost was calculated. Finally, based on the above studies, the suitability index was introduced to several stabilizers to understand the most suitable stabilizer for mud concrete block.

This inventory was based on the literature study of several stabilizers already used in the construction technology. The idea was to identify the most suitable stabilizer for earth technology which can be developed in the Sri Lanka context. For an example, pines are a good earth stabilizer but cannot be found in large scale to stabilize larger earth buildings. Also, the production method was studied in order to understand their carbon footprint and environmental impact. For an example, there are many chemicals which can be developed to stabilize soil, but their production method is not eco-friendly. A good example is a tar. Tar can stabilize earth blocks. But the availability and the production method involved carbon expensive process.

### 3.1.1 Selection of most suitable stabilizers for further experiments.

Many soil stabilizing techniques were selected from the main three types of soil stabilizing technologies mentioned in chapter 2. From the mechanical soil stabilization technology, the self-compacting technology was selected to use full technology to improve the technology of mud concrete. The experimental programme is shown in see figure 3.1 on page 40. For chemical stabilization, fly, bottom ash, rice husk ash, and iron dust were selected to further experiments. For polymer stabilization technology, natural rubber latex, pines, Dawul kurudu, and sugar cane bagasse were selected for further experiments.

After selecting experimental stabilizers, an elaborate analysis was conducted to understand the most suitable stabilizer for mud concrete block. The primary concern of this experiment was to realize the compressing strength development. Then performing stabilizing technologies were further tested to understand the compressing strength test, tensile splitting strength, suitable soil mix design water content and manufacturing method. To develop a soil stabilizing technology both engineering properties and mechanical properties should be in line with standards in the world. For this research, all the engineering properties and mechanical properties were tested according to engineering.

## 3.2 The first of the phase

At the very beginning, different stabilizers were mixed along with soil with the particle size distribution according to MCB. The phase one experiments are purely blind mixes or mixes shown in Shown in see Figure3.2 on page 41. The soil composition was not changed in this stage. The stabilizer composition was used in a range of 0% to 50%. Because there is no use of having a stabilizer more than 50% of the total weight of the block. Unconfined Compressive Strength (UCS) test was conducted according to BS–EN–772 and ASTM C1825–18 Standard guide for developing masonry unit. In


**Fig. 3.1** Experimental program

order to understand the strength gain due to the addition of the stabilizer, Test method for brick, cement blocks, and masonry units (ASTM and International, 2006; British Standards Institution BSI, 2006).

Then optimized required amount of stabilizer to the stabilize soil. However, this experiment is not conducted to develop the stabilizer fully or to alternate the production method. A simple wet mix was used for this experiment merely to understand the quality of the stabilizer. Following this if there is a good progress with selected stabilizer; they were selected for further studies such as soil mix design and strength developments.

## 3.3 Second phase of the study

Two components were tested in this phase. The first was to test whether the strength could be further improved by adding any other activator/additive. If the activators/additives enhance the quality of stabilizer do the optimum add mixture content *(see Figure3.3)*. Because the literature emphasizes the fact using one stabilizing technology is not smart but combining two different stabilizing methods can gain the strength (Deboucha and Hashim, 2011).

For example, the use of fly ash can make an internal bonding in the mud concrete


**Fig. 3.2** Blind mixes with different alternative stabilizers and mud concrete mix

**Fig. 3.3** Adding activators additives to mud concrete block mix

block mixture. But in order to improve the density qualities, it should be vibrated or develop the self-compacting quality of the mixture. Since the self-compacting should be investigated calculated vibration was introduced to make a better bonding in the mud concrete mixture. If the stabilizer is effective, the use of additives to enhance the strength of the stabilization was studied. A list of other additives was investigated during the literature survey. For an example, the fly ash alone did not make a bond instead it made simple strength to stable the mud concrete block mixture. But the use of additive made much better strength in the mud concrete block mixture. Similar to the first phase of the study, the compressive strength was tested in comparing to the additive addition of the mixture. The compressive strength development was recorded in the graph and measured the strength development in a period of one-month on weekly basis.

## 3.4 Third Phase of the study

The third phase of the study was to identify the best soil mix proportions for the different stabilizers. The soil has different particle size combinations. The structural strength is gained by a stabilizer only on specific particle size combination. For instance, the suitable mix proportion of the cement stabilized mud concrete block is Gravel (35%) - Sand (60%) and Fine (5%) (silt and clay) - sieve size below 4.25 mm (Udawattha et

**Fig. 3.4** Sieving soil into three different soil particle combination

al., 2016c). In order to investigate suitable soil mix design proportions, the soil was separated into three different particles sizes such as gravel, sand, and clay shown in see Figure3.4. The fraction of such particle sizes were mixed with selected stabilizers to understand the suitable soil mix design. This method was developed and optimized at the University and published in the journal of case studies in construction materials..

### 3.4.1 Factors affecting mix proportions

The fundamental theory of any concrete mix is that it should be satisfactory in both wet and dry conditions (ASTM C1825). The satisfaction level of wet mixture is the quick flow and the workability. The dry satisfaction is the strength and strength development during the period of the time. Also, the dry satisfaction comes along with the durability and long-term use of the said mixture. Besides these requirements, the said mix should be economical to produce and economical to work with to prepare a mixture to make blocks. Thus mud concrete is made by using several mixes such as soil, stabilizer, and water and the best mix proportions should be aligning with suitable workability. Thus the choice of mix proportions is larger because of the variables in the soil. The soil itself composed of many different chemicals compositions. Therefore, the number of variable quantities and the unity of possibilities are in large number. All the combinations cannot be tested and experimented and investigate at once. As a result of that, phase three of


**Fig. 3.5** Classification of soil particles

the study only focused on the particle size constitution of the soil.

### 3.4.2 The type size and sieve sizes of the soil.

The mud concrete block mixture type, size of aggregates plays different roles in the total strength gain. Not only is the composition of the soil but also the size and shape of the aggregate of the soil are very important for the strength development in particular mix development.

In fact, the particle size may impact the total strength than the stabilizer (R. Arooz et al., 2015). Therefore, the study of an alternative stabilizer should come along with the type sieve size of the soil *(Figure 3.4)*. Hence the third phase of the experiment was focused to understand the types sieve size of the soil and to confirm the suitable mix design for the developed stabilizer. Soil has three different particles shown in Figure3.5. The type of soil varies from the source of the soil.

### 3.4.3 Workability

The workability of a soil mix is very important to make mud concrete blocks. The placing conditions, block types and block sized also affect the workability of the mud concrete block mixture. However, all the workability conditions cannot be tested in lab conditions. But the quick flow effect and the self-compacting nature can be tested and developed in lab condition as shown in Figure3.7 and Figure3.8. The real world workability can only be tested and developed in a real-world manufacturing yard. This could be after research work when the product is streamlined to the manufacturing

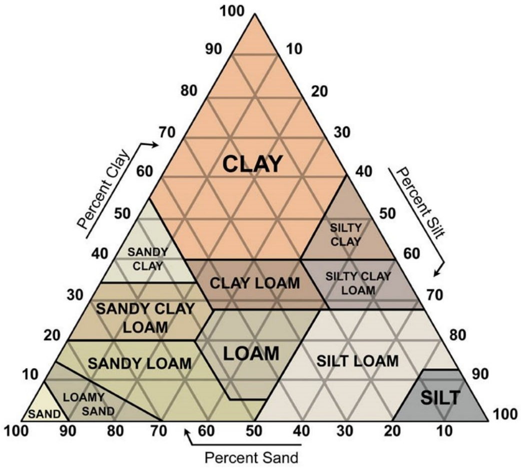



**Fig. 3.6** Different sizes of soil particles

*Source :Classification Of Soils*

**Fig. 3.7** Testing block manufacturing and workability of soil

process.

The main factor affecting the workability is the moisture content. The moisture content influence in mixing as well as stabilizing the soil mixture. Not only the size but also the shape, the form, and texture of the particles affect the workability of the mixture. Not only the gravel fraction but also the finer fraction of the soil mixture controls the cohesiveness of the mix. The workability is directly affected by the fiber content of the mixture. It is essential for soil/ mud mixture to be cohesive, then the self-compaction will result in uniform and non-porous mass of the block.

The mix design workability of a mud, soil cement or any other alternative stabilizer was measured by using slump test. The workability and quick flow ability of the soil was studied by using novel slump test developed by a sister research.

**Fig. 3.8** Slump test development for soil mix design study

## 3.5 The fourth phase of the study

This section was conducted to understand the engineering properties of the developed mud concrete block. In this phase, the optimized stabilizer ratio and soil composition were studied according to the standard testing procedure. The other reason for this experimental phase is to standardize the strength development mud concrete block mixture. The local and microscale strength gain were studied by using chemical analyzers and microscopic analyzers. The electron microscope images are useful to understand the bonding pattern of the stabilizer. The local and microscale studies are as follows.

### 3.5.1 Xray fluorescence study

The X-ray fluorescence analysis was conducted to understand the chemical composition of selected stabilizers. The equipment was available at the University of Sri Jayewardenepura and the University of Peradeniya. The author used both facilities to understand the chemical composition of selected soil and selected stabilizers. The method is simple, a sample of mix placed inside the chamber. A gamma ray is a boomerang on the sample to analyze the chemical composition of the sample. Three samples were


**Fig. 3.9** Conducting SEM study

tested to get the average results. Finally, the chemical composition was taken from the software given along with the equipment.

### 3.5.2 Bulk SEM Analysis

The stabilizer can work on a local scale as well as micro scale. The use of the microscope is to understand the microscale bonding developments shown in figure 3.9. Scanning electronic microscope (SEM) is one of the best methods to understand micro scale strength developments. Also, the SEM images can be used to understand the morphology of the sample. But there are drawbacks of this study. Material composition in one location might not be the same. Therefore, these results are hard to generalize.

### 3.5.3 Engineering property analyze

After understanding microscale changes in the total block, the engineering properties were studied. Most of the testing and studies were conducted according to BS standards to confirm the quality of the new walling blocks. Following standards methods used to confirm the quality of a walling material. The engineering properties as follows.

### 3.5.4 The density of the material

Typical density of the materials developed by the different mixes had been evaluated to understand the suitability of different stabilizers. The most common norm is to have high density to make a suitable walling material. Because the high density is a good engineering property. Factors affecting mix proportions. But this is not true for all the walling materials. One of the common walling materials such as Cabook has high pores at the same time it has a very high density. Therefore, the density of walling materials should be read along with the mix proportion and the strength of the walling material. The initial dry weight and the immersed water blocks were measured and developed the density calculations.

### 3.5.5 Determination of shrinkage

Shrinkage was an observed factor of these casted blocks. Both volumetric changes and length changes were observed in polymer stabilized earth blocks. Shrinkage is a huge drawback for engineering wall unit because shrinkage can reduce the total strength of the wall. The shrinkage is a simple measure of volumetric changes during the curing process. The shrinkage was measured until the total volume comes to a constant level. The shrinkage was measured by using the following equation 3.1.

$$Shrinkage(mm^3) = \frac{V1}{V2} \tag{3.1}$$

V1 = Mold volume/Original block volume

V2 = Volume of the cured block

### 3.5.6 Determination of water absorption

Water absorption is one of the most important aspects of a walling material. Water absorption was measured by using blocks segmented by wet compressive strength Shown in see Figure 3.10. According to the ASTM D570 standard, specimens were kept in an oven at 106C until a constant weight is achieved. Then the specimens were placed in a desiccator to be cooled to the room temperature. Once the block temperature comes to the room temperature, the weight of the block was measured. Then, they were submerged in a water bath for 24 hours for saturation of water. Eventually, water absorption was measured as the amount of percentage of water confined per unit of dry weight.


**Fig. 3.10** Water absorption test

Water absorption was calculated using the following equation (3.2).

$$WaterAbsorption(gcm-3) = \frac{w-d}{v} \tag{3.2}$$

h = specimen height, cm  l = specimen length, cm

w = specimen width, cm

V = specimen volume = l  w  h, cm3

D = pre-immersion mass of the specimen, g

W = specimen mass after immersion and blotting, g

#### 3.5.6.1 Porosity

High porosity is a drawback in engineering materials. The porosity is also a measure of the density of the materials. The porosity also refers to the number of voids inside the material. Because of the void spaces, the water absorption is increased compared to the porosity measure. Interestingly, there are high pores walling materials such as cabook. Even though the cabook is a highly dense material, its porosity is also very high. The priority is a measure of the void to the solid ration of a particular material. It is measured by the ratio of the volume of void space (VV) to the total or mass volume of the same material (VT). The porosity of developed materials was calculated by using the following equation (3.3).

$$Porosity(\phi) = \frac{vv}{vt} \tag{3.3}$$

vt= Total Volume

vv= Solid Volume

#### 3.5.6.2 Determination of wet and dry compressive strengths

Construction materials should have specific engineering properties. A walling material should have the properties of strengths. Compressive strength is one of the crucial factors for a walling material. It has a minimum level of strength that a walling material should achieve as per the standard. There are several methods to study the compressive strength of a masonry unit. But this study used only the destructive strength testing method. The British standards BS EN 772 interpolate the method of conducting destructive compressive strength test. The university structural testing lab has the equipment to measure the compressive strength. First samples were prepared and test the compressive strength after placing the sample on the steel plate of the equipment by using compressive strength testing machine *(ADR Touch 2000 BS EN Compression Machine with Digital Readout and Self Centring Platens)* calibrated by Sri Lanka standard institute. The minimum required compressive strength was confirmed by the same standard. Sri Lankan standards institute also confirm the same standards strength as 2 $N/mm^2$ and a wet strength of 1 $N/mm^2$. The National Engineering Research and Development Center (NERD) is also referred to the same standards and strength as the conformity of the quality masonry unit. Wet compressive strength was tested in a similar manner after submerging blocks inside water for more than 24 hours. The compressive strength was calculated by using the following equation (3.4).

$$Compressive\ strength = \frac{P}{A} \tag{3.4}$$

P= Maximum bearing load

A= Surface area

#### 3.5.6.3 Tensile splitting strength

The tensile ability of a masonry unit is not a required standard. But in order to develop a masonry unit for other and special uses such as seismic foundations, paving materials etc. , the tensile quality of a wall construction block is important. Also, the polymers are good at tensile strength. Earth blocks are good at compression. Therefore, the combination can only be tested by using conducting tensile splitting strength test. The test was conducted according to the BS–EN12390:2004 (2003). The university has two tensile testing machines. The first one is to measure small-scale materials tensile splitting strength. The second to measure the tensile quality of larger structural units. First, the sample was placed on two poles parallel to the load, and the breaking load of the sample was measured as tensile splitting strength.

#### 3.5.6.4 Organic matter content

Bioreceptivity of walling materials depends on the availability of organic compounds. Therefore the organic matter content was tested with ASTM D2974 standards shown in Figure3.11 . Grinded materials were oven dried for 24 hrs at 1000°C and then burned in a muffle furnace for 48 hrs at 440°C. After that, the ash content was measured and organic matter content was calculated by using the following equation (3.5).


**Fig. 3.11** Measuring organic Matter Content of walling materials

$$O = \frac{100 - a}{100} \tag{3.5}$$

O = Organic Matter content

a = Ash Content

### 3.5.7 Capillary action

Capillary action of each wall sample was tested using ASTM C1585-13 standards. The experimental setup was arranged according to the standards and the test was conducted. Each specimen was weighed at the given time periods by the test standards and then capillary water absorption and coefficient of each material were calculated using the following equation (3.6).

$$I = \frac{mt}{axd} \tag{3.6}$$

I = absorption (mm)

mt = the change in specimen mass (grams)

### 3.5.8 Surface roughness

Surface roughness is a measure of the texture of a material surface. Surface roughness directly affects the moisture retention on walling material which increases the bio receptivity. Surface roughness value of each material was tested using a 3D scanner.

## 3.6 The fifth phase of the study

The key objective of this research is to develop an alternative stabilizer for mud concrete block. There is no real value of this study; if the study does not suit the real world applications such as wall constructions. Therefore, the manufacturing process should be optimized in order to introduce the novel walling materials.

The followings approaches were considered in optimizing manufacturing framework. The experiment was conducted to conceive both labor and mold combinations. Further, the mixing technologies were observed and questions were asked about the manufacturing methods with workers of the practical grounds.

### 3.6.1 Real world simulation method

The real world simulation methods are to change and optimize the real-world combination into the manufacturing process. Because the developed method of manufacturing mud concrete technology and alternative stabilizer could be impractical in the real world scenario. To understand the real world scenarios not only the manufacturing but also changing the manufacturing constraints such as labor components, a number of methods and the types of mold should be simulated in a controlled environment.

The main reason for running the real-world simulation is because of the inability of conducting computer-based simulations to understand this real-world issue. Computer-based simulations are comparatively easier than real-world simulation. Addition real-world simulation consumes lots of energy and materials in order to understand phenomena or a progress output. The other reason for conducting real-world simulation is to understand how Sri Lankan labor response for such a block manufacturing process with different alternative stabilizers.

### 3.6.2 Linear Optimization model

Linear optimization is a method of simulating a real-world scenario based system into a controlled experiment model. The idea of a controlled environment is to understand the problems and then optimization problems are ubiquitous in the experiment in real-world systems. These types of simulation optimization applications commonly used in the food manufacturing process and product chain manufacturing process. However, this study also similar since the developed stabilized mud concrete blocks shall be developed into a new production chain; in order to address a common issue which may come out of the production process of the mud concrete block, a real-world simulation was conducted. The method used in this model is to start from workman questions itself. Since this is a new production technology and novel method of manufacturing the mud concrete block, the first step was to map the problems. They cannot come up with solutions since they are doing the manufacturing. Therefore, we have to analyze and give solution for their problems in order to develop the manufacturing process of mud concrete block technology.

### 3.6.3 The optimum manufacturing method

There is no optimum manufacturing method, only input which a study can do is to improve the existing method of the manufacturing mud concrete block. Thus it can be another step to improve the production method of manufacturing mud concrete blocks. The optimum can be excluded by understanding input-output scenario or the efficiency of the process shown in table 3.1 on page 55. However, formulating a mathematical solution and finding formula can be interesting in order to find out the optimization method. After discovering the problem in the mud concrete block manufacturing technology: the problem should be investigated as an issue to be exposed. The suitable

**Table 3.1** Mathematical simulation for optimization

| Scenario | A | B | Optimum |
|---|---|---|---|
| X1 | 1 | 0 | Op1 |
| X2 | 0 | 1 | Op2 |
| X3 | 1 | 1 | Op3 |
| X4 | 0 | 0 | Op4 |

method for this is to use a scenario method. In a scenario method, a different combination of labor, molds and different stabilizer can be tested and studied in a real-world environment. Not only the composition of elements of the manufacturing process of mud concrete block. Also the size, amounts of mud stabilizers can be studied. For instant use of chemical activators, the resistant to use chemicals in a manufacturing process can be studied.

### 3.6.4 Real world simulation model

The scenarios for the real world testing was conducted by simulation basic inputs in the Mud concrete block manufacturing process such as [1] labor [2]Number of molds and [3] a number of sites. The key objective of this research is to understand the optimum combination of labor and molds. Attributes of the optimization model. The main attributes for this study are the labor component, the number of molds and number of sites. Other constraints such as the way of manufacturing and way of mixing were optimized then and there. The amount of labor (man hour) govern the speed of the output. In some production process by increasing can increase the production speed. But there is an optimum level that the efficiency can be optimized.

### 3.6.5 Optimization Mould for MCB manufacturing

The mold is one of the key decisions while programming for the optimum combination for the manufacturing mud concrete block. The main series of decision can be made according to a flowchart. The table 3.2 explains how the mold was optimized by considering the property of materials to most of the efficient combination of making a number

**Table 3.2** Optimizing block mold material

| Mould material | Pros | Cons |
|---|---|---|
| Wood | Flexible Availability<br>Low cost | Not Durable Heavy<br>Need more machinery |
| Steel | Durable<br>Low-cost Availability | Expensive<br>Need precisions |
| Fiber Glass | Mouldable into<br>many shapes | Hazardous<br>Expensive |

of blocks from one mold. The number of blocks per one mold and a number of blocks from one sheet was stimulated by using the optimization model by changing a number of molds and numbers of sheet input-output scenario. The material, of course, decided by considering available technology. The general survey was conducted in order to understand the capability of each and every material in the market. Their pros and cons were analyzed accordingly *(see table 3.2)*.

The steel was finalized as the best material for manufacturing Mud concrete block in Sri Lanka after analyzing the survey done within the construction community. The table 3.2 explains how the material decision was made according to their pros and cons analysis. The most efficient method of manufacturing the mold was designed by using the 3D software in order to understand how this would look like in the real world and the practicality of it. The optimum was measured by the optimum number of blocks (block efficiency) and the wastage of steel sheet. One mold per one sheet was optimized by considering its ability to build mud concrete block with a minimum number of sheets. However, the other combinations such as two molds from one sheet, two molds from two sheets and three molds from two sheets were stimulated by using excel programme made by the user. Finalizing mold was done by using sketch-up 3D model and a cut-list plus for measuring cutting methodology and wastage of steel sheet. The price per one mold was measured considering the available market condition in the country. However, the mold manufacturing method and the process was carefully designed by considering Sri Lankan Labour skills. Sri Lankan craftsmanship is not very much skilled with machinery based manufacturing and construction. Therefore, a simple cut and the joining

**Table 3.3** Optimizing best labor combination

| | Practice | No of mold | No of Cycles | No of Sites | Nos. labor | Number of blocks | Cost per block |
|---|---|---|---|---|---|---|---|
| Scenario 1 | One | 1 | 4 | 1 | 2 | 2500 | $ 0.15 |
| | Two | 2 | 4 | 1 | 2 | 2500 | $ 0.11 |
| | Three | 2 | 1 | 2 | 2 | 5000 | $ 0.08 |
| | Four | 2 | 2 | 10 | 3 | 2500 | $ 0.07 |
| Scenario 2 | Five | 3 | 4 | 1 | 2 | 2500 | $ 0.11 |
| | Six | 3 | 1 | 2 | 2 | 2500 | $ 0.07 |
| | Seven | 3 | 1 | 10 | 2 | 2500 | $ 0.05 |
| Scenario 3 | eight | 3 | 1 | 1 | 3 | 2500 | $ 0.06 |
| | nine | 3 | 4 | 2 | 3 | 2500 | $ 0.06 |
| | ten | 3 | 1 | 10 | 3 | 2500 | $ 0.06 |

system was used in order to build the mold. Nevertheless, the final design for Mud concrete block manufacturing was tested with a real-world scenario by producing the mold in a workshop. The design was changed slightly after understanding the practicality of the mold manufacturing as well as the block manufacturing process.

### 3.6.6 Optimizing Labour composition

Labour is a crucial factor for the manufacturing mud concrete block. The manufacturing process of mud concrete block may not require skilled labour However labour with the first-hand experience would be better considering the sensitive process which they have undertaken. The labour combination for the manufacturing mud concrete block was measured and optimized by using the scenario-based method as explained in the methodology section *(see the table 3.3)*. The labor combination started at two labor, one mold, four cycles per day and one site[1].

Linear optimization method was used to understand how the labor, number of molds and the number of the cycle can be optimized. The table four shows how the experiment was done in a real-world scenario. All the data was collected by a quantity surveyor and analyzed by using excel data sheet.

It was found that the effect also can be increased by employing more number of

[1] Single labor cannot handle mud concrete block production because of the labour demand for mud concrete

molds and number of man hours into the scenario. However, an increase in labor and molds always do not provide results, because labor can be an idol in such a condition. However, the final optimum combination of manufacturing MCB if scenario one practice number four.

### 3.6.7 Block size optimization

After developing all the aspects of the Mud concrete technology, the block size should be optimized to alter existing walling technology in Sri Lanka. The block size is a factor governs by many aspects. The first aspect is the weight of the block. The weight of the block is important when the construction starts. The other constraint is the size of the mold and sizes of the mold manufacturing process.

## 3.7 The sixth phase of the study

The durability of a masonry unit is important to standard a walling block. There are many methods to evaluate the durability of a masonry unit. Only the most important durability test methods were conducted. Also, novel methods such as surface decay due to natural rain also conducted by this study. The sample is mounted in a rigid steel section, and then water was sprayed horizontally at a pressure of 50Kpa. The test was conducted per period of ten hours and the 15 minutes interval surface decay was measured by using a scale. A freeze-thaw cycle test was conducted to mud concrete block units. This was conducted due to a request made by a reviewer from a cold temperature country. The dry mass of dried material was measured by using the following equation (3.7).The total study and experimental results were published in Case studies in construction and building materials in 2017 in journal paper named mud concrete paving blocks (Udawattha, Galabada, and Halwatura, 2017).

$$Weight\ loss\ freew\ thaw\ cycle\ (L) = \frac{Scaled\ off\ mass\ (M)}{Area\ of\ the\ test\ surface\ (A)} \tag{3.7}$$

### 3.7.1 Moss growth test

MCB and FSEB were cast and other materials were collected from the market. Concrete beam with 25cm height was constructed as the base and bituminous paint layer was applied on the top of the beam to prevent moisture penetration. 1m x 1m walls of each material were constructed on the beam with the same distance and with a small roof to prevent rainwater accumulation on walls. Two brick walls were plastered with rough cement plaster and cement slurry plaster. A mixture of moss, buttermilk, and water was blended according to the ratio of 1:2:2. The mixture was painted on wall samples with a paintbrush and two coatings were applied. Moss covered area of each wall was measured weekly and the color change of walling material due to the moss growth was compared using photos.

### 3.7.2 Mold growth test

**Table 3.4** Mold growth-rating criteria

| Rating | Mold coverage |
|---|---|
| 0 | No growth |
| 1 | 0 - 10% |
| 2 | 11 - 30% |
| 3 | 31 - 60% |
| 4 | 61 - 100% |

The test was conducted according to the ASTM D3273-94 and test specimens were constructed with the size of 150mm x 100mm x 7mm. Potato Dextrose agar media was used as the growth media for the fungus culture. Fungus spores were transformed to the sterilized growth media using an inoculating loop. The growth media containing petri dish was incubated for 7 days. The potato dextrose agar medium containing flask was autoclaved for 15 min and glassware (Petri dishes) were autoclaved for 30 min at $121^0$C temperature and 15 psi pressure; for sterilization. After the sterilization process, cooling media was poured into sterilized Petri dishes about one-half full and allowed to solidification.

#### 3.7.2.1 Culture Transformation

Culture transformation is shown in Figure 8. Fungus spores from fungus stock culture were picked up using a disinfected inoculating loop and touched the top of the agar media and streaked from side to side all the way to have a zigzag pattern from edge to edge. The petri dish with agar media was incubated for 7 days

#### 3.7.2.2 Environmental chamber

A Glass environmental chamber was filled 1 inch from the bottom using mold growth media which was prepared by mixing topsoil, compost, and coir dust. Then the media was wetted and the chamber was incubated for 24 hrs. After that, the prepared fungus culture was transferred to the growth media in the environmental chamber and incubated for 14 days. After 14 days test specimens were vertically hanged in the chamber.

#### 3.7.2.3 Evaluation of mold growth

Mold growth on each sample was observed weekly and rated the mold growth area according to the ASTM D3273-94 standards shown in table 3.4 on page 59. At the end of the test after 4 weeks microscopic images were taken to identify mold growth due to mold are microscopic species.

## 3.8 Phase seven-Suitability of Mud concrete blocks

### 3.8.1 Thermal performances

The building envelops created by using masonry unit should have the thermal performance to reduce the excessive heat gain to the building. The thermal performance can be measured by conducting a thermal conductivity test. The thermal performance of real world-built wall samples can be tested. For this study, both experimental methods were used. The thermal performance of a real-world building can be measured by studying the time land and decrement factor. Time lag refers to the time taken to transfer an outdoor temperature to the interior of the building. The decrement factor refers to the outdoor and indoor surface temperature variation. The method calculating decrement factor is shown in the following equation (3.8).

$$Tdec = \frac{T(out)\max - T(out)\min}{T(in)\max - T(in)\min} \tag{3.8}$$

Tdec = Decrement Factor

T(out) = Outdoor temperature ($^0$C)

T(in) = Indoor temperature ($^0$C)

### 3.8.2 Embodied energy and carbon footprint calculation

**Table 3.5** Embodied energy analysis of different walling materials

| Type of walling materials | Source | Country | Size (Area) | MJ/Kg, $MJ/m^2$, MJ/ton and $MJ/m^3$ |
|---|---|---|---|---|
| Brick (Clay) | (G. P. Hammond and Jones, 2008) | USA | – | 3MJ/kg |
| Brick (Limestone) | | | – | 0.85MJ/kg |
| Timber Panels | | | – | 8.5MJ/kg |
| Brick wall | (Rohintan,Emmanuel, 2004) | Sri Lanka | 10 $m^2$ | 12458 MJ |
| Cement masonry | | | 10 $m^2$ | 969 MJ |
| Cabook wall | | | 10 $m^2$ | 1648MJ |
| Random rubble wall | | | 10 $m^2$ | 3282MJ |
| Wattle and daub wall | | | 10 $m^2$ | 12.5MJ |
| Artisan Burned Brick | | UK | 10 $m^2$ | 8100MJ |
| Small-Scale Brick | (Hashemi et al., 2015) | | 10 $m^2$ | 10670MJ |
| General Clay Brick Cement | | | 10 $m^2$ | 35420MJ |
| Stabilised Soil Blocks | | | 10 $m^2$ | 7910MJ |
| Hollow Concrete Block | | | 10 $m^2$ | 1760MJ |
| Artisan Burned Brick/Block | | | 10 $m^2$ | 1270MJ |
| Limestone | (Joseph and Tretsiakova-McNally, 2010) | Northern Ireland | – | 240 MJ/ton |
| Rammed earth | (Reddy and Jagadish, 2003) | | – | 450 MJ/ton |
| Soil cement * | | | – | 850 MJ/ton |
| Soft-wood lumber | | | – | 2,226 MJ/ton |
| Local granite | | | – | 5,900 MJ/ton |
| Engineering brick | | | – | 8,200 MJ/ton |
| Burnt clay brick masonry | (Reddy and Jagadish, 2003) | Indian | 1 $m^3$ | 2141MJ/ $m^3$ |
| Hollow concrete block | | | 1 $m^3$ | 819MJ/ $m^3$ |
| Hollow concrete block | | | 1 $m^3$ | 971MJ/ $m^3$ |
| Soilcement block * | | | 1 $m^3$ | 646MJ/ $m^3$ |
| Soilcement block * | | | 1 $m^3$ | 810MJ/ $m^3$ |
| Steam-cured mud block | | | 1 $m^3$ | 1396MJ/ $m^3$ |

#### 3.8.2.1 Method of analysis

The analysis protocol mainly designed by considering available data and statistics and the overall objective of the research. Other than the Mud concrete blocked concrete block most of the other data were referred from energy Content and Carbon Emission (Pooliyadda and Dias, 2000). Therefore, as same as Pooliyadda the statistical analysis and process analysis was used to study the embodied energy can carbon footprint of masonry units. There were attempts to calculate the embodied energy and carbon footprint of different wall construction materials shown in table 3.5 on page 62. Novel method to study the embodied energy was developed by this study was published in the journal of energy and building (Udawattha and Halwatura, 2016b).

### 3.8.3 Life cycle cost of different walling materials

According to British standards, a building should withstand more than sixty years. Therefore, such a masonry unit total life cycle should be studied in order to decide the suitability of such wall masonry unit. There were many attempts and study techniques used to evaluate the life cycle cost shown in table 3.6. Life cycle costing can be done in many ways. But this study used a life cycle assessment from cradle to grave scenario. This study was published in the Journal of the case studied in construction materials in journal paper named Life cycle cost of different Walling material used for affordable housing in tropics (Udawattha and Halwatura, 2017). The total life-cycle cost is calculated by using the following equation (3.9).

$$LCC = IC + (MC + EC + Oc) + UC - Rv \tag{3.9}$$

IC = Initial Cost ,MC = Maintenance Cost ,EC = Energy Cost

Oc = Operation cost ,UC = Utility cost ,Rv = Resale Value

An initial cost of sample wall was calculated and then evaluated by using a house BOQ. Finally, both per square price and per square feet price were compared. The maintenance cost such as painting cost repair cost was evaluated and compared with existing wall construction materials. The operation cost is a sum of the energy cost incurred during the total lifespan of the building. The resale value of the wall construction units was measured after studying the resale value of the same masonry units for similar use after the demolition of the wall. Finally, the net present value of the sum of the LCC was calculated and evaluated.

**Table 3.6** Previous studies of wall construction life cycle studies

| Type of walling materials | Source | Country | Size (m2) | Life-span |
|---|---|---|---|---|
| Gypsum wall board | (Adalberth, 1997) | Sweden | 700-1520 | 50 |
| Brick ,<br>Cement fiber board,<br>Wood plank,<br>Galvanized steel sheet | (Takano et al., 2015) | Finland | 120 | 50 |
| Wood and steel frame | (Cole and Kernan, 1996) | Canada | 4620 | 50 |
| Bricks | (Crawford, 2011)<br>(Dutil and Rousse, 2012) | Australia<br>Canada | 254.2 | 50 |
| Brick,<br>Cement blocks,<br>Wattle, and daub | (Rohintan,Emmanuel, 2004) | Sri Lanka | $10m^2$ | 60 |
| Brick | (Fay et al., 2000) | Australia | 128 | 50 |
| gypsum plaster<br>covering all<br>internal surfaces;<br>woodchip | (Feist, 1997) | Germany | 156 | 80 |
| FC Sheet,<br>Building paper (reflective foil)<br>Insulation and Air gap<br>Softwood plates, studs,<br>noggins<br>Plasterboard | (Hamidul Islam D, 2012) | Australia | 101 | 50 |
| Brick | (Scheuer et al., 2003)<br>(Keoleian et al., 2001)<br>(Keoleian et al., 2001) | USA | 228 $m^2$ | 50 |
| Steel structure, steel cladding | (Z. Li, 2006) | Japan | 15000 | – |
| Timber studs and wall framing,<br>plaster board, insulation,<br>skirting,<br>brickwork, mortar,<br>cavity ties, ashings<br>Fibre cement weatherboard<br>Wooden panelling<br>External rendering | (Mithraratne and Vale, 2004) | New Zealand | 94 | 100 |
| aluminium/glass curtain wall,<br>artially concrete masonry<br>unit/brick facing,<br>glass fibre heat insulation, U | (Scheuer et al., 2003) | USA | 1 | 75 |
| wooden ,lightweight steel | (Suzuki et al., 1995)<br>(Thormark, 2002)<br>Winther and Hestnes | Japan<br>Sweden<br>Norway | 125322,982<br>120<br>110 | 40<br>50<br>50 |
| Exposed brick | (Sartori, 2008) | Norway | 4800 | 1 |
| Diff. | (Zimmermann et al., 2005) | Switzerland | Na.Avg. | 50 |

## 3.9 Materials

### 3.9.1 Cement

This type of cement has been widely used for many years in general and mega construction projects, ready-mix preparation and in pre-cast concrete production. It is also being used in mortars and grouts (Jayawardana et al., 2012). There is no exposure to Sulphates in the soil or in groundwater. The strength class of the cement is 42.5 N and it is available in 50kg bags in bulk. As per the Sri Lanka Standards Institution 2009 and Tokyo super cement company specifications-2015, the chemical and physical properties of SLS 107 cement follows in table 3.7.

**Table 3.7** Chemical and physical properties of SLS 1247 cement

| Description | | Typical Test results | Standard requirement for SLS 1247 |
|---|---|---|---|
| 1 | Chemical composition | | |
| | Magnesium Oxide MgO % | 2.5 | – |
| | Sulphur Trioxide SO3 % | 2.3 | Max : 3.50 |
| | Chloride Cl % | 0.01 | Max : 0.10 |
| | Loss on ignition % | 1.5 | – |
| | Heat of Hydration | | |
| | 7 Days (KJ/kg) | 275 | – |
| | 28 Days (KJ/kg) | 320 | – |
| 2 | Physical Properties | | |
| | Finess (Blaine) cm2g | 3350 | – |
| | Expansion soundness {(}Le-Chaterlier{)} mm | 1 | Max : 10.00 |
| | Autoclave % | 0.04 | Max : 0.80 |
| | Time of setting {(}Vicat{)} Initial {(}Minutes{)} | 130 | Min: 60.00 |
| | Compressive Strength {(}N/mm2{)} | | |
| | 2 Days | 19 | Min: 10.00 |
| | 28 Days | 50.5 | 42.5-62.5 |
| | Mortar bar Expansion 14 Days % | 0.005 | – |
| | Sulphae Expansion at 180 Days {(}%{)} | 0.046 | – |

### 3.9.2 Soil

Experimenting with soil is not an easy task. Because the soil has different formation all around the world (Hossain et al., 2007). Even the same soil sample selected from one location has vibrant variation even if it is the same soil(Udawattha and Halwatura, 2017). In order to develop a particular mix ratio, this study has used only one soil type from the university. Before starting the experiment, the selected soil sample was collected and stored for the total experiment. The soil was collected after removing a 600mm top layer of the soil and the untouched soil transported to soil collection yard at the materials testing lab in the Department of Civil Engineering, University of Moratuwa.

Several sieve analysis was conducted to understand the particle composition of the selected soil shown in Appendix B on page 206. Finally, chemical composition and chemical percentage study were conducted by using XRF and XRD analyzer. The results of XRD analysis shown in Figure3.13. The prevalent mineral in selected soil is Kaolonite and Dickite. Kaolinite and Dickite are geo-mineral found all around the earth shown in Figure3.12.

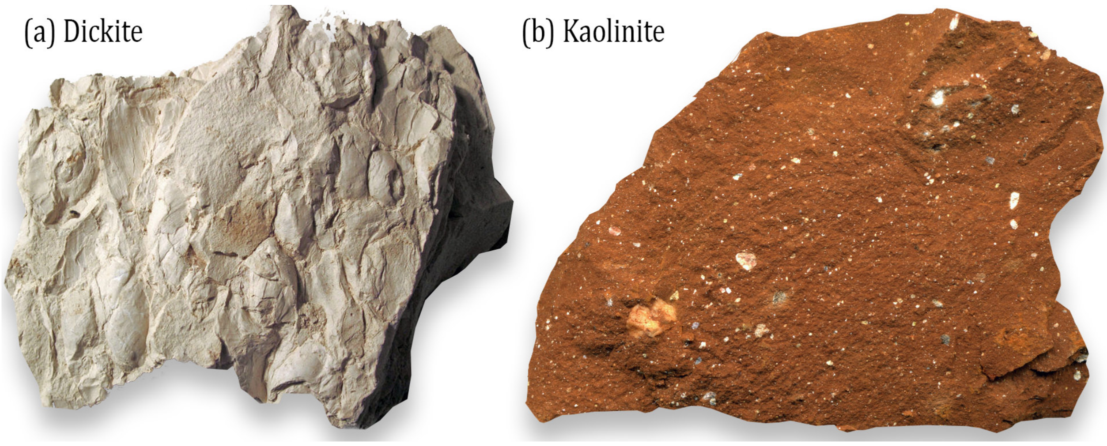



**Fig. 3.12** Prevalent minerals in selected soil
source: Wikipedia

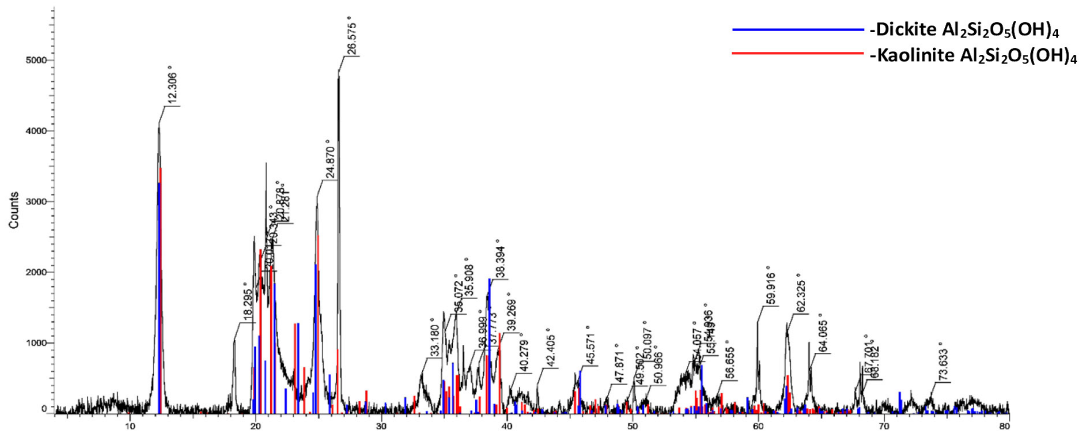



**Fig. 3.13** Soil Mineralogy

**Table 3.8** Chemical composition of selected soil

| Chemical composition | Percentage (%) |
|---|---|
| Al2Si2O5(OH)4 | 33.12% |
| Al2O3 | 1.73% |
| Al2Si2O5(OH)4 | 27.36% |
| CaO | 18.13% |
| Fe2O3 | 3.85% |
| K2O | 0.12% |
| Mn3O4 | 0.06% |
| P4O10 | 0.67% |
| SiO2 | 8.53% |
| TiO2 | 0.03% |
| LOI | 6.40% |

### 3.9.3 Lime

Lime is common construction materials in Sri Lanka. But after the introduction of wall putty technology, urban hardwares have stopped selling lime. Therefore, for this study, lime was purchased from the manufacturing site itself located in Katunayaka. Lime is white color powder and came with bags.

### 3.9.4 Fly Ash

Fly ash was collected from the Lakvijaya power plant. A university truck was sent to the Lakvijaya power plant and fly ash was collected to polythene bags and transported to the lab. After receiving fly ash, they were subjected several studied to understand the chemical and particle size distribution shown in table 3.9.

**Table 3.9** Chemical composition of fly ash

| Chemical composition | Precentage |
|---|---|
| $SiO_2$ | 36.27% |
| $Al_2O_3$ | 4.03% |
| $Fe2O_3$ | 2.61% |
| CaO | 25.33% |
| MgO | 1.03% |
| Ignition loss | 28.62% |
| Unknown | 1.27% |

### 3.9.5 Bottom Ash

Bottom ash also is a similar kind of by-product from the coal combustion process. The coarser components of the ash call as bottom ash. The bottom ash is 10% of the waste coal. The chemical composition of the bottom ash is shown in table 3.10. Bottom ash is heavy metal materials and there are environmental risks pertained when using bottom ash for any construction. However, the bottom ash contains more than 50% of unburned carbon. The carbon can be melted at the very low degree of heat. Such a heat-melted carbon can create a bond in the particle. On the other hand, the literature shows that ash can be developed to make bond by using additives. Therefore, it would be useful to change this waste bottom ash chemical composition to use as an alternative stabilizer for mud concrete block.

**Table 3.10** Chemical composition of bottom ash

| Chemical composition | Precentage |
|---|---|
| SiO2 | 52.45% |
| $Al2O_3$ | 17.01% |
| $Fe2O_3$ | 8.43% |
| CaO | 7.10% |
| MgO | 2.12% |
| $SO_3$ | 0.48% |
| Na2O | 0.57% |
| K2O | 1.90% |

Nevertheless, most of the studies suggest that bottom ash is not a suitable stabilizer

**Table 3.11** Chemical composition of rice husk ash

| Chemical composition | Precentage |
|---|---|
| $SiO_2$ | 85.20% |
| $Al_2O_3$ | 0.15% |
| $Fe_2O_3$ | 0.16% |
| CaO | 0.55% |
| MgO | 0.35% |
| $SO_3$ | 0.24% |
| $Na_2O$ | 1.12% |
| $K_2O$ | 3.68% |
| Loss on ignition | 8.55% |

for soil (Erandi et al., 2013; Güllü, 2014). Also, the quality of bottom ash varies from one day to another in the same coal combustion process. Therefore, the properties of the bottom ash are difficult to understand. But, since the bottom ash is a huge environmental issue in Sri Lanka. An experiment was conducted to develop bottom ash as cementitious materials to stabilized mud concrete block mixture.

### 3.9.6 Rice husk ash

Paddy husk ash (RHA) is a by-product from the combustion of paddy husk. Nowadays, paddy cultivation is one of the dynamic industries in East and South-East Asian regions. Hence, the accumulation of paddy husk waste is booming day by day. Hence, disposal of paddy husk is becoming an important issue these days. Even though it is being used as a fuel in small industries as well as in houses; burning and dumping as a waste is a regular practice in most of the countries.

Normally paddy husk takes a long time for the complete burning to become fully burnt pure Paddy husk ash. Also, burnt ash is very lesser in quantity compared to the paddy husk involved in the burning. The world Paddy harvest is estimated at 500 million tons per year. Considering that; 20% of the grain is husk from which a total of 20 million tons of ash can be obtained from after combustion. Paddy husk has a very low nutritional value *(see the table 3.11)* and as it takes a very long time to decompose. It is not appropriate for making compost or manure. Therefore, the production of paddy husk begins to impact the environment since it is not being disposed of properly. Other uses of rice husk ash in Sri Lanka is to use as a biomass for the production clay tile and brick.

### 3.9.7 Natural Polymers.

#### 3.9.7.1 Natural Rubber Latex

Natural Rubber Latex (NRL) as a polymer has several superior qualities when compared with the other natural polymers. Elastomeric high tensile strength, resilience and also abrasion resistance due to lower water absorption are the major qualities to be considered (Muhammad and Ismail, 2012; Shobha et al., 2013). Natural Rubber Latex (NRL) was used to identify the enhancement of strength and the stability of a block by binding soil particles together and tighter (Begum et al., 2014). Use of rubber can also increase the degree of sustainability as it is produced at a low cost and low embedded energy. Natural latex rubber is a local product and available in tropical countries like Brazil, the Philippines, India, SriLanka etc.

Therefore, this technology can be developed in the following countries as well. In addition to rubber manufacturing countries, some of the earthquake-prone countries already using natural rubber as a foundation material to absorb earth forces. In most cases, they are using rubber cubes and use as Earthquake-resistant Foundations. Thus this study is not to develop earthquake-resistant foundation material. This study was conducted to improve the flexural quality of earth blocks by using natural rubber latex polymer.

Natural Rubber Latex (NRL) which is used as the soil stabilizer was collected as samples from the Rubber Research Institute, Telawela Road, Rathmalana. Ammonium Hydroxide ($NH_4$OH) and Sulphur (S) were obtained from the chemical stores and mixed them separately with the intention of improving the physical properties of NRL. The key to the study was to test the possibility of mixing NRL with soil and cement.

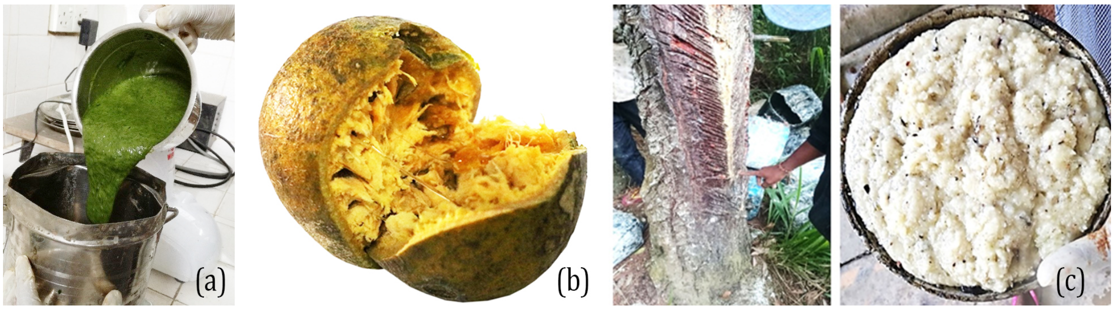



**Fig. 3.14** Natural polymer extraction

#### 3.9.7.2 Dawul Kurudu *(Neolitsea cassia)*

Dawul kurudu is a very famous polymer used in the Asmi production industry in Sri Lanka. Therefore, Dawul kurudu tree is a very famous tree in Sri Lanka. Dawul kurudu is available at the university premises. Leaves were collected from trees and resins were extracted by using a house blender shown in Figure3.14 section (a).

#### 3.9.7.3 Pines Gum *(Pinoideae)*

Pines is not a tropical plant. But it grows in some of the upcountry areas in Sri Lanka. However, pines resin extraction is an industry in Sri Lanka. Because pines resin is used for several productions such as turpentine manufacturing process and many paint manufacturing processes. Pines latex was acquired from pines plantation located at the border of Sinharaja forest shown in Figure3.14 section (c) (6.465185,80.6134803).

#### 3.9.7.4 Sugarcane Bagasse*(Saccharum officinarum)*

Sugarcane bagasse is a fibers waste materials, aby product to use as biomass to produce energy for sugar manufacturing process. The sugarcane bagasse is a pulpy collection after the sugar extraction from sugarcane. However, sugarcane bagasse is available in large quantities in Sugar manufacturing counties. However, fibrous materials can make cross-links in soil materials. Sugarcane bagasse also works as fiber and stable soil (Hejazi et al., 2012). For this experiment sugarcane bagasse was collected from Sevenagala sugar factory (6.3827262,80.9052086).

#### 3.9.7.5 Bael Resin *(Aegle marmelos)*

Bael is a common fruit available in Tropical countries. Bael fruit is similar to apple or wood apple size of 5cm to 12cm. However, Bael fruit resin has much advanced natural polymers such as Xanthotoxol and furocoumarins shown in Figure3.14 section (b) on page 71 (Chang et al., 2015; Lambert and Rinaudo, 1985; Nolte et al., 1992). These substances can create polymer bond to stabilize the soil. Bael fruit was used in many ancient paintings including the Sigiriya frescos (Kodituwakku and Katupotha, 2014). For this experiment, the Bael fruit was collected from near the plantation located in Pilliyandala. And then the resins were collected to make a cream of resigning to stable the soil. In fact, the idea was not to develop Bael resin as it, the idea was to mass produce similar polymer synthetically.

#### 3.9.7.6 Jack Resin *(Artocarpus heterophyllus)*

Jack is a very common tree in Sri Lanka. Jackfruit is a very famous fruit and jackfruit is boiled to make extremely nutritious food. However, jackfruit resins were used for many industries in Sri Lanka. Some of the rural areas are still collecting jack resin to use as liquid gum. And also, jack resin was used to make kitchen equipment. For this study jackfruits were collected from a nearby location near the university. And then slowly collected the required amount of resins to make mix developments. It was very difficult to collect the required amount to make mud concrete block to test minimum ratios to test the strength developments.

#### 3.9.7.7 Agarwood Resin *(Aquilaria malaccensis)*

Agarwood is fragrant dark wood in Sri Lanka. Agarwood also produces little amount of fragrant resins. However, agarwood is a very expensive timber in Sri Lanka. Nevertheless, agarwood resin has some form of bonding ability, Therefore, even though the agarwood is expensive, a little amount was collected from an Agar-wood plantation. Based on the University request, the plantation has extracted some amount of resins by using stem secretion process.

#### 3.9.7.8 Wood Apple Resin *(Limonia acidissima)*

Wood apple is also similar to Bael in Sri Lanka. But wood apple fruit does not produce any resins inside the fruit. But the reins were produced inside the tree trunks. These resins were used by many ancient masons to make painting walls. And also some of the artists have used wood apple resins to create varnish to protect Kandyan era paintings. Therefore, this study also used similar wood apple resins manufactured from the stem secretion process.

## 3.10 Standards

### 3.10.1 Engineering standards for this study

This study was conducted to develop a new walling material. Thus, the final objective of the study is to developed practical wall construction material. Such an invention must be in line with general engineering standards. Therefore, for the conformity of the quality of the novel materials and to study engineering and mechanical properties of the novel materials series of standards shown in table3.10. The standards were listed according to the experimental phase of this study.

#### 3.10.1.1 Specific gravity determined according to ASTM D854

The specific gravity was measured according to the ASTM D854. Specific gravity is the fraction of the density of a material to the density of a reference material; equivalently, it is the ratio of the mass(M) of materials to the mass of a reference material respect to the similar material volume. The specific gravity is important to understand the materials density quality and to improve the mix ratios. In addition, all the specific gravity indicators can improve the self-compacting nature of the mixture. The specific gravity measurement according to ASTM D854 determines the specific gravity of soil

**Table 3.12** Engineering standards for this study

| Requirement | British Standard | American Society for Testing and Materials | Sri Lankan Standards |
|---|---|---|---|
| Total Study | BS 3921:1985 - Specification for clay bricks | ASTM C1825 - 18 Standard Guide for Developing Specifications for Masonry Units | |
| Compressive strength (N/mm2) | BS-EN-772-1 Methods of test for masonry units Part 1: Determination of compressive strength | ASTM C67 - 05 Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile | Specifications for Compressed Stabilized Earth Blocks: SLS 1382 |
| Tensile splitting strength (N/mm2) | BS-EN-772-1 Methods of test for masonry units Part 6 Methods of test for masonry units. Determination of bending tensile strength of aggregate concrete masonry units | ASTM C1006 - 07(2013) Standard Test Method for Splitting Tensile Strength of Masonry Units | Specifications for Compressed Stabilized Earth Blocks: SLS 1382 |
| Density | BS-EN-772-1 Methods of test for masonry units Part 13 Methods of test for masonry units.Determination of net and gross dry density of masonry units (except for natural stone) | ASTM C20 - 00(2015) Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water | – |
| Water Absorption | BS-EN-772-1 Methods of test for masonry units Part 11 Methods of test for masonry units. Determination of water absorption of aggregate concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units | ASTM D570 - 98(2018) Standard Test Method for Water Absorption | – |
| Porosity | BS-EN-772-1 Methods of test for masonry units Part 4 Methods of test for masonry units. Determination of real and bulk density and of total and open porosity for natural stone masonry units | ASTM C830 - 00(2016) Standard Test Methods for Apparent Porosity | – |
| Freez thaw | BS-EN-772-1 Methods of test for masonry units Part 18 Methods of test for masonry units. Determination of freeze-thaw resistance of calcium silicate masonry units | ASTM C1645 - 16 Standard Test Method for Freeze-thaw and De-icing Salt Durability of Masonary Units | – |
| Cold water absorption (%) | BS-EN-772-1 Methods of test for masonry units Part 6 Methods of test for masonry units. Determination of bending tensile strength of aggregate concrete masonry units | ASTM C1403 - 15 Standard Test Method for Rate of Water Absorption of Masonry Mortars | – |
| Shrinkage | BS 3921:1985 - Specification for clay bricks | ASTM C426 - 16 Standard Test Method for Linear Drying Shrinkage of Concrete Masonry Units | – |
| Organi Matter | BS 1377-3:1990 Methods of test for soils for civil engineering purposes. | ASTM D2974 - 14 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils | – |
| Capilary Action | BS EN 1015-18:2002 Methods of test for mortar for masonry. Determination of water absorption coefficient due to capillary action of hardened mortar | ASTM C1585 - 13 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes | – |
| Surface Roughness | – | ASTM C744 - 16 Standard Specification for Prefaced Concrete and Calcium Silicate Masonry Units | – |

and soil samples. However, soil and soil mixes also can be calculated by using this method. The method is to oven dry the sample and then crushed to lowest fine particles and then study the materials distribution in a pycnometer. But, the Civile engineering department has a digital specific gravity meter which can measure the specific gravity by using a small mass of samples.

#### 3.10.1.2 Atterberg limits

Atterberg limit is a very important measure to understand the shrinkage limit, plastic limit and liquid limit of a soil. The soil is not a homogenous material found on earth; instead, there are many types, many kinds of soils on earth. However, depending on the soil particle size and moisture content, the soil may behave in four stages such as solid, semi-solid, plastic and liquid.

### 3.10.2 Sieve analysis

The soil comes in different sizes and shapes of particles. Before, stating with mix designs the particle size should be analyzed. The particles size of selected the soil samples. The method to evaluate the particle size distribution as follows. A sample of soil dried inside the oven until the weight becomes a constant minimum of 24 hours. Cooled back to the room temperature. After cooling back to room temperature the soil samples weight was measured by using a scale and then poured into a sieve analysis machine.

Then the weight of each and every sieve was separately measured along with the weight of the sieve. After that, the data were analyzed according to a spreadsheet developed according to ASTM D424.

The sieve analysis was conducted in many stages of this total study. Some time to understand the strength formation, some blocks were tested and checked the particle size distribution after the destructing testing. Also, some of the materials used in this study have very fine particles such as fly ash. To study the particle size of very fine materials, the hydrometer test was conducted according to ASTM D422 63(2007).

#### 3.10.2.1 Hydrometer sieve analysis for fines soil/materials samples

In a condition of very fine particle distribution, the typical sieves cannot be used to analyze the particle size distribution. In order to study the particle size, the standards procedure is to do a hydrometer test. In the hydrometer test, the materials were mixed with water and stir for a period of ten minutes. And then the hydrometer was read according to following time laps starting from 0, 4,9,16,25,36,49, and 60 minutes 6 hours one day etc.

The primary requirement of most of the construction materials is the strength. The strength is measured by using a compressive strength test. There are two types of compressive strength testing such as destructive method and nondestructive method. Which is very difficult for a nondestructive method to evaluate the strength of the newly developed mix proportion or even new stabilizer. Therefore, for this study, only the destructive method was used according to the following standards.

## 3.11 Experimental location

Most of the experiments were conducted in the University premises. The experiments were conducted in the department civil engineering university of Moratuwa lab. And the soil was collected from the university premises so the homogenous soil can be used throughout the experimental programme. Skilled labor was used for the construction and manufacturing of the molds were done at the university premises. All the experiments were done at the University premises. The soil also collected from the backyard of the university.

## 3.12 Equipments

There are many types of equipment used in this total study. Most of the equipment was acquired from the structural testing and materials testing lab, department of civil engineering, University of Moratuwa. The equipment which is not available in the lab was designed and manufactured by the author. Some of the equipment was hired by other universities and rented from the nearby equipment supplier.

## 3.13 Summary

This chapter provides the method to develop alternative stabilizer stabilized mud concrete block. Standard procedure to study different possible stabilizers and experiments conducted to optimize their use in different soil conditions. The focus of this study method is to optimize a particular alternative stabilizer to develop an engineering walling block. Therefore, the basal study focused on engineering properties such as compressive strength density etc. In addition to engineering properties, certain mechanical properties should be there to introduce the particular walling block for practical use. To test with mechanical properties certain standards such as compressive strength and tensile were used.

# CHAPTER 4

# EXPERIMENTS AND RESULTS OF ALTERNATIVE STABILIZING TECHNOLOGIES

## 4.1 General

This study was not conducted in a linear form, concluding results one after another. Some experiments and decisions for were purely based on the previous experiment. A new line of experiments was created and done in order to get the final results of the experiment. Some of the stabilizers were tested to understand the effectiveness of other stabilizers. But most of the stabilizing technologies were separately studied. Therefore, each and every stabilizing technology will be presenting separately depending on the phase of the study shown in Figure 4.1 on page 79. In addition, there are three types of stabilizers were discussed in the literature survey and methodology section. Out of three different stabilizing technologies, novel stabilizing technologies were studied separately. Then combined stabilizing technology for mud concrete block was developed.

## 4.2 Mechanical soil stabilizing techniques

Mechanical soil stabilization is not sustainable as they need some amount of machinery. Therefore, at the very beginning, the mechanical stabilizing method did not get the attention. But after developing the mud concrete block, the workability and self-compacting nature were studied. The self-compacting nature got the attention due to

**Fig. 4.1** Different mix design blocks prior to test

**Table 4.1** Wet compressive strength for test cubes of stage one: series two

| Moisture % | Average wet compressive strength (N/$mm^2$) | | |
|---|---|---|---|
| | No vibration | 15s vibration | 30s vibration |
| 13.0 | 12 | 9.2 | 10.3 |
| 14.0 | 15.4 | 12.5 | 13.8 |
| 15.0 | 14.6 | 7.8 | 8.1 |

many reasons.The total study and experimental results were published in Case studies in construction and building materials in 2017 in journal paper named mud concrete paving blocks (Udawattha, Galabada, and Halwatura, 2017).

### 4.2.1 Machinery compaction of soil

Introducing an additional load and compressing soil to make an earth block is a very old method of making earth blocks. The idea was to reduce the pores spaces inside the earth block and increase the density of the soil block. However, the rammed earth and cement stabilized earth blocks (CSEB) are using the same technology. Thus, this study experimented with the introduction of vibration to the mud mixture shown in table 4.1 on page 79. The effect of compaction was studied in contrasting to the vibration and compaction times. Several vibration patterns were introduced for mud concrete mixes stating from o seconds, 15 seconds vibration and 30 seconds vibrations. Found that self-compaction can deliver the same strength if the moisture content is optimized with respect to the composition of the mud concrete mixture (Udawattha, Galabada, and Halwatura, 2017).

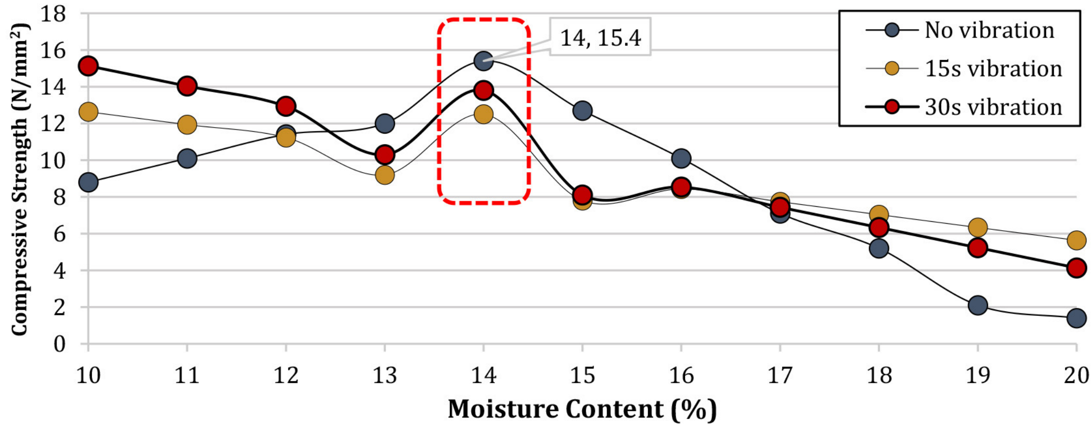



**Fig. 4.2** Moisture content and self-compaction study

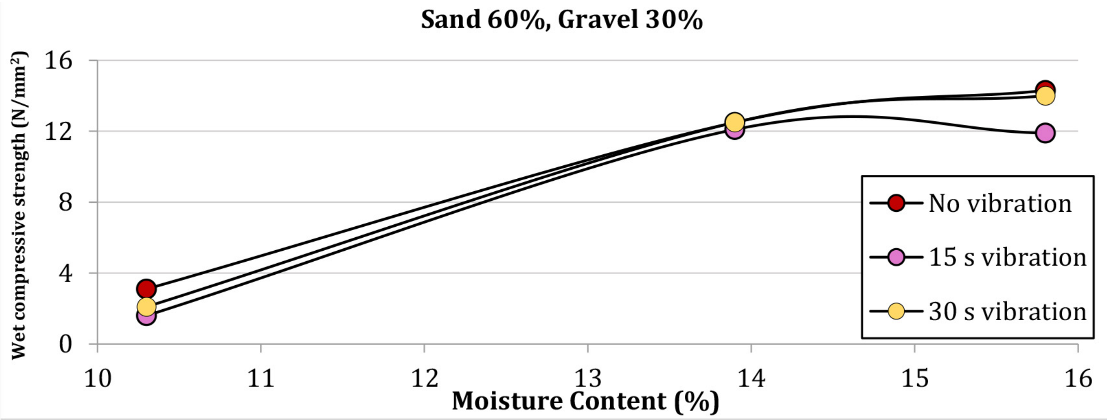



**Fig. 4.3** Wet compressive strength with sand 60% and gravel 30%

### 4.2.2 Self-compacting mud concrete technology

The idea of the self-compacting mixture is to optimize the moisture content of the mud concrete block mixture. The self-compaction nature of mud concrete mixtures were studied by using novel slump test developed by a sister research conducted parallel to this study (F. R. Arooz and Halwatura, 2018).

Results of this experiment *(seen in the Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.19* show that self-compacting good method of stabling mud concrete without using a single drop of energy or equipment. Therefore, the technology of the self-compacting nature of mud concrete block was developed used in any stabilizer technology used to experiment in the future and sun drying was tested as an effective curing method shown in the Figure 4.7 on page 82.

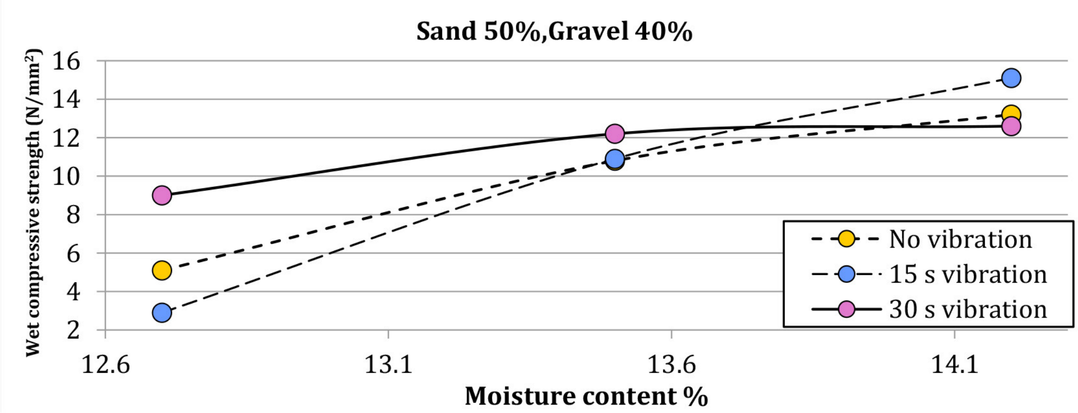



**Fig. 4.4** Variation of wet com. strength with sand 50% and gravel 40%

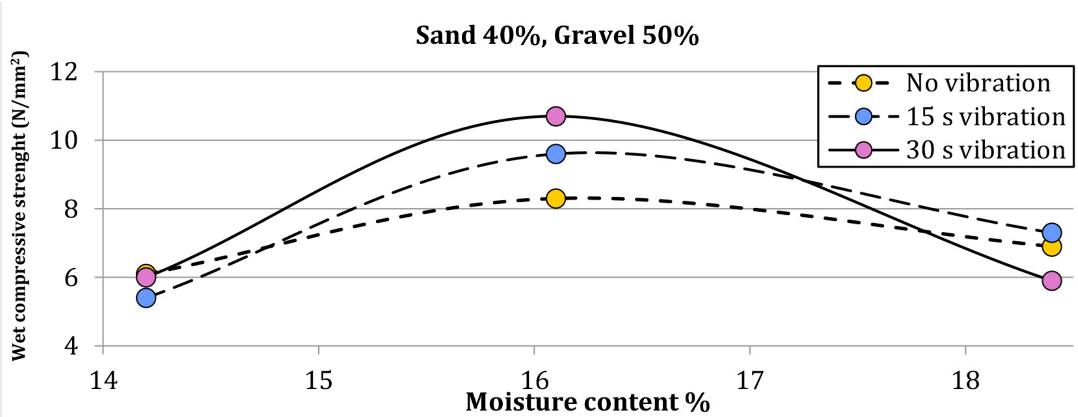



**Fig. 4.5** Variation of wet com. strength with sand 40% and gravel 50%

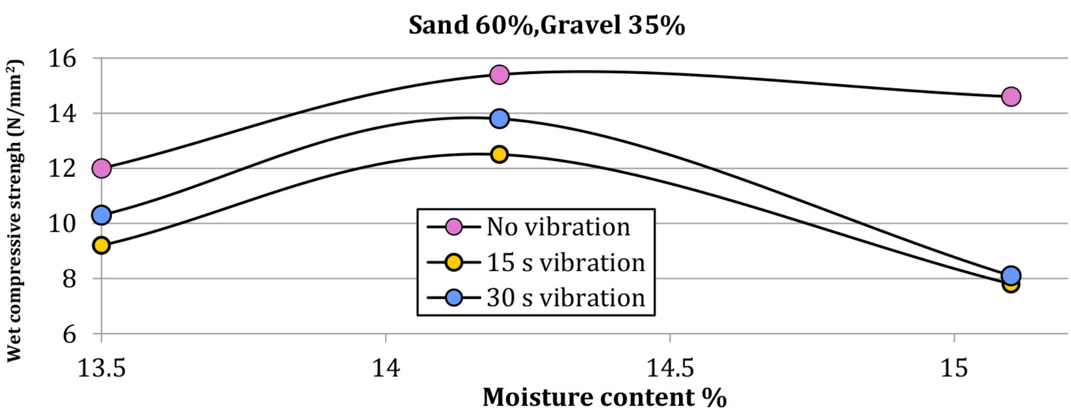



**Fig. 4.6** Variation of wet compressive strength with moisture content.

## 4.3 Chemically soil stabilizing technologies

An experimental program was designed to study the behavior of soil as the percent of the additive of chemicals. Not only chemicals but also, the idea was to change the chemical composition of soil by additive several additives equal to cement.

**Fig. 4.7** Sun drying after removing excessive moisture

### 4.3.1 Lime

**Table 4.2** Initial experiment results with lime and cement

| Lime and soil mix dry strenght | | | | |
|---|---|---|---|---|
| Lime (%) | 14days | 30days | 60days | 90days |
| 0% | 0.27 | 1.58 | 1.6 | 1.6 |
| 4% | 0.29 | 2.6 | 2.68 | 2.72 |
| 8% | 0.68 | 3.04 | 3.2 | 3.3 |
| 12% | 0.75 | 3.07 | 3.3 | 3.51 |

| Lime cement and soil mix dry strenght | | | | | |
|---|---|---|---|---|---|
| Lime (%) | Cement (%) | 14days | 30days | 60days | 90days |
| 0% | 4% | 0.27 | 1.58 | 1.6 | 1.6 |
| 4% | 4% | 0.29 | 2.6 | 2.68 | 2.72 |
| 8% | 4% | 0.68 | 3.04 | 3.2 | 3.3 |
| 12% | 4% | 0.75 | 3.07 | 3.3 | 3.51 |

The results of this experiment shown in table 4.2 on page 82 show that 4% to 8% range of lime can stable soil up to the required strength within a period of one month. Then the strength increased. But cement stabilized mud concrete block 4% cement can gain strength to the required within a period of one-month *(see the figure 4.8 on page 83*. Interestingly, lime stabilized mud concrete blocks shows fewer pores section. Therefore the study was conducted to identify the porosity and cold water absorption. The cold water absorption shows fewer pores spaces and absorbs the comparative high amount of water. In addition, there are three types of stabilizers were discussed in the literature survey and methodology section. Out of three different stabilizing technologies, novel

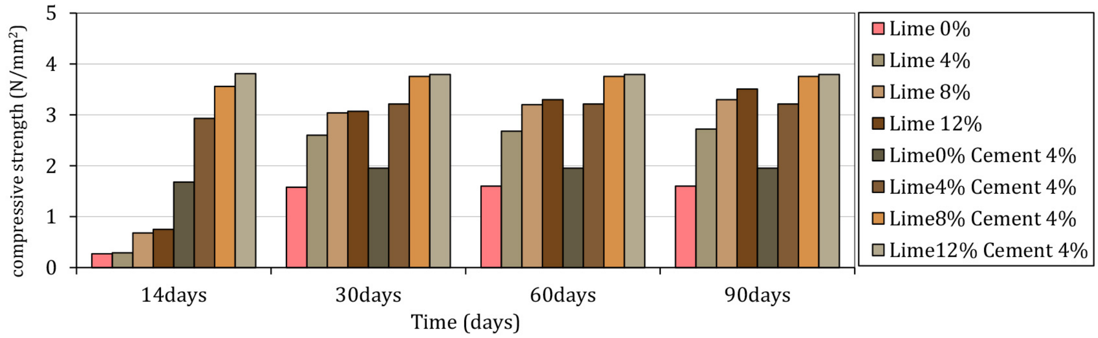



**Fig. 4.8** The initial experiment results with lime and cement

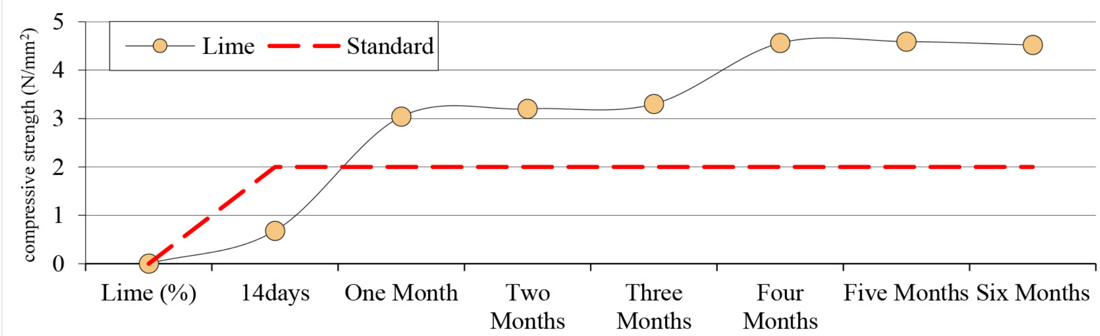



**Fig. 4.9** The Long-term strength development

stabilizing technologies were studied separately. Then combined stabilizing technology for mud concrete block was developed.The total study and experimental results were presented in 8th International Conference on Sustainable Built Environment in 2017 in conference paper named Character of lime as an alternative stabilizer to improve the long-term strength of mud concrete block. The use of lime as an alternative stabilizer and the character of stabilizing soil, mud was discussed in the paper. Furthermore, this study is still continuing to understand the long-term strength gain and carbonation of lime stabilized mud concrete block as a continuation of results shown in Figure 4.9 on page 83.

### 4.3.2 Fly Ash

#### 4.3.2.1 Study on Strength Variation with fly Ash Addition

Eight mix designs subjected to this study to understand the strength development of fly ash stabilized mud concrete block. The mix design was started from 0% fly to 35%.

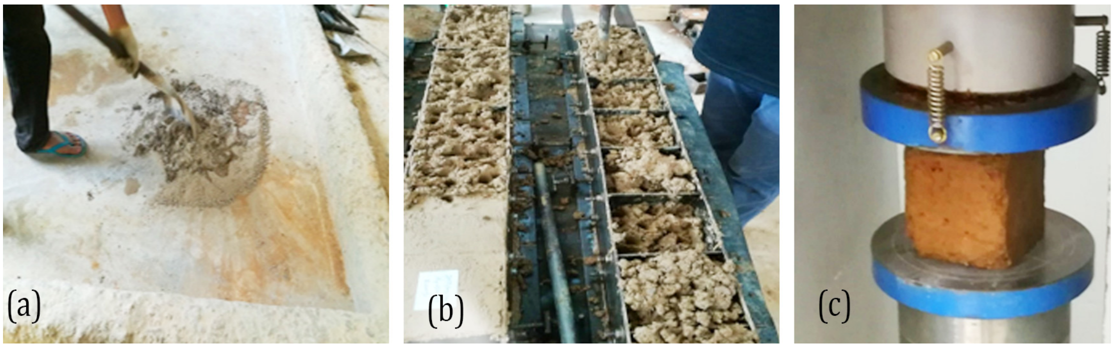



**Fig. 4.10** Dry strength variation of different fly ash ratios

The same soil was mixed with fly and 100mmX100mm cubes were cast to understand the strength development. Results of this experiment shown in figure 4.11 and table 4.3. Not only dry strength but also wet strength was taken into consideration shown in table 4.4. Both dry and wet compressive strength shows some form of strength gain, but not enough according to required standards.

**Table 4.3** Dry strength variation of different fly ash

| | Fly Ash 0% ($N/mm^2$) | Fly Ash 5% ($N/mm^2$) | Fly Ash 10% ($N/mm^2$) | Fly Ash 15% ($N/mm^2$) | Fly Ash 20% ($N/mm^2$) | Fly Ash 25% ($N/mm^2$) | Fly Ash 30% ($N/mm^2$) | Fly Ash 35% ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|
| 7 days | 0.34 | 0.3 | 0.32 | 0.29 | 0.57 | 0.38 | 0.29 | 0.3 |
| 14 days | 0.73 | 0.5 | 0.46 | 0.77 | 0.88 | 0.58 | 0.16 | 0.3 |
| 21 days | 0.66 | 0.66 | 0.81 | 1.07 | 1.03 | 0.58 | 0.93 | 0.86 |
| 28 days | 0.67 | 0.61 | 0.74 | 0.85 | 1.33 | 0.79 | 0.76 | 0.75 |

According to results shown in figure 6 and table 2, the optimum fly ash content was confirmed as 20% of the dry weight of the total mixture. The increase of fly ash more than 20% did not perform any strength development.

**Table 4.4** Wet strength variation of different fly ash

| | Fly Ash 0% ($N/mm^2$) | Fly Ash 5% ($N/mm^2$) | Fly Ash 10% ($N/mm^2$) | Fly Ash 15% ($N/mm^2$) | Fly Ash 20% ($N/mm^2$) | Fly Ash 25% ($N/mm^2$) | Fly Ash 30% ($N/mm^2$) | Fly Ash 35% ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|
| 7 days | 0.30 | 0.36 | 0.30 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 |
| 14 days | 0.39 | 0.28 | 0.31 | 0.25 | 0.21 | 0.17 | 0.13 | 0.09 |
| 21 days | 0.35 | 0.24 | 0.23 | 0.15 | 0.09 | 0.03 | -0.03 | -0.09 |
| 28 days | 0.31 | 0.29 | 0.30 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 |

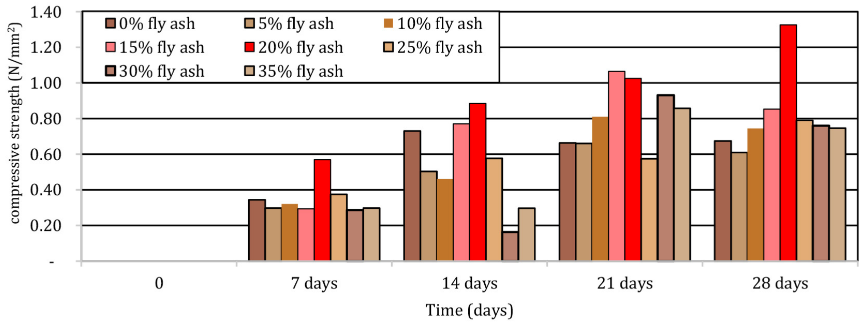



**Fig. 4.11** Dry strength variation of different fly ash ratios

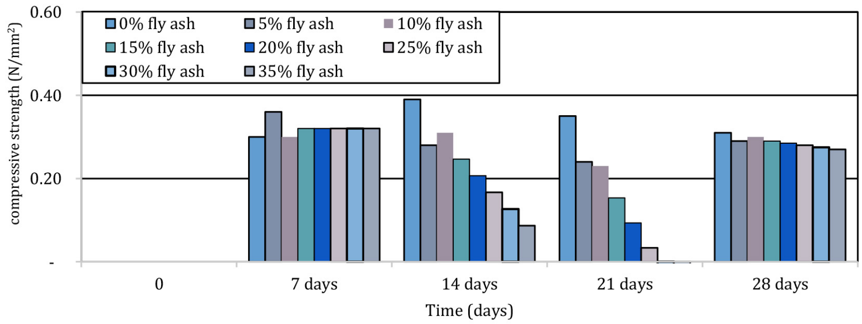



**Fig. 4.12** Wet strength variation of different fly ash ratios

#### 4.3.2.2 Workability improvement

A workability study was conducted to understand the quick flow effect of fly ash stabilized mud concrete block shown in Figure 4.13 on page 85. Because it was felt to the hand that fly ash mixing with soil and mud is easier than mixing cement with soil. Once the fly ash is increased gradually, 30% of water is not enough to maintain the workability within the expected level due to water absorption of Fly ash.

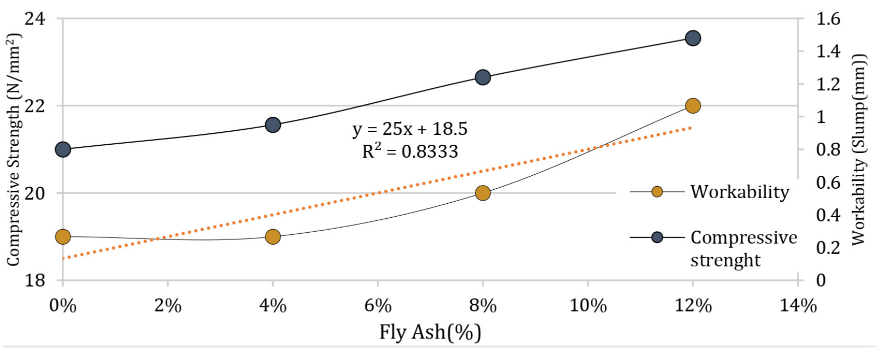



**Fig. 4.13** Increase of workability with Fly Ash percentage

#### 4.3.2.3 Compressive Strength Variation

For each mix proportions that have considered, the compressive strength was tested with unconfined compressive strength test. Both wet strength and dry strength was tested from 7 days, 14 days, 21 days and 28 days as mentioned early. Here the value of pressure is changed in between 0.3N/mm$^2$ and 0.7N/mm$^2$ Figure 4.11 on page 85. Hence increasing of the dry compressive strength of cubes can be neglected when adding the Fly ash less than 12%. But can be noticed that clearly there is some impact to the dry compressive strength of cubes by adding the Fly ash.

There is no any significant pressure value difference within 28 days. Wet strength variation was different from the dry strength variation. Pressure variation is almost like to the straight line. Hence there's no any effect to the wet compressive strength by adding the Fly ash to the soil in less than 12%.

#### 4.3.2.4 Failure Pattern of cube

Tested cubes have been failed with a prismatic failure criterion. With this failure pattern, it can be concluded that the casting of the cubes was done properly. Therefore, can be sure that the mixture was homogeneous throughout the cube. Hence Obtained results are accurate enough. With the results of a first experimental study can be identified that there is no any significant effect on soil stabilizing when adding Fly ash less than 12%. But there was a significant effect on workability increase of wet mix with an increase of Fly ash more than 15%. The compressive strength of soil cubes can be increased by reducing moisture content but when the moisture content has dropped the workability will also reduce. With these two results, the second study was done to observe the strength variation with reduction of moisture content while maintaining the workability at a constant range by adding Fly ash.

**Table 4.5** Results of fly ash alternative stabilizer

| Mix No | Soil(%) | Cement(%) | Fly Ash(%) | Water Content(%) | Sump(mm) | Compressive strength(N/mm$^2$) |
|---|---|---|---|---|---|---|
| 1 | 90 | 6 | 0 | 30 | 19 | 0.80 N/mm$^2$ |
| 2 | 90 | 6 | 4 | 29 | 19 | 0.95 N/mm$^2$ |
| 3 | 90 | 6 | 8 | 28 | 20 | 1.24 N/mm$^2$ |
| 4 | 90 | 6 | 12 | 27 | 22 | 1.48 N/mm$^2$ |

#### 4.3.2.5 Study of Strength Variation with Moisture Content

In this attempt 4, no of mixtures were considered table 4.6 on page 88 . Fly ash content was changed in these 4 mixtures. Then water was added as mention amounts in the table. Then workability could be maintained around 20 mm of slump height. With these results, it was clear that even the workability was supposed to reduce with the reduction of moisture content, with an increase of Fly ash it remains unchanged by enhancing workability.

#### 4.3.2.6 Strength Variation

Unconfined compressive strength test was done on each of these test cubes after 28 days. They were also subjected to the same curing method for 7 days as in $1^{st}$ attempt. According to the graph, the compressive strength variation showed some strength increment in this study. By reducing the percentage of moisture content level, can be enhanced the compressive strength of soil cubes while keeping the workability of the mixture at a proper level by adding the Fly ash as required.

#### 4.3.2.7 Morphology analysis of fly ash stabilized mud concrete

The figure 4.51 and figure 4.15 on page 89 shows that fly ash stabilized mud concrete block tend crack at micro scale.figure 4.15 [2] shows there are so many fly ash bubbles detached from the MCB mixture. More enlarged image of [c] and [d] shows some bubbles are surfing on the mixture. A crack study of the enlarged image of the figure 4.15 [a] shows that fly ash can make a smooth surface. But, SEM images do not show any stabilizing effect from fly ash.

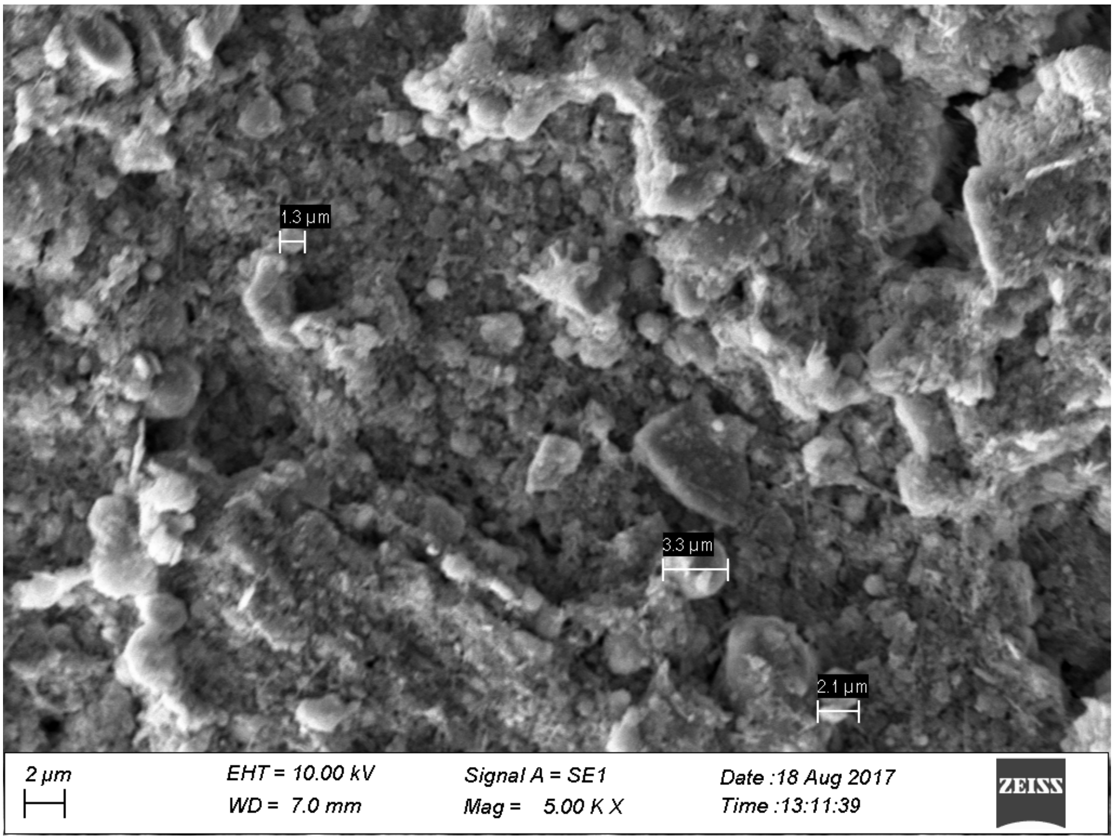



**Fig. 4.14** SEM images of fly ash stabilized mud concrete block

### 4.3.3 Bottom Ash

Bottom ash for the tests was received from coal combustion plants of Lakvijaya power plant Norochcholai, Puttalam, Sri Lanka. Those bottom ash (BA) was sieved through a 1.7mm sieve since there were larger particles and conducted a mix design study shown in Figure 4.16 on page 90, [a] shows mixtures poured moulds, [b] shows casted blocks prior to testing, [c] shows compressive strength test and [d] shows the failure pattern of the BA stabilized cube.

**Table 4.6** Bottom ash mix design for initial experiment

| Mix no | Soil % | Cement % | Bottom Ash(BA) % |
|---|---|---|---|
| 1 | 96% | 4% | 0% |
| 2 | 94% | 4% | 2% |
| 3 | 92% | 4% | 4% |
| 4 | 90% | 4% | 6% |
| 5 | 88% | 4% | 8% |

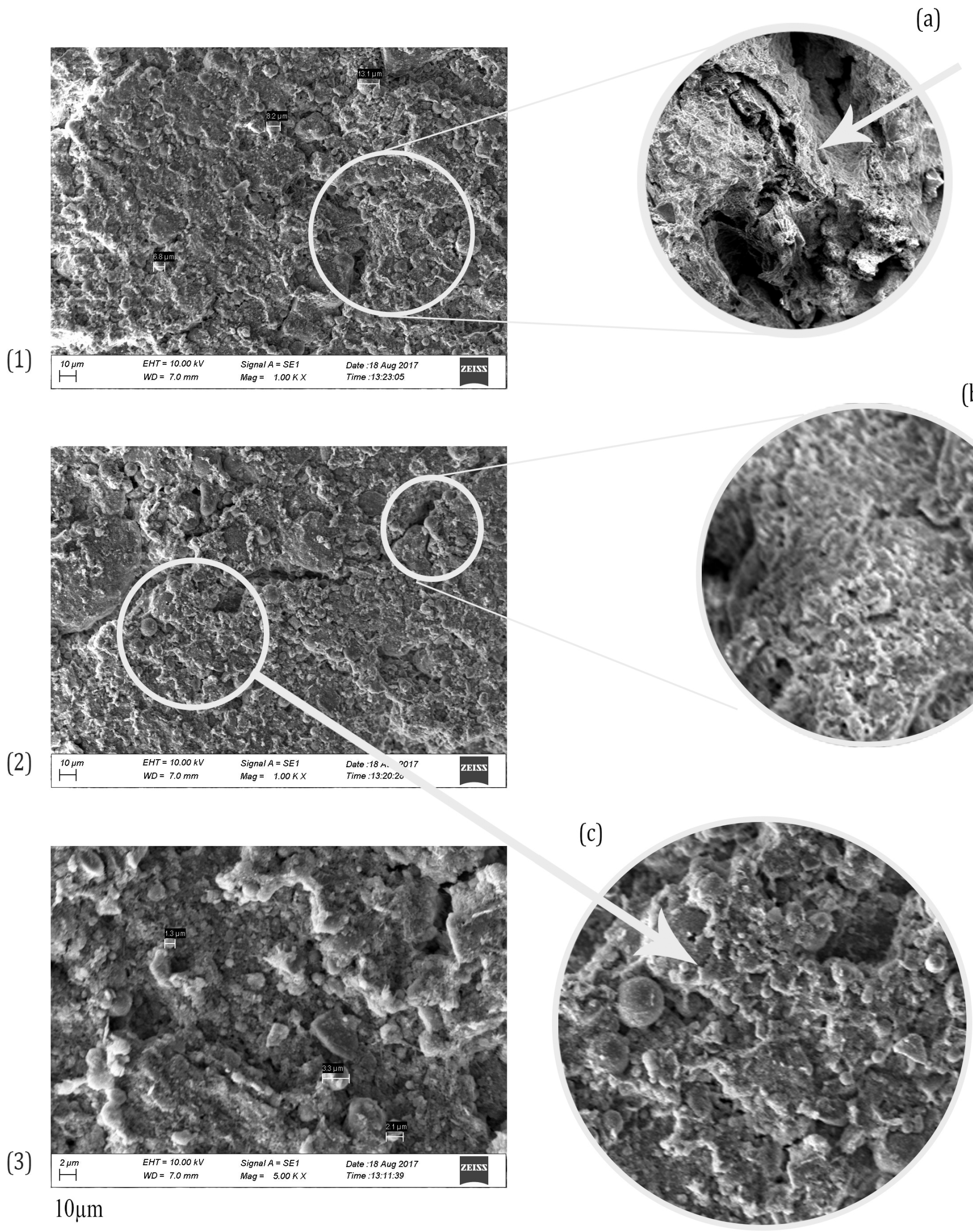



**Fig. 4.15** SEM images

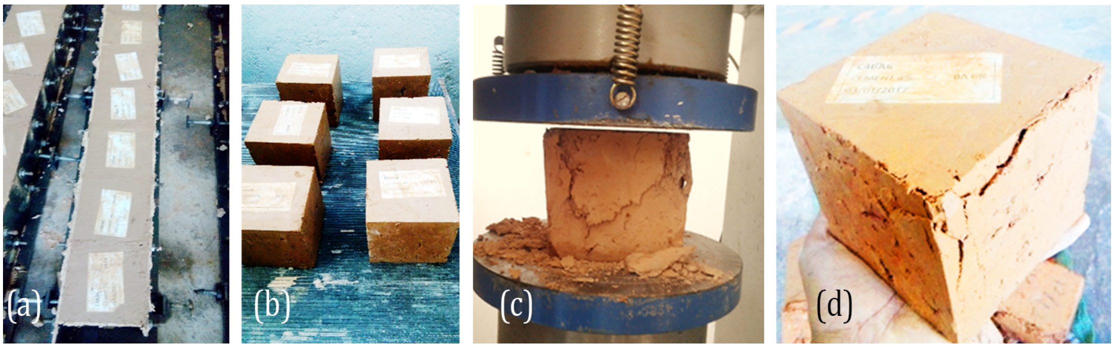



**Fig. 4.16** the casting of test cubes (100x100)

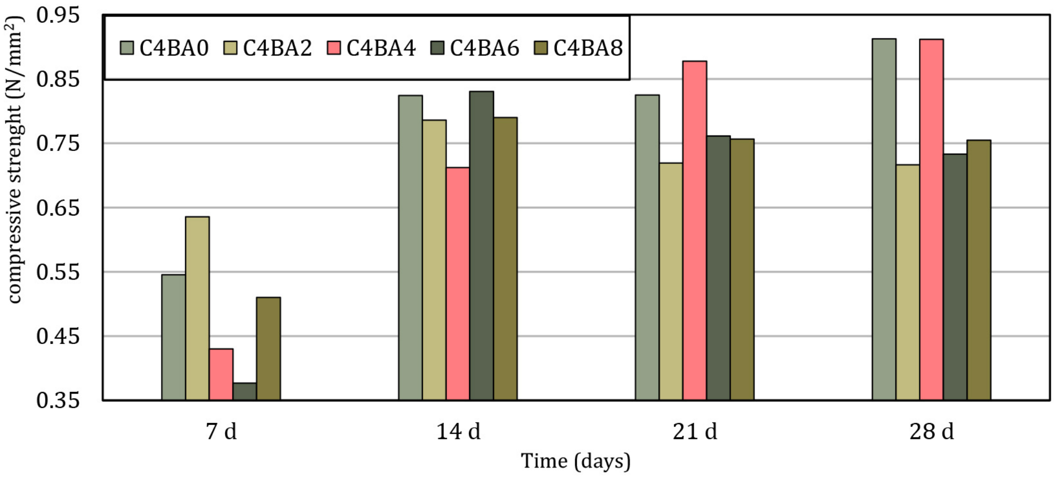



**Fig. 4.17** Compressive strenght test results of BA stabilized MCB

Total of 24 numbers of 100x100x100mm test cubes were cast with one mix proportion shown in table 4.6 on page 88. The unconfined compressive strength of three cubes was tested from each of wet and dry state of test cubes. This was tested at 7, 14, 21 and 28 days respectively in order to identify the strength gain.

#### 4.3.3.1 Workability of soil bottom ash mixture

Measuring of workability of the wet mixture with the standard slump test was practically difficult in this case. Atterberg test consumes more time which results in the mix getting hard. Hence an alternative test was proposed to get a measure on workability.

A small-scale slump like cone was used to produce a vertical cone with the mix. It was done on the flow table. The cone was made with three layers of the mix with each having 20 blows. After removing of the slump mold 5 drops have given by the

**Table 4.7** Dry strength variation of different bottom ash ratios

| | Bottom Ash 0% (N/mm2) | Bottom Ash 5% (N/mm2) | Bottom Ash 10% (N/mm2) | Bottom Ash 15% (N/mm2) | Bottom Ash 20% (N/mm2) | Bottom Ash 25% (N/mm2) | Bottom Ash 30% (N/mm2) | Bottom Ash 35% (N/mm2) |
|---|---|---|---|---|---|---|---|---|
| 7 days | 0.20 | 0.34 | 0.21 | 0.26 | 0.28 | 0.17 | 0.00 | 0.00 |
| 14 days | 0.31 | 0.26 | 0.27 | 0.24 | 0.19 | 0.14 | 0.00 | 0.00 |
| 21 days | 0.31 | 0.28 | 0.20 | 0.18 | 0.10 | 0.00 | 0.00 | 0.00 |
| 28 days | 0.24 | 0.24 | 0.21 | 0.20 | 0.20 | 0.23 | 0.23 | 0.00 |

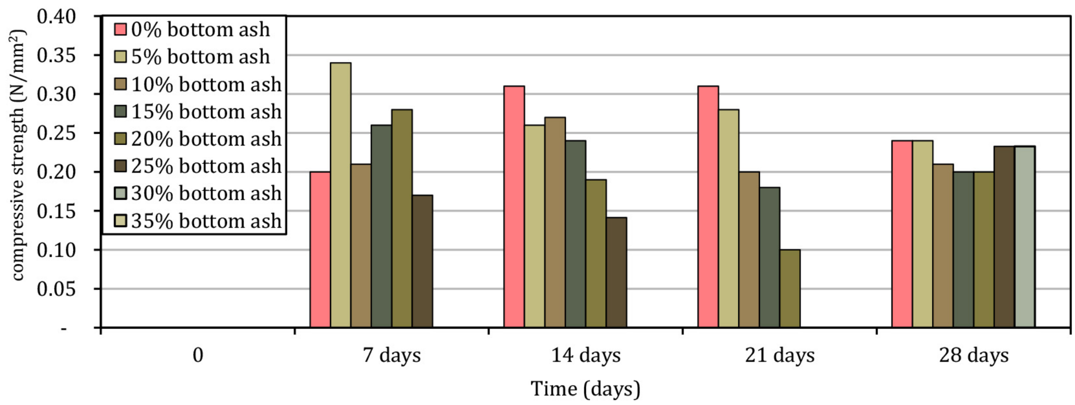



**Fig. 4.18** Dry strength variation of different Bottom ash ratios

flow table. A drop of the height of the slump was taken as the measure of workability. By keeping this value constant, the same range of workability of every mixture can be achieved. The unconfined strength of test cubes was tested for every mix proportion for both wet and dry condition. Three cubs were tested from each category.

#### 4.3.3.2 Strength variation with time

In every mix proportion, there is a strength gain with the time. Strength achieving of each mix is almost the same. 7-day strength is much less and after that, no significant strength gain has achieved *(see the Figure 4.17)*. For strength gaining of individual mixtures, there is no significant effect from the addition of bottom ash.

Tested 28-day compressive strength varies almost like a straight line, which indicates no considerable strength improvement with the addition of bottom ash shown in table 4.7. Strength gaining is limited for cement. Although no strength gaining was experienced a change in workability was experienced.

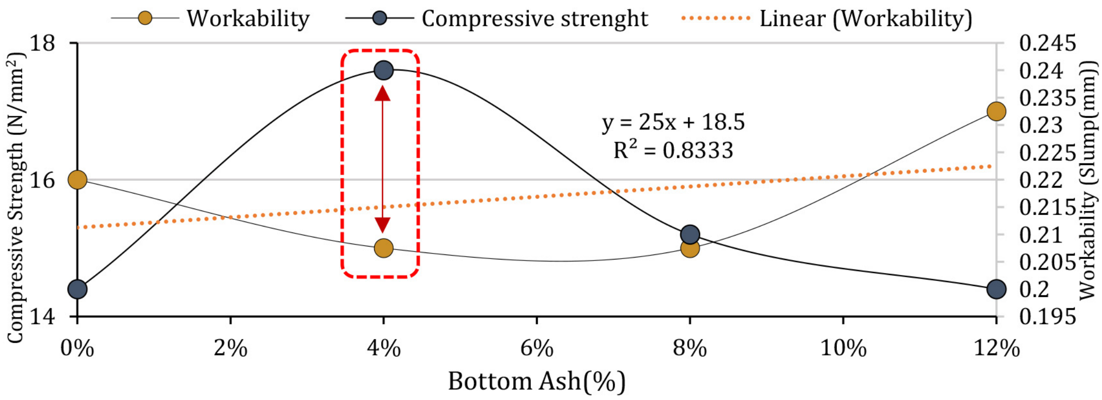



**Fig. 4.19** Increase of workability with Bottom Ash percentage

#### 4.3.3.3 Variation of workability

Although there is no strength gain with the addition of bottom ash, there is a slight increase in workability according to the results shown in Figure 4.18 on page 91 . Strength gain with time is there, which is stabilization of soil happened. Addition of bottom ash does not affect significantly on improving the compressive strength of mud mix. Addition of bottom ash was the effect on the workability of the wet mix, a slight increase of the workability with an increase of bottom ash percentage.

#### 4.3.3.4 Morphology analysis

Figure 4.21 on page 94 shows microscope scanning electronic images of bottom ash stabilized mud concrete blocks. Bottom ash is leftover ash particles wasted after coal ash combustion process. Figure 4.21 [1] shows the mix with leftover BA particles. However, the same figure enlarged version shown in Figure 4.21 [2] shows some bottom ash particles. The enlarged version of [b] shows a terrain of a mix between BA and soil. The [a] focused to the Rocky surface created by BA stabilized mud concrete block. Bottom ash is high carbon and silicon material. Figure 4.21 [c] shows a sample of leftover bottom ash particle. Much larger very shows that there is a tendency of making a stronger bond between soil particles.

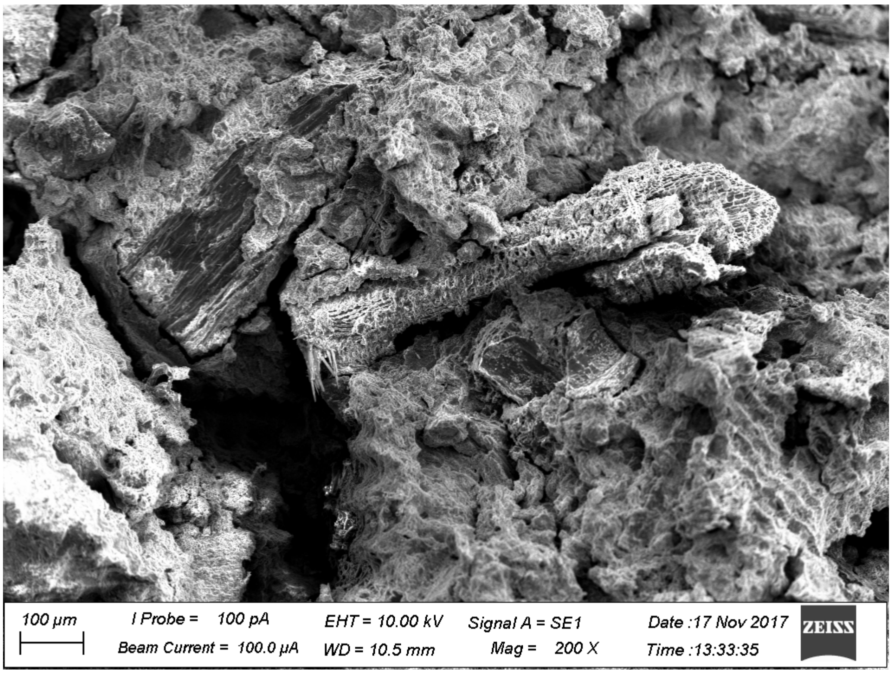



**Fig. 4.20** SEM images of BA stabilized mud concrete block

### 4.3.4 Rice Husk Ash

**Table 4.8** Rice husk ash mix design and compressive strength

| | Rice husk ash 0% (N/mm2) | Rice husk ash 5% (N/mm2) | Rice husk ash 10% (N/mm2) | Rice husk ash 15% (N/mm2) | Rice husk ash 20% (N/mm2) | Rice husk ash 25% (N/mm2) | Rice husk ash 30% (N/mm2) | Rice husk ash 35% (N/mm2) |
|---|---|---|---|---|---|---|---|---|
| 7 days | 0.2 | 0.43 | 0.52 | 0.61 | 0.6 | 0.59 | 0.58 | 0.57 |
| 14 days | 0.31 | 0.52 | 0.64 | 0.76 | 0.71 | 0.66 | 0.61 | 0.56 |
| 21 days | 0.31 | 0.63 | 0.74 | 0.85 | 0.73 | 0.61 | 0.49 | 0.37 |
| 28 days | 0.24 | 0.66 | 0.78 | 0.9 | 0.74 | 0.58 | 0.42 | 0.26 |

Both wet and dry compressive strength were studied in order to identify the most suitable mixing ratio shown in Figure 4.22. The table 4.8 shows the dry and wet CS of the casted cubes. According to figure 4.22, highest dry compressive strength (2.151 N/mm$^2$) had observed in cube with 15% of RHA. With 5%, 10% and 20% of RHA, dry compressive strength is lower than 15% of RHA. Lowest dry compressive strength (0.8589 N/mm$^2$) had observed in cube with 10% of RHA. However, the cube with 15% of RHA achieved the minimum DCS of 2 N/mm$^2$ according to National Engineering Research and Development Centre of Sri Lanka (Research and of Sri Lanka, 2009) dry standard value for a load bearing construction. According to figure 4.23, highest WMDC (1.07 N/mm$^2$) had observed in cube with 15% of RHA. The lowest WMCS

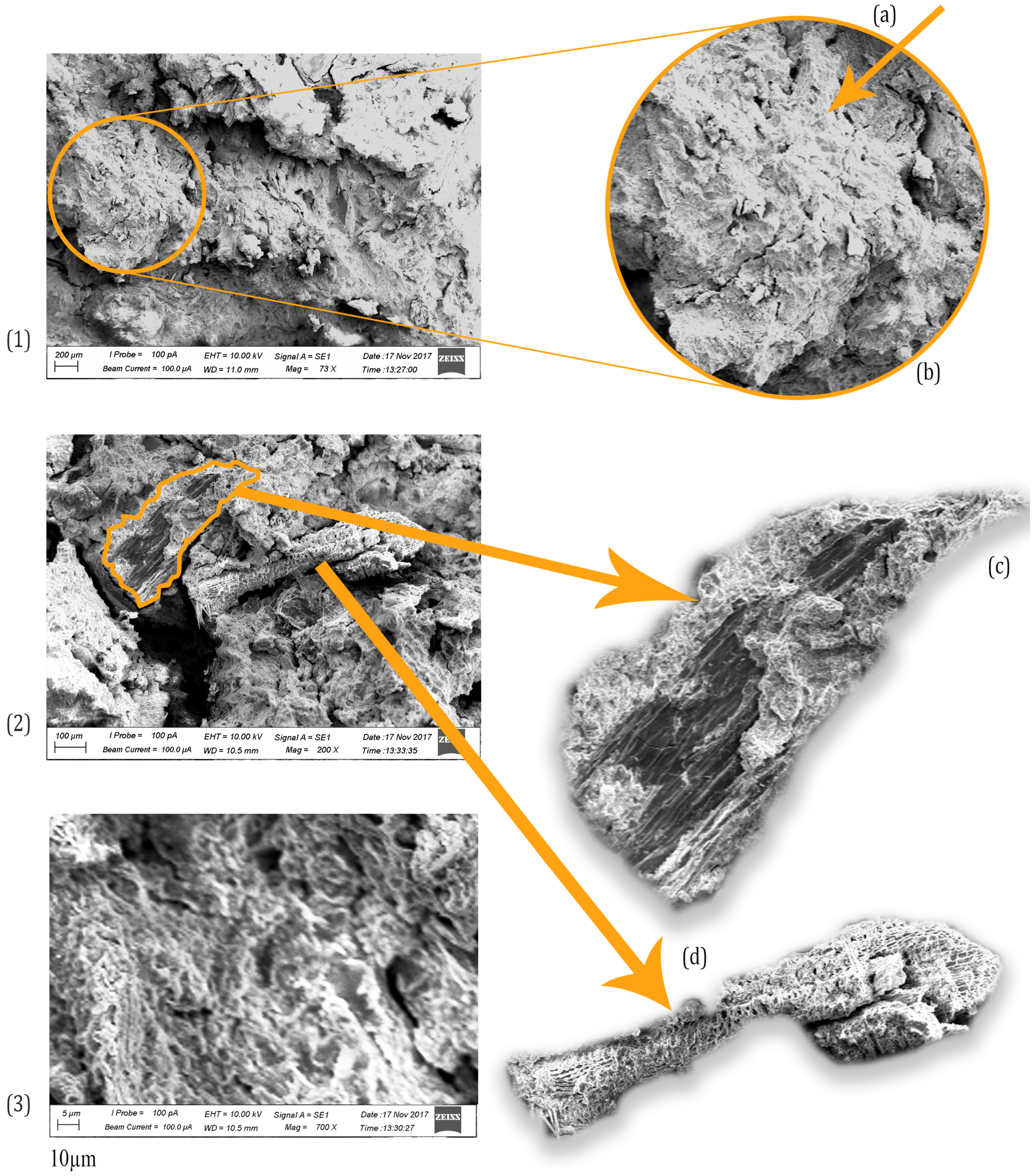



**Fig. 4.21** SEM images

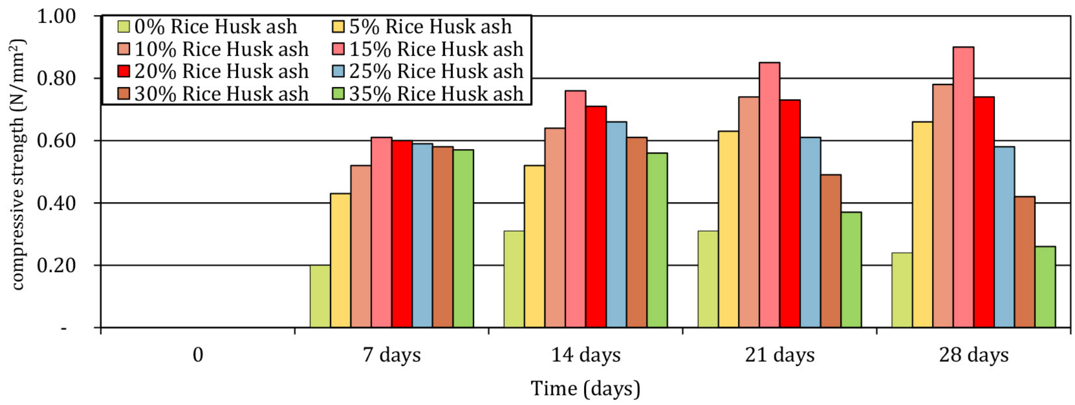



**Fig. 4.22** Dry strength of different rice husk ash contents with time

**Table 4.9** Initial experiment with Rice husk ash alternative stabilizer

| Treatment No. | Soil | RHA | NaCl | NaOH | Water | No of Test Cubes | Total |
|---|---|---|---|---|---|---|---|
| T1 | 85% | 15% | 2% | 4% | 20% | Wet - 3 Dry - 3 | 6 |
| T2 | 85% | 15% | 2% | 6% | 20% | Wet - 3 Dry - 3 | 6 |
| T3 | 85% | 15% | 2% | 5% | 20% | Wet - 3 Dry - 3 | 6 |

(0.14 $Nmm^2$) is in cube with 10% of RHA. However, the cube with 15% of RHA also achieved the minimum WCS of 1 $N/mm^2$ according to NERDS as the wet standard value for a load bearing construction.

Both wet and dry CS are required in order to identify the most suitable mixing ratio with maximum wet and dry CS. Figure 4.5 shows the dry and wet CS of the casted cubes. According to figure 4.23 on page 95, highest dry compressive strenght (2.15 $N/mm^2$) had observed 15% of RHA. Other two values are lower than it. Highest

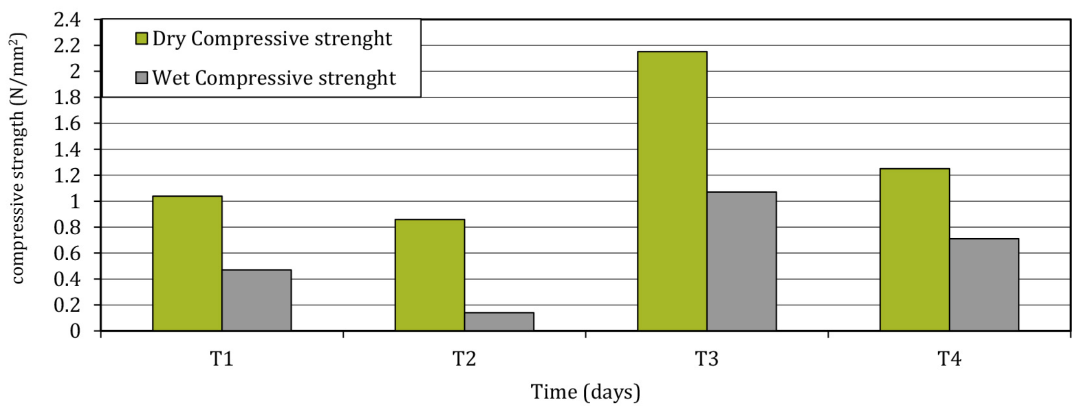



**Fig. 4.23** Average Dry Mean Compressive Strength

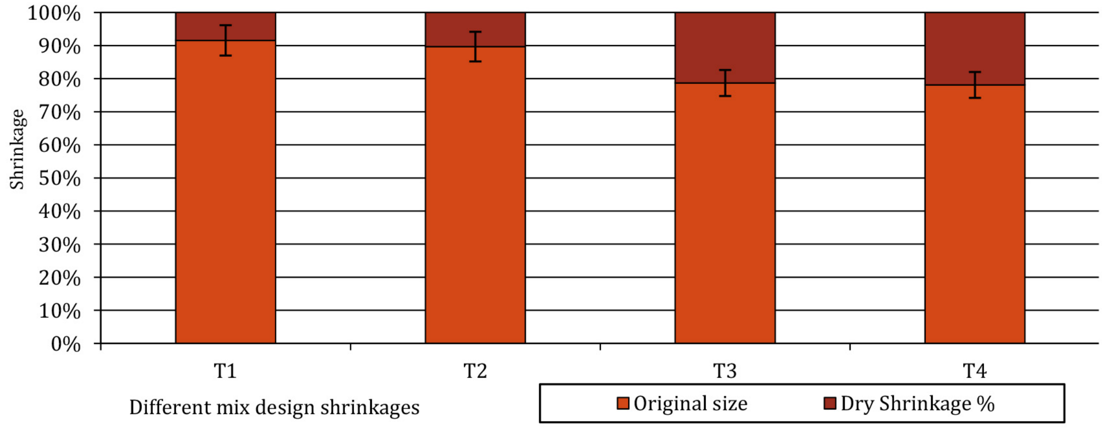



**Fig. 4.24** Different rice husk ash mix design and shrinkages

WMCS (1.07N/mm$^2$) had observed 15% of RHA and the other two values are lower than it. In this experiment, F value of DCS is lower than 0.05 ($F < 0.05$), hence the dry RHA treatments were significantly different from each other while 5% and 10% of RHA treatments are significantly same. According to the Duncan's Multiple Range Test (DMRT), $T_3$ (15% of RHA) is the best treatment.

4.3.4.1 Determination of Shrinkage according to experiment one mixing ratios

Shrinkage of the cubes blocks is also a valuable aspect in the construction section. After 21 days of sun drying process, all the dimensions of cubes as length, width, and height were recorded in order to measure shrinkage. Then the cubes were separated for wet basis and dry basis. Here, shrinkage also divided in to wet and dry basis. Figure 4.24 shows the dry and wet shrinkage of the experiment one casted cubes.According to figure 4.24 on page 96, lowest dry shrinkage% (8.42%) had observed in cube with 5% of RHA. Highest dry shrinkage% (21.9%) had observed in cube with 20% of RHA. When increasing RHA, it increased shrinkage% also. In this experiment, the F value is lower than 0.05 ($F < 0.05$), hence the RHA percentages were significantly different from each other.T1 and T2 (5% and 10% of RHA) are significantly the same and also T3 and T4 (15% and 20% of RHA) are significantly the same *(see the figure 4.24 on page 96)*. But, T3 and T4 are significantly differing from the T2 and T1. According to figure

4.24, lowest wet shrinkage% (8.4%) had observed in cube with 5% of RHA. Highest wet shrinkage% (20.14%) had observed in cube with 20% of RHA. When increasing RHA, it increased shrinkage%.

#### 4.3.4.2 Morphology study

Finally, morphology analysis was conducted to understand the stabilizing effect of RHA. Figure 4.25 on page 98 shows rice husk ash stabilized mud concrete make sense of bonding. [a] shows a clear indication of proper mixing. The figure 4.25 [2] shows a much larger image of RHA. However, there are some leftover rice husk particles (*see the figure 4.25 section [c]*).[d] also shows some terrain creation by RHA stabilized mud concrete.

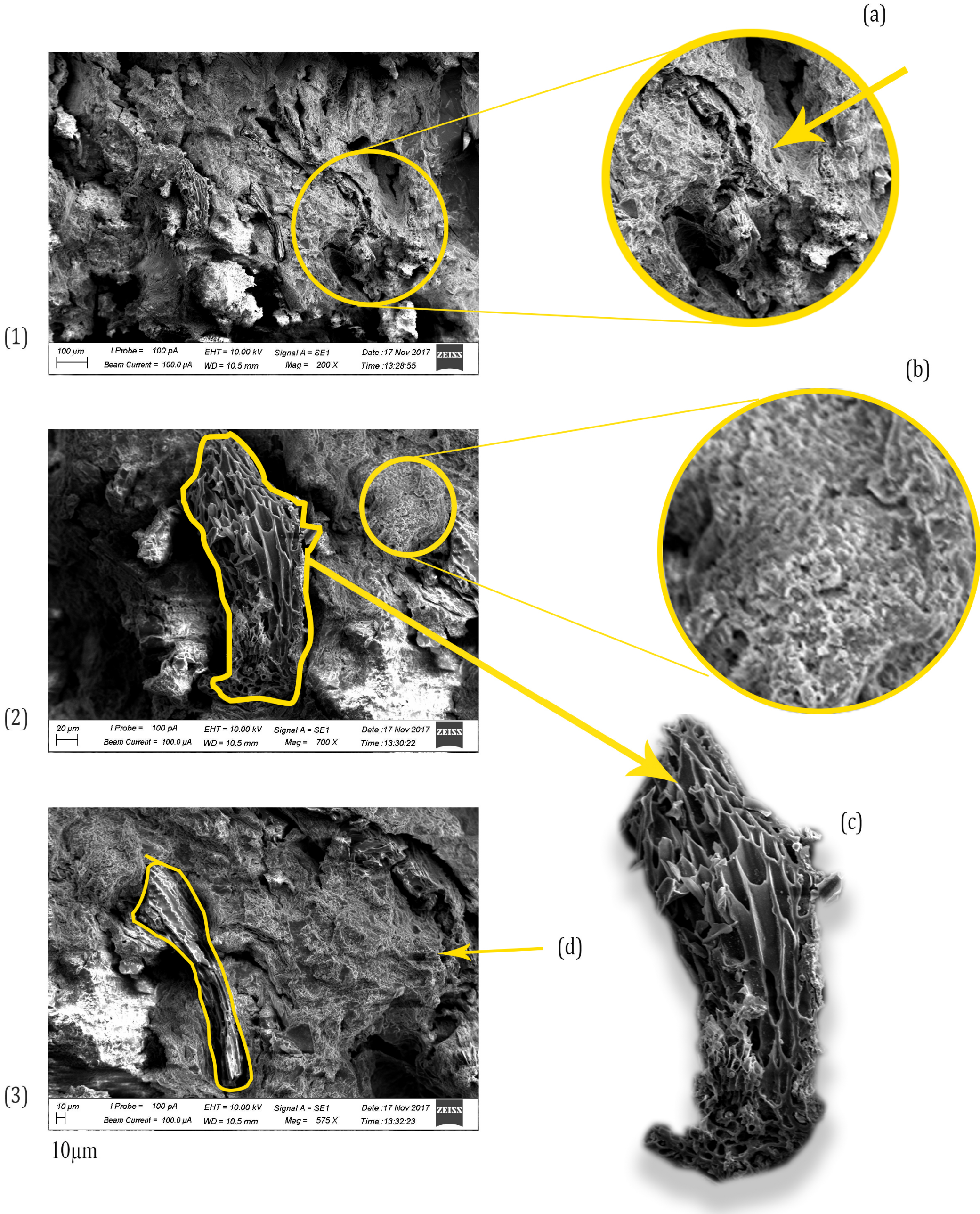



**Fig. 4.25** SEM images

## 4.4 Polymer stabilizing technology

### 4.4.1 Natural rubber latex (NRL) soil stabilization

The experimental shown in figure 4.26 on page 100 *(a-mixing NRL and soil, b-mix of NRL and soil, c-curing NRL stabilized blocks and d,c shows casting process)* schedule was in line with the experimental phases developed by along with the research objectives. The key to the study was to test the probability of mixing NRL with soil and cement. Therefore, the first casting schedule was conducted to understand the possibility of mixing soil,NRL and Cement. The results of this experiment shown table 4.10 on page 99.

**Table 4.10** Compressive strength of NRL cement and soil mix

| Rubber Precentage% | Cement Composition (% ) | Compressive strenght (N/mm$^2$ ) |
|---|---|---|
| 0.0% | 4% | 0.51 |
| 0.5% | 4% | 0.76 |
| 1.0% | 4% | 0.73 |
| 1.5% | 4% | 0.72 |
| 2.0% | 4% | 0.90 |
| 2.5% | 4% | 0.87 |

At the very beginning, NRL was mixed along with soil with the particle size distribution according to MCB results and test whether NRL can be mixed with soil and cement. The results found that it can only be done within a short period of time. Then the experiment was conducted to understand the optimum dry rubber content to produce a stronger earth block.

The initial experiment started with a blind mix of NRL and soil and then a microscopic study was conducted as shown in Figure 4.27 on page 101 to observe the NRL links between 2 soil particles. Soil can be mixed with NRL only for a short period. Mixing for a longer period will turn soil into lumps and finally end up with large soil chunks *(see figure4.26 section b on page 100)*. Astonishingly, cement and rubber did not produce the required strength. Therefore cement was removed from the experimen-


**Fig. 4.26** Preparation of sample blocks for testing

tal program. But the NRL alone stabilized mud concrete blocks in figure 4.27 on page 101 shows a gradual improvement of strength parallel to the increase of NRL dry content shown in Figure 4.28 on page 101. Then the NRL mix experiment was investigated to test with $NH_4OH$ and Sulphur content. The results of the experiment were in contrast to the general knowledge of rubber stabilization by using Sulphur, since the necessary heat for the rubber S vulcanization process was not sufficiently provided during the sun drying process. Hence, they tend to show lower strengths shown in Figure 4.28 on page 101.

**Table 4.11** NRL stabilized blocks with addition of chemicals

| Mixture (Rubber) | Rubber | Rubber+$NH_4OH$ | Rubber+sulphur |
|---|---|---|---|
| 0% | 0.510.51N/mm$^2$ | 0.480.51N/mm$^2$ | 0.890.51N/mm$^2$ |
| 1% | 0.760.51N/mm$^2$ | 2.200.51N/mm$^2$ | 0.730.51N/mm$^2$ |
| 2% | 0.730.51N/mm$^2$ | 2.100.51N/mm$^2$ | 0.860.51N/mm$^2$ |
| 2% | 0.720.51N/mm$^2$ | 2.290.51N/mm$^2$ | 0.850.51N/mm$^2$ |
| 4% | 1.550.51N/mm$^2$ | 2.410.51N/mm$^2$ | 0.890.51N/mm$^2$ |
| 6% | 2.280.51N/mm$^2$ | 2.790.51N/mm$^2$ | 0.830.51N/mm$^2$ |
| 8% | 2.790.51N/mm$^2$ | 2.640.51N/mm$^2$ | 0.800.51N/mm$^2$ |
| 10% | 2.600.51N/mm$^2$ | 2.610.51N/mm$^2$ | 0.770.51N/mm$^2$ |

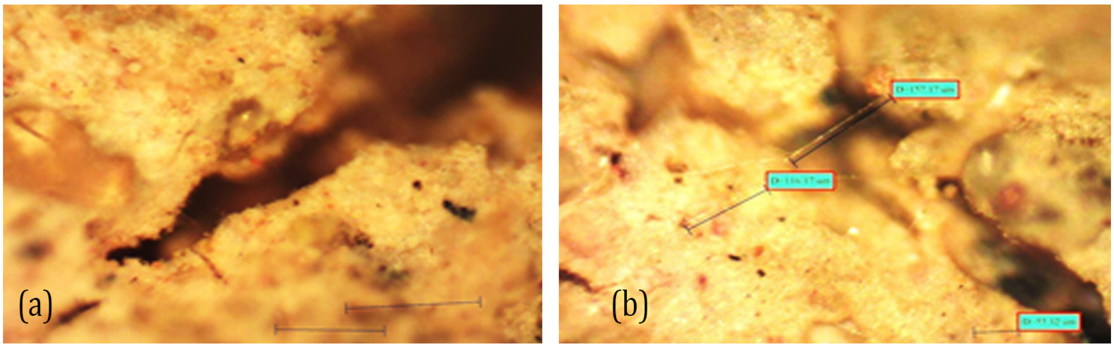



**Fig. 4.27** Microscopic images of rubber bonds between two soil particles

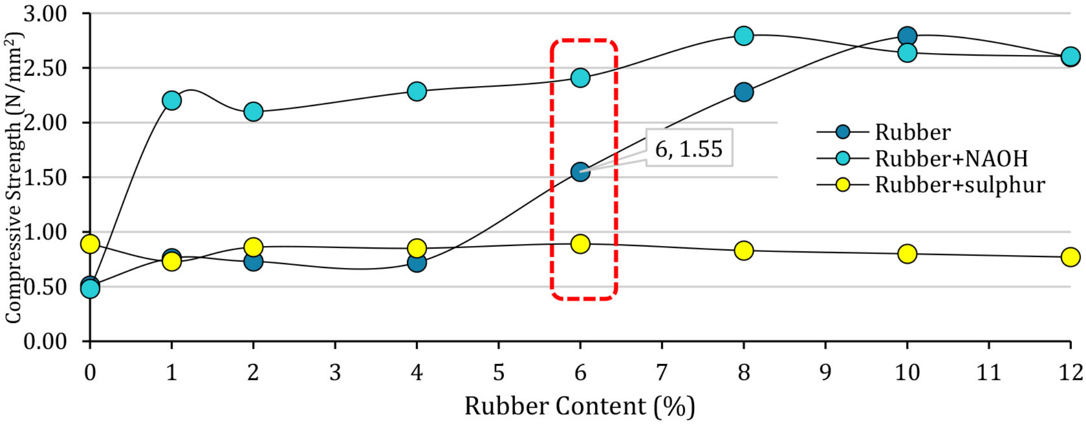



**Fig. 4.28** Compressive strength of NRL and soil mix designs

4.4.1.1 Results of the experiment with Sulfur and Ammonia

The results shown in the figure is interesting, the idea of adding $NH_4OH$ was to improve the workability of the mixture. The initial experiment shows that rubber cannot be mixed for a long time. Therefore, the common chemical to delay the hardening process of the NRL is ammonia ($NH_4OH$). However, this did not lead to good results. The addition of $NH_4OH$ had caused a reduction in the overall strength shown in figure 4.28 on page 101. In addition, the mixing of ammonia had a series of practical difficulties.

Apart from that, there was not a significant increase in workability, due to the addition of $NH_4OH$. Then another experiment was conducted to see if the addition of Sulphur could improve the strength of the NRL stabilized mud concrete block. According to the results increase of Sulphur did not help to improve the strength of the NRL stabilized mud concrete blocks shown in Figure 4.28 on page 101.

**Table 4.12** Particle size and strength development

| NRL % | 1% | 2% | 3% | Average |
|---|---|---|---|---|
| Gravel 100% | 0.2 N/mm$^2$ | 0.5 N/mm$^2$ | 0.4 N/mm$^2$ | 0.4 N/mm$^2$ |
| Sand 100% | 0.9 N/mm$^2$ | 1.2 N/mm$^2$ | 1.1 N/mm$^2$ | 1.1 N/mm$^2$ |
| Fine 100% | 1.9 N/mm$^2$ | 2.8 N/mm$^2$ | 2.4 N/mm$^2$ | 2.4 N/mm$^2$ |

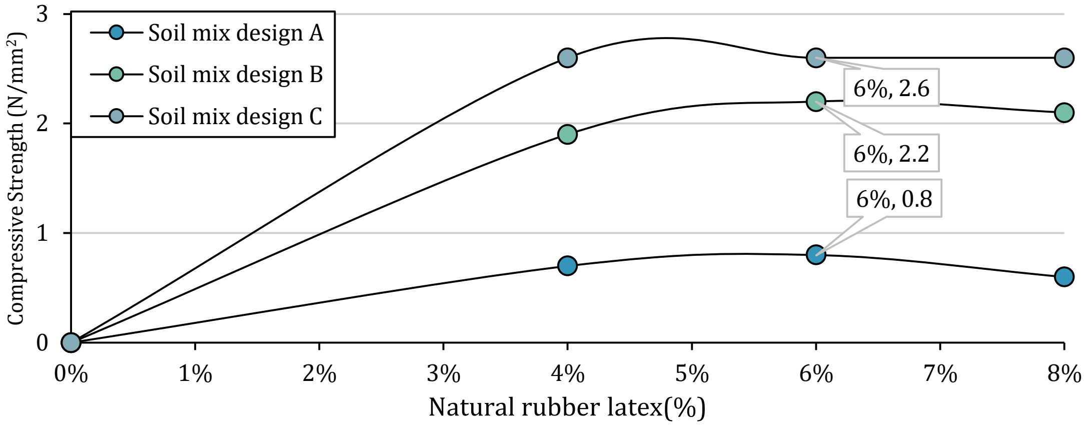



**Fig. 4.29** Compressive strength of NRL and soil mix designs

4.4.1.2 Mix Proportion

Now that the study has confirmed that the 6% of NRL can give the optimum strength more than 2 N/mm$^2$ and the use of Sulfur haven't added any advantage to the total mixture of the NRL stabilized mud blocks. The use of $NH_4OH$ can improve the workability but in the end, the addition of ammonia could reduce the total strength of the block. Thence, three different soil mix designs *(shown in Appendix B on page 206)* were mixed with NRL 6%. According to the results shown in the table 4.13 on page

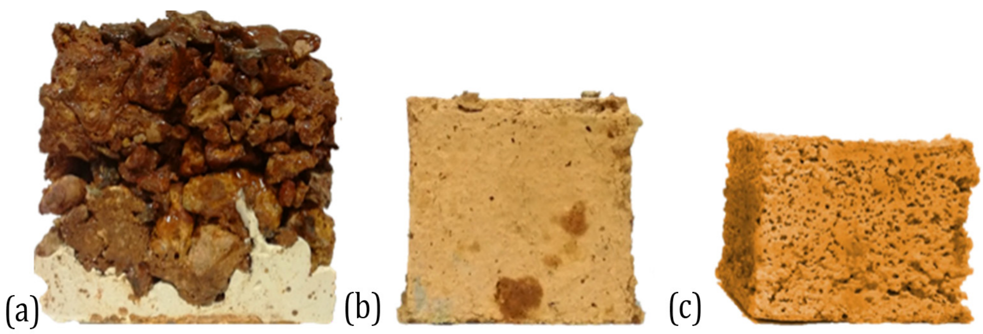



**Fig. 4.30** shrinkage over time with different soil particles

103, there was a tendency to improve the strength of the block when the particle size is reduced. Lower the particle size gets, higher the strength of the block. This is basically

**Table 4.13** Soil mix proportions and compressive strength

| Name | Mix design | 4% | 6% | 8% |
|---|---|---|---|---|
| Soil A | G35%S60% F 5% | 0.7 $N/mm^2$ | 0.8 $N/mm^2$ | 0.6 $N/mm^2$ |
| Soil B | G25% S70% F5%, | 1.9 $N/mm^2$ | 2.2 $N/mm^2$ | 2.1 $N/mm^2$ |
| Soil C | G15% S80% F5%, | 2.6 $N/mm^2$ | 2.6 $N/mm^2$ | 2.6 $N/mm^2$ |

because rubber latex is not able to create stronger bonds with higher particle sizes such as gravel together. See the figure 4.29 on page 102, when sand and fine content is comparatively higher than the gravel content the strength shows higher. But when gravel is 35% the strength was below the margin of the $2N/mm_2$. Therefore, this experiment showed that NRL cannot create stronger bonds to keep high soil particles together. The figure 4.30 on page 102 shows how three different soil particles were being bonded together with NRL. The figure 4.30 [a] shows how gravel creates the bond with NRL.[b] shows the sand stabilized with NRL and [c] shows how fine get mixed with NRL. The figure 4.30 on page 102 conclude that smaller soil particle mixed with NRL tend to shrink during the curing time.

After the mix design experiment, the particle size distribution was confirmed as 15% gravel, 85% of sand and 5% of clay content. The experiment with NRL and soil mix ratio fixed as 6% of the dry weight of soil and the $NH_4$OH and sulfur was removed from the mix due to no effect on the total mix of the NRL stabilized blocks *(see figure 4.30 on page 102)*. After the experiments, the confined mix was subjected to physical and mechanical property study. In this study density, water absorption and shrinkage were tested as a physical property test.

**Table 4.14** Density of NRL stabilized earth blocks

| | NRL % | Soil A | Soil B | Soil C |
|---|---|---|---|---|
| NRL Mix 1 | 1% | 1903 | 1897 | 1883 |
| NRL Mix 2 | 2% | 1824 | 1826 | 1817 |
| NRL Mix 3 | 3% | 1725 | 1748 | 1748 |
| Average | 2% | 1817 | 1823 | 1816 |

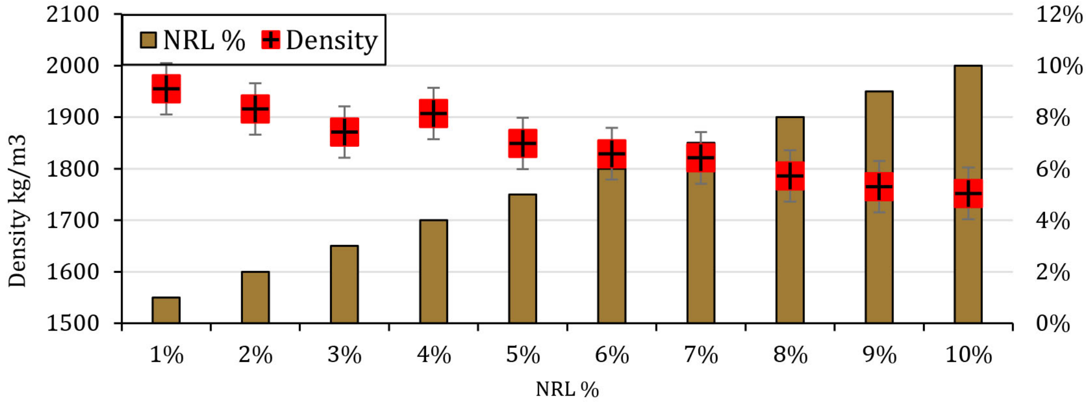



**Fig. 4.31** Different NRL% and water absorption result

4.4.1.3 Physical property test

density The density was measured and evaluated to understand the quality improvement of the block. Because the density is the basal development for an engineering walling block. The natural rubber stabilized earth blocks density results shown in Figure 4.31 on page 104.

High gravel content composed mud concrete block mix design with Lower NRL content shows comparatively higher density. When sand and fine percentages are increased, the density of the materials is also increased. The results are shown in table 4.14 on page 104 clearly indicate that density of the soil A and B is higher than soil C. This is because the soil C has a large amount of smaller soil particles. When the rubber content is increased the density becomes lower *(see the table 4.14 on page 104)*.

Water absorption test results Measurement of water absorption shown in Figure 4.32 on page 105 was an important aspect because it is a fundamental reason for the reduction of wet compressive strengths of wall construction material, especially in walling materials. As much as the material is reluctant. The compressive strength and modulus of rupture of stabilized adobe bricks with this NRL addition, the strength improved by up to 5% and water absorption reduced up to 10%. These additives help to increase the strength and to reduce the water absorption through the densification of the natural rubber latex in the brick body.


**Fig. 4.32** NRL stabilized blocks are immersed in water for the study

The following results shown in Figure 4.33 on page 105 explains the highest water absorption was from the 1% NRL mixed blocks (13.85%). However, the least water absorbing is considered to be the most suitable as a walling material. It was 5% with P values in each percentage of NRL mixed treatments, were lower than 0.05 (P0.05). Thence each and every water absorption measurements obtained at each NRL percentages were significantly different. According to the experimental results, when the NRL content is more than 5%, the standard is achieved to deliver a good quality walling block.

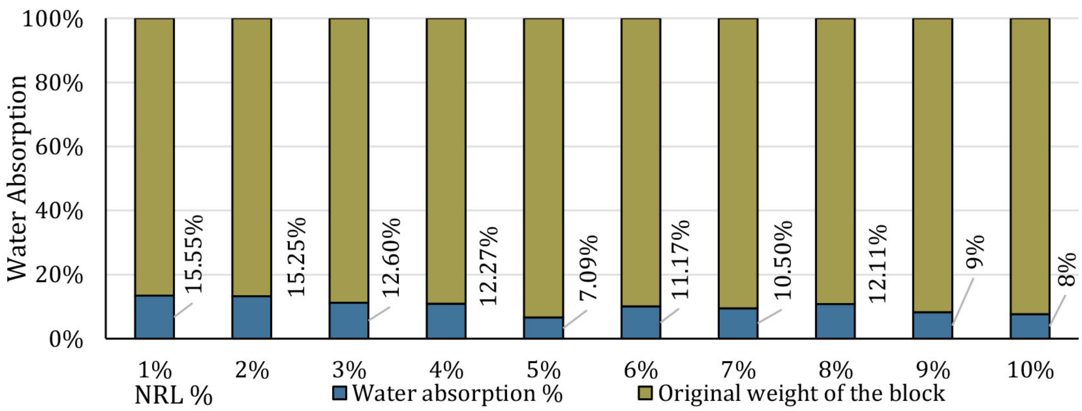



**Fig. 4.33** Different NRL% and water absorption result

Determination of shrinkage of blocks Shrinkage was an observed phenomenon at this experiment. The results are shown in Figure 4.34 on page 106. Highest shrinkage was measured at 10% of NRL and the lowest at a range of 1%-4%. It was observed that at high natural rubber content the shrinkage was increased. Shrinkage was a drawback obtained by this block. Reducing the shrinkage as much as possible is the best factor for a walling material strength.

When NRL is mixed with smaller soil particles, created bonds were tightly packed as NRL is a stabilizing substance that captures each and every particle densely. Consequently, this resulted in shrinkage as seen in the diagram 4.35 on page 107.

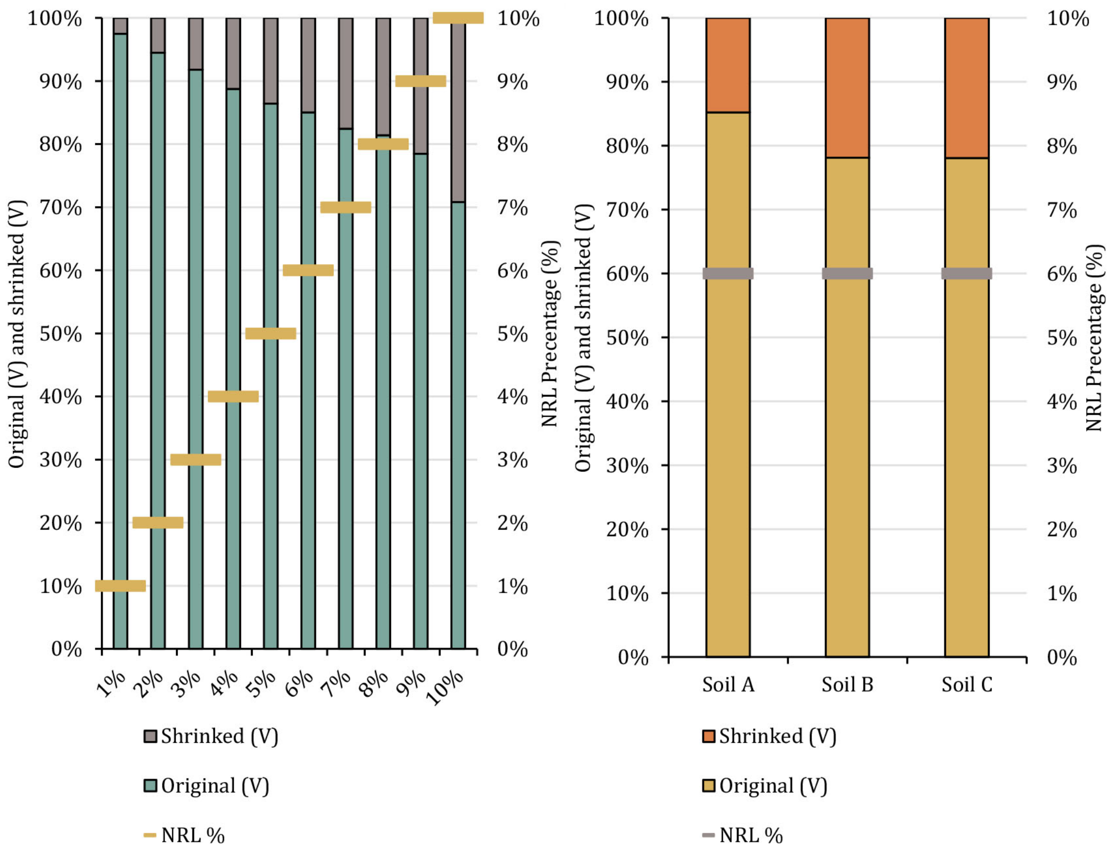



**Fig. 4.34** shrinkage results over time with different soil particles

Weight loss during the curing period Interestingly the study had found that the NRL stabilized mud concrete was subjected to weight loss during the curing period *(see the Appendix C on page 207)*. This was another drawback to this material. This is because of water evaporation. Therefore, the weight loss study was subjected to the phase three

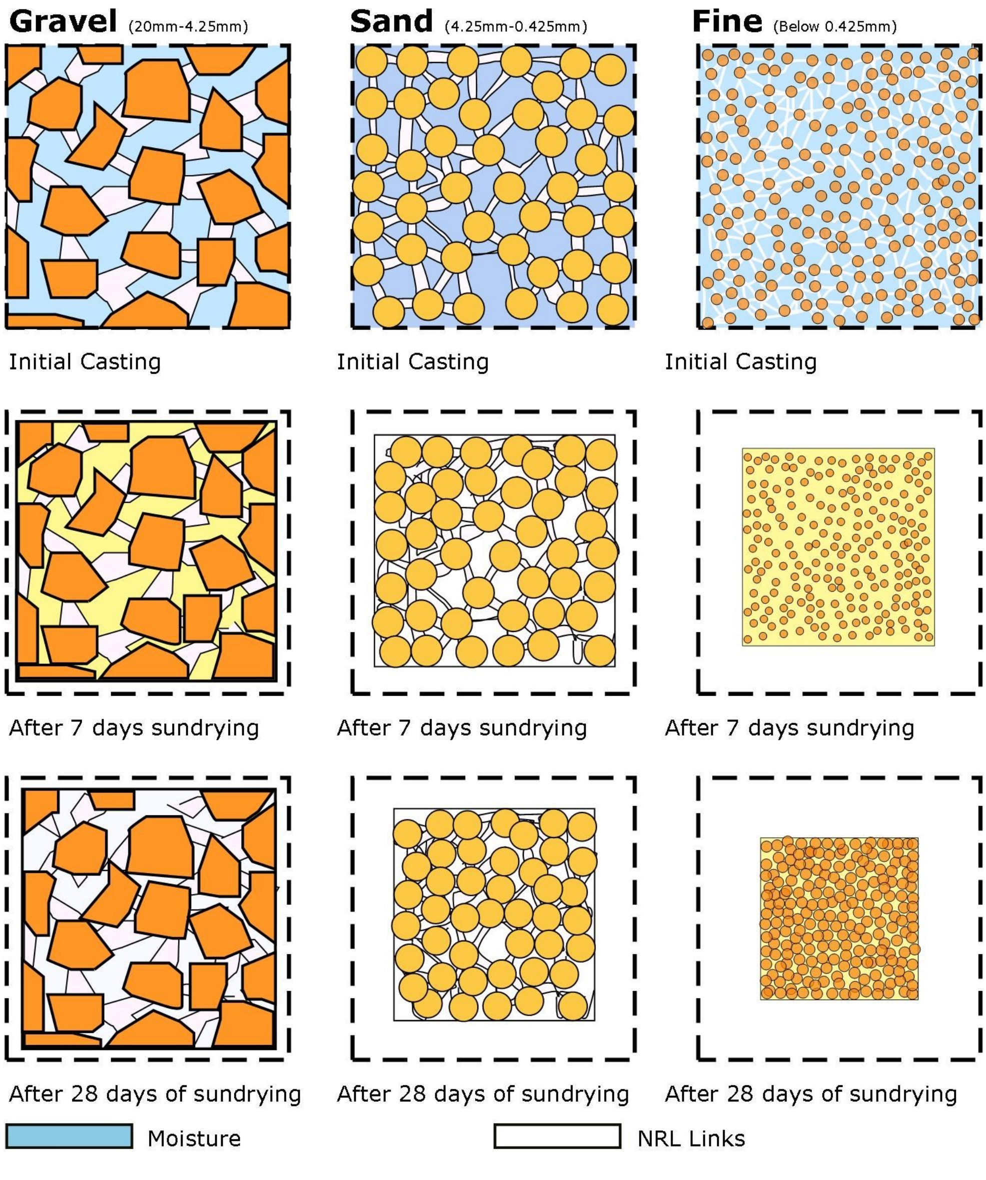



**Fig. 4.35** The phenomena of rubber links tense soil particles

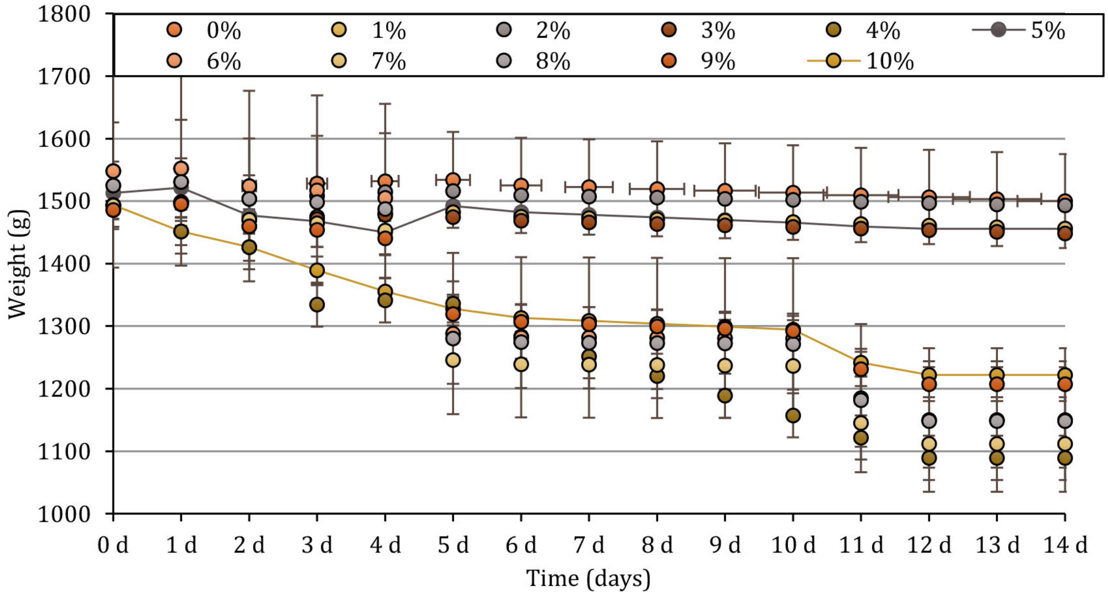



**Fig. 4.36** NRL(%) and weight loss during the curing period

study with different soil mixtures shown in Appendix C on page 207.

The study found that the increase of NRL content helps to increase the weight loss during the curing period *(see the figure 4.36 on page 108)*. The block samples with low NRL values had cured while maintaining its original weight. But high NRL stabilized mud concrete blocks like NRL (7% to 10%) have reduced the weight to a large extent. This was an interesting phenomenon where the excess moisture had been removed by the curing process. However, even though the amount of water evaporation accounts for weight loss, there is a weightless addition to water weight of the mix. therefore, this is another major drawback of the NRL stabilized earth blocks.

#### 4.4.1.4 The compressive strength test results

After finalizing the best mix proportions based on phase one study and phase two confirmed the best manufacturing method. Another experiment was conducted to find the best mix proportions to build NRL stabilized mud concrete block. For this study, the key indicators were compressive strength and tensile splitting strength. Crushing pattern is shown in Figure 4.37 on page 109.

First, the different NRL values were subjected to one soil proportion to test the


**Fig. 4.37** Crushing Pattern of different NRL mixes

optimum NRL combination. Then the different NRL values were subjected to selected soil proportionate such as Soil A, Soil B, and Soil C. The experimental results shown in figure 4.38 on page 109 indicate that the increase of NRL helps improve both dry and wet strength. The increase of NRL dry percentage, in turn, improves the strength. The standard requirement for a walling block is 2N/mm$^2$(Research and of Sri Lanka, 2009).

The results shown in figure 4.39 on page 110 has confirmed the optimum NRL percentage as 6%. Therefore, the NRL ratio of 6% was ideal as the minimum requirement to build walling block. A costing study was analyzed in order to understand the strength vs. cost shown in figure 4.40 on page 110. The confirmation of optimum NRL content, ten different NRL proportions starting from 1% to 10% were taken as NRL values and three different soil combinations were selected to build experimental blocks to check the strength development. The results shown in figure 4.40 on page 110 confirm the

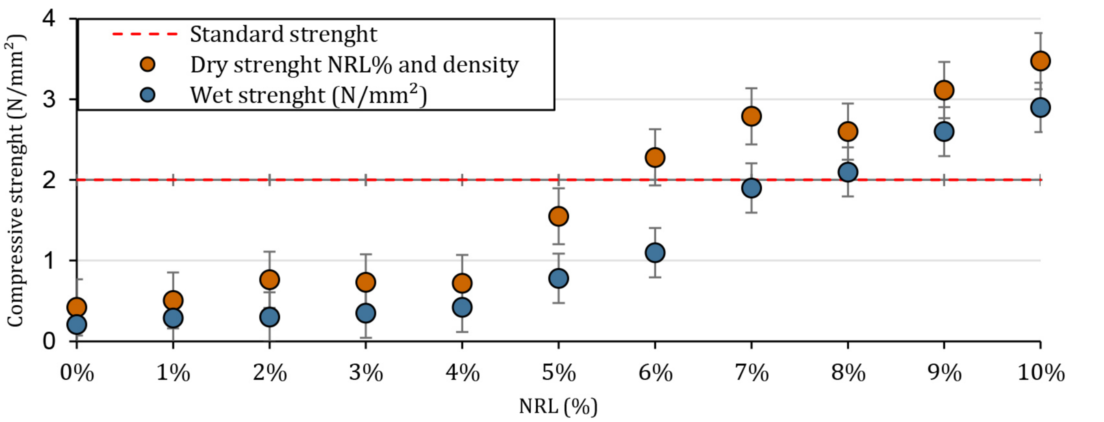



**Fig. 4.38** Different NRL ratios and compressive strength

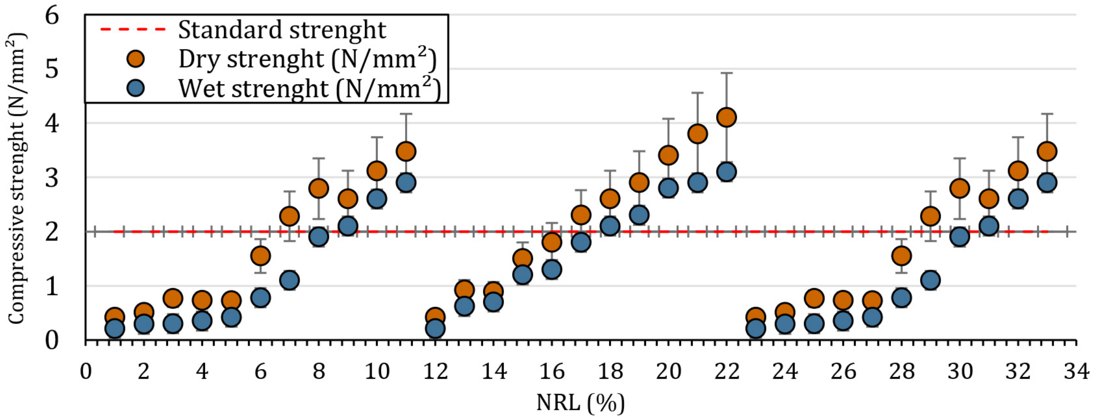



**Fig. 4.39** Different soil mix designs and compressive strength

same condition of smaller soil particles is bonding with NRL rather than larger gravel particles.

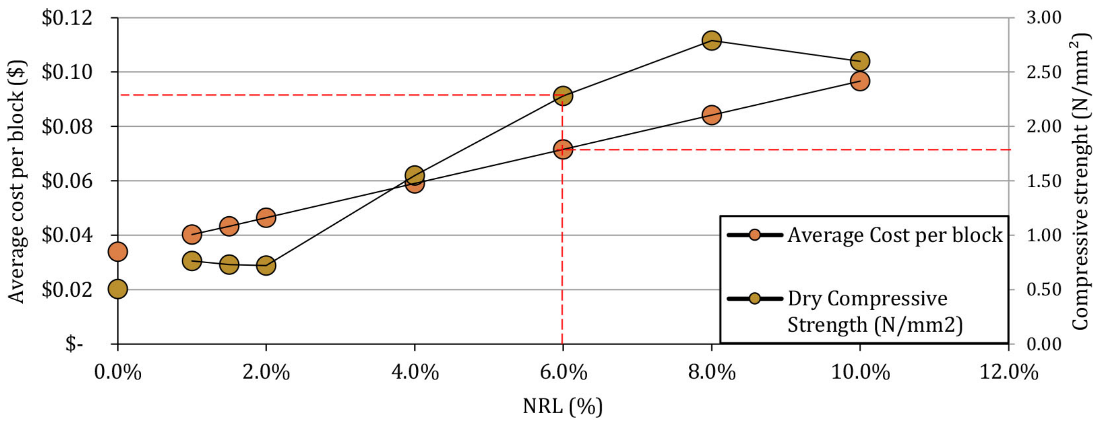



**Fig. 4.40** Compressive strength and cost per block

After the confirmation of NRL, an extensive study was done in order to understand the mix proportion as well as the best NRL value to build the NRL stabilized earth blocks. Soil mix proportions of Soil A, B and C mixed with different NRL dry weight of 1% to 10% and checked the strength and found that; minimum of 6% of the dry weight of NRL was required to produce the standard strength and when the particles are smaller and NRL percentage is higher, the strength was going into an upper scale. The results showed that high sandy soil was much better than gravel soil to build NRL stabilized mud concrete blocks.

Tensile splitting strength The tensile splitting strength of NRL stabilized MCB. According to the results shown in Figure 4.41 on page 111, the increase of NRL percentage can improve the TSS. The maximum TSS was achieved at the NRL % of 10%. There was a gradual increase of tensile splitting strength of soil in the presence of NRL.

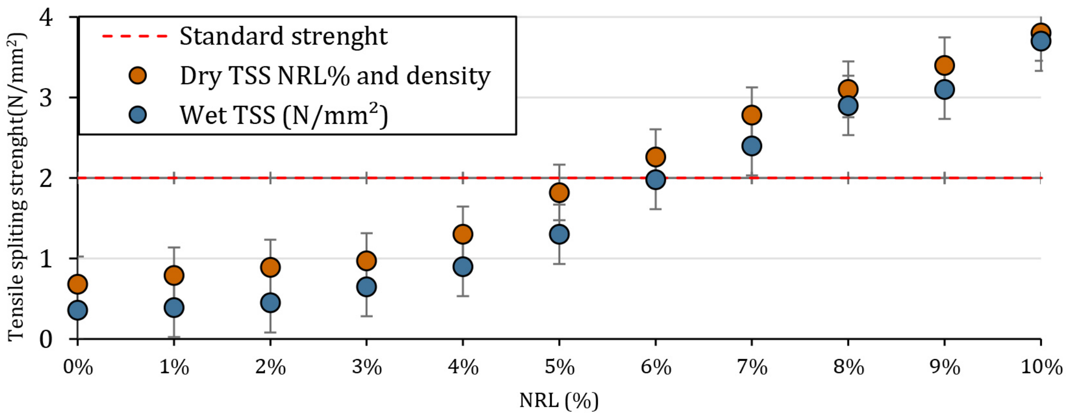
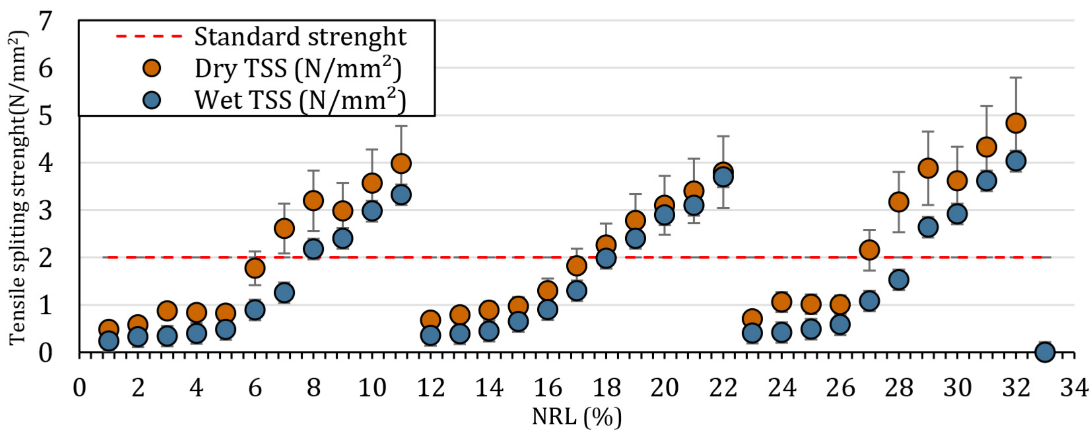



**Fig. 4.41** Tensile splitting strength of different NRL % combinations




The

**Fig. 4.42** Tensile splitting strength of NRL mixed different soil mix

After the confirmation of NRL, an extensive study was done in order to understand the mix proportion as well as the best NRL value to build the NRL stabilized earth blocks. Soil mix proportions of Soil A, B and C mixed with different soil compositions and NRL mixtures shown in Figure 4.42 on page 111. It was similar to the compressive strength results. When the particles were getting smaller, the NRL could make a stronger bond and keep the particles together. This will ultimately create the bond in the NRL stabilized MCB. Precisely, small particle dense soil is vulnerable to make

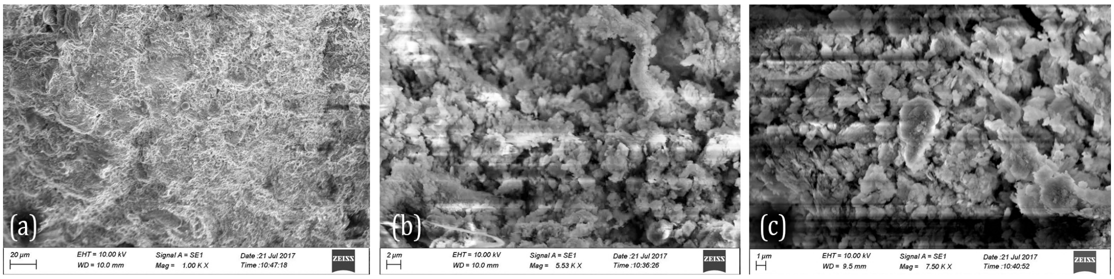



**Fig. 4.43** Scanning electron microscopic images of NRL stabilized MCB

better bonding with NRL. High gravel soil cannot create a better bonding with NRL. The tensile splitting results show in Figure26 on page 30 clearly indicates that Soil type C (Gravel 15%, Sand 80% and fine 5%) gives the optimum tensile splitting strength. Whereas the Soil type A *the original MCB soil mix proportion* (Gravel 35%, Sand 60% and fine 5%) doesn't require strength to make a walling material. After the confirmation of the suitable mix proportion, scanning microscopic image analysis was conducted to understand how the bonding was done in the NRL stabilized MCB.

Scanning Electronic microscopic images SEM images shown in Figure 4.43 on page 112 were taken in order to identify how NRL acts with soil particles and to observe their bonding behaviors. 6% NRL applied block which was cast for the final study was used. The images show that finer particles of the soil has combined with NRL and created much dense filler materials finally made the binding in the MCB. This suggests the reason for the high strength of high fine soil blocks.

### 4.4.2 Natural polymers as an alternative stabilizer

The total study and experimental results were published in the journal of Materialia in journal paper named performance of natural polymers for stabilizing earth blocks

(Udawattha, Silva, et al., 2018).

The literature survey has shown many natural stabilizers which can stable soil. But out of them, considering the availability, seven natural polymers were selected for further study. Seven different natural polymers were mixed soil and test the strength. The results of this experiment show that Pines resin (PR) Dawul, Kurudu (DK) and Sugarcane resin (SB) can improve the geotechnical properties of soil into engineering properties. BR, WAR, AWR, and JR are not suitable to the stable mud concrete block mixture *(table 4.15)*. Since Pines resin (PR) Dawul Kurudu (DK) and Sugarcane resin (SB) were only produced the strength, they were confirmed for further experiment. Only three selected because its very expensive to collect natural polymers from plants and trees. To extract some polymer need several weeks (Udawattha, Silva, et al., 2018). Mixing and casted block are shown in Figure 4.44.

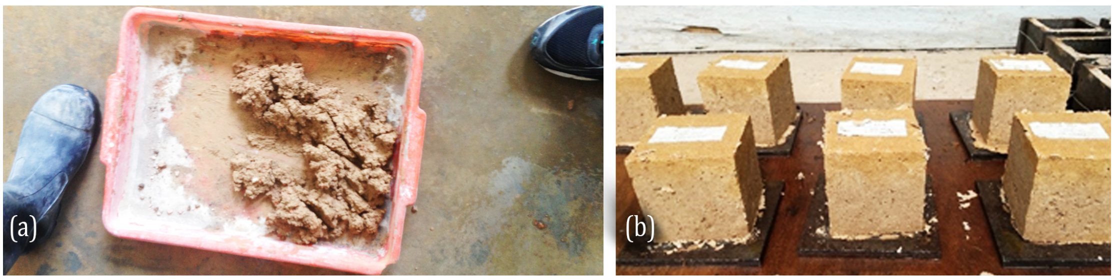



**Fig. 4.44** Natural polymer stabilized earth blocks

#### 4.4.2.1 Soil Mix development

To confirm the mix design with natural polymers three different soil particle combinations were subjected to another study. Three soil mixes *(see the Appendix B on page 206)* were mixed with three different polymer combinations such as 5%, 10% and 15% *(see the figure 4.45)*. The results shows that when the soil particle is small, polymers capable to create bond between soil particles.

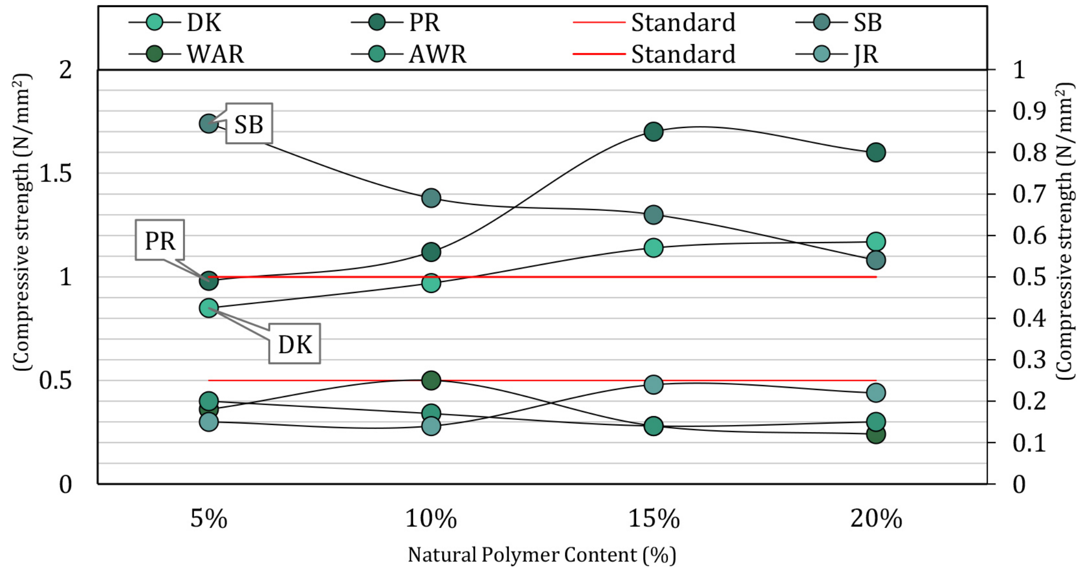



**Fig. 4.45** Initial experiment natural polymers

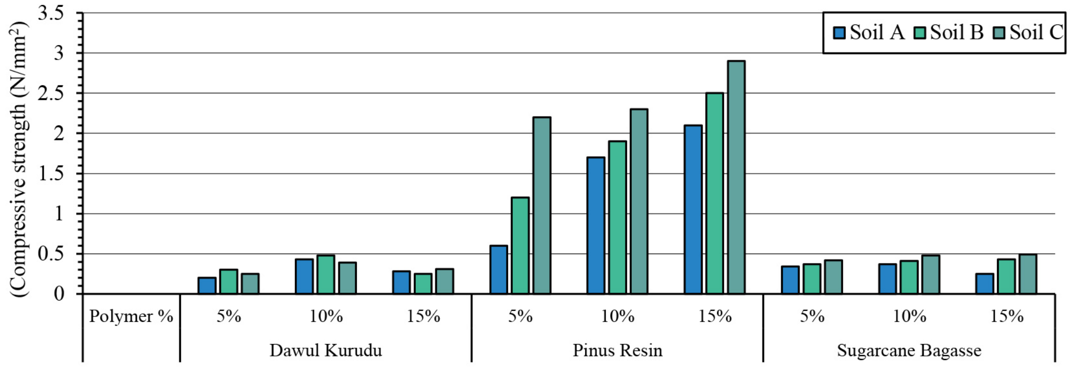



**Fig. 4.46** Soil mix design optimization

The selected three natural polymers were further studied to understand the soil mix design. The results shown in figure 4.46 on page 114 that soil C contained 15% of gravel, 80% of sand and 5% of fine establishes the suitable strength. In addition, samples blocks show that small particles soil mix design blocks were smoother than high gravel soil samples blocks.

### 4.4.2.2 Density

Natural polymers have a lesser density than soil. Natural polymers are not capable of improving the density shown in figure 4.47 on page 116. Out of the selected polymers,

**Table 4.15** Natural polymers experimental programme

| Name of Polymer | Acronyms | Mix Name | NP (%) | Soil (%) | Compressive strength (N/mm^2) |
|---|---|---|---|---|---|
| Dawul Kurudu | DK | DK1 | 5% | 95% | 0.85 |
| | | DK2 | 10% | 90% | 0.97 |
| | | DK3 | 15% | 85% | 1.14 |
| | | DK4 | 20% | 80% | 1.17 |
| Bael Resin | BR | BR1 | 5% | 95% | 0.02 |
| | | BR2 | 10% | 90% | - |
| | | BR3 | 15% | 85% | 0.12 |
| | | BR4 | 20% | 80% | 0.13 |
| Pines Resin | PR | PR1 | 5% | 95% | 0.98 |
| | | PR2 | 10% | 90% | 1.12 |
| | | PR3 | 15% | 85% | 1.7 |
| | | PR4 | 20% | 80% | 1.6 |
| Sugar Cane Resin | SB | SB1 | 5% | 95% | 0.87 |
| | | SB2 | 10% | 90% | 0.69 |
| | | SB3 | 15% | 85% | 0.65 |
| | | SB4 | 20% | 80% | 0.54 |
| Jack Resin | JR | JR1 | 5% | 95% | 0.15 |
| | | JR2 | 10% | 90% | 0.14 |
| | | JR3 | 15% | 85% | 0.24 |
| | | JR4 | 20% | 80% | 0.22 |
| Agarwood Resin | AWR | AWR1 | 5% | 95% | 0.2 |
| | | AWR2 | 10% | 90% | 0.17 |
| | | AWR3 | 15% | 85% | 0.14 |
| | | AWR4 | 20% | 80% | 0.15 |
| Wood Apple Resin | WAR | WAR1 | 5% | 95% | 0.18 |
| | | WAR2 | 10% | 90% | 0.25 |
| | | WAR3 | 15% | 85% | 0.14 |
| | | WAR4 | 20% | 80% | 0.12 |

pines resin (PR) shows somewhat suitable density improvement. Soil mix designs such as high gravel soil mix designs show good density. But overall the density improvement made due to the addition of natural polymers were not enough to make a suitable engineering masonry unit. Pines resin has shown better density that other two natural polymers. But overall results are not fair to proceed.

Cold water absorption test Cold water absorption test is a standard method to evaluate the suitability of a walling material. The minimum standards are the 7%. Not only water absorption but also the repercussion after water absorption must be studied. The

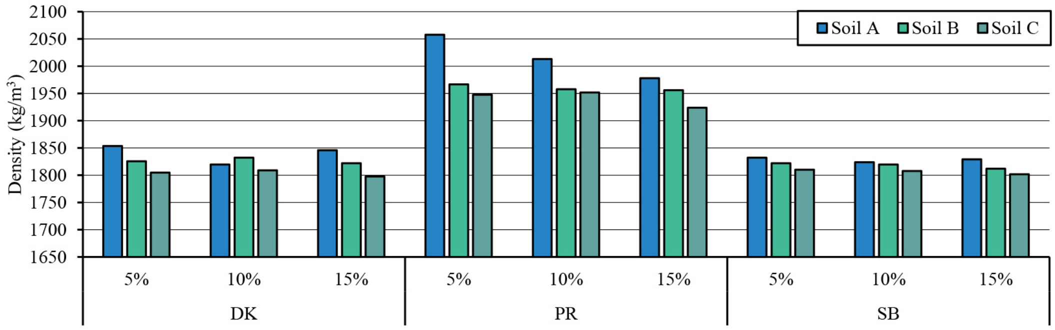



**Fig. 4.47** Density variation

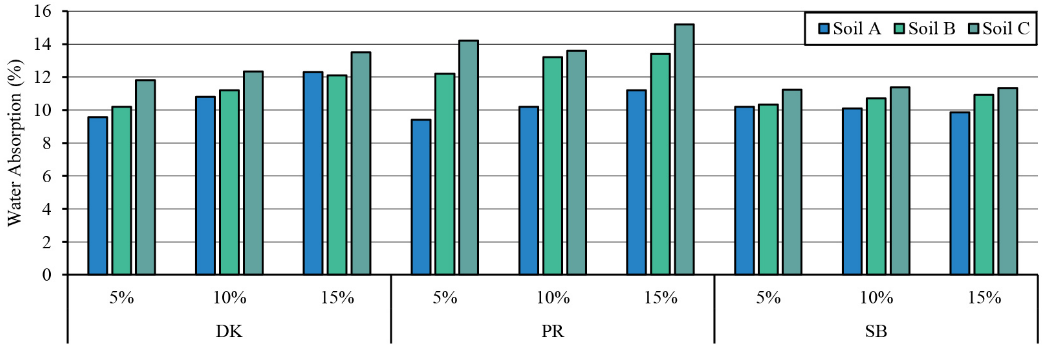



**Fig. 4.48** Water absorption variation

results of this experiment shown in Figure 4.48 on page 116 that none of the natural polymers were capable of created a less water absorbing wall construction masonry unit.

#### 4.4.2.3 Linear shrinkage

Shrinkage results are shown in figure 4.49 on page 117. Out of three natural polymers pines, resin stabilized earth blocks hows some form of less shrinkage after the curing process. Another polymer stabilizes earth blocks tend to reduce the total volume during the curing period. The study was conducted comparative to the particle size distribution of the soil. Results show that when lower particle sizes are mixed with soil, natural polymers with shrinking ability tend to make particle closer to each other and shrinking the total volume of the block. The results shown in figure 4.49 shows that PR stabilized earth blocks doesn't shrink over the time whereas DK and SB stabilized earth blocks tend to shrink over the time.

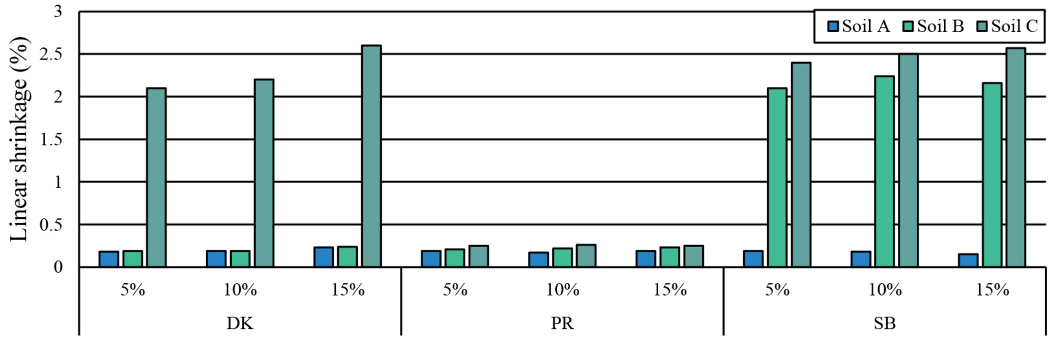



**Fig. 4.49** Linear shrinkage variation

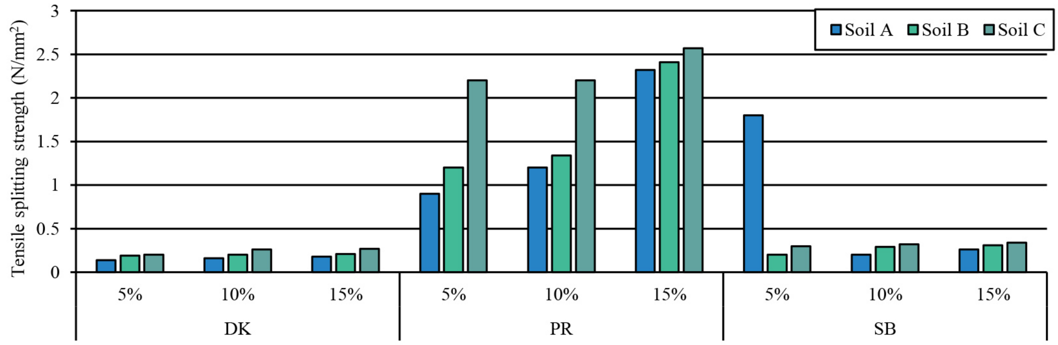



**Fig. 4.50** Tensile splitting strength of natural polymer stabilized mud concrete

#### 4.4.2.4 Tensile splitting test

TSS results were unexpected. Because the study was conducted to improve the tensile quality of earth blocks by utilizing natural polymers as an alternative stabilizer. But according to results shown in Figure 4.50 on the page, 117 only PR stabilized earth blocks are up to the standard. Other two NP stabilized earth blocks 't did not show any advancement in the TSS strength. Even in the PR stabilized earth block mix designs, the Soil C with a lesser amount of gravel particles shows the highest strength.

#### 4.4.2.5 Morphology analysis study

1-Pines Resin stabilized earth sample a- 20X magnified image of PR stabilized earth block, b-magnifies images of DK stabilized earth block c-SB stabilized earth block sampled-PR bonded soil e- DK fiber f-SB bonded soil 2- Dawul Kurudu stabilized earth sample 3- Sugarcane bagasse stabilized earth sample The morphology study was con-

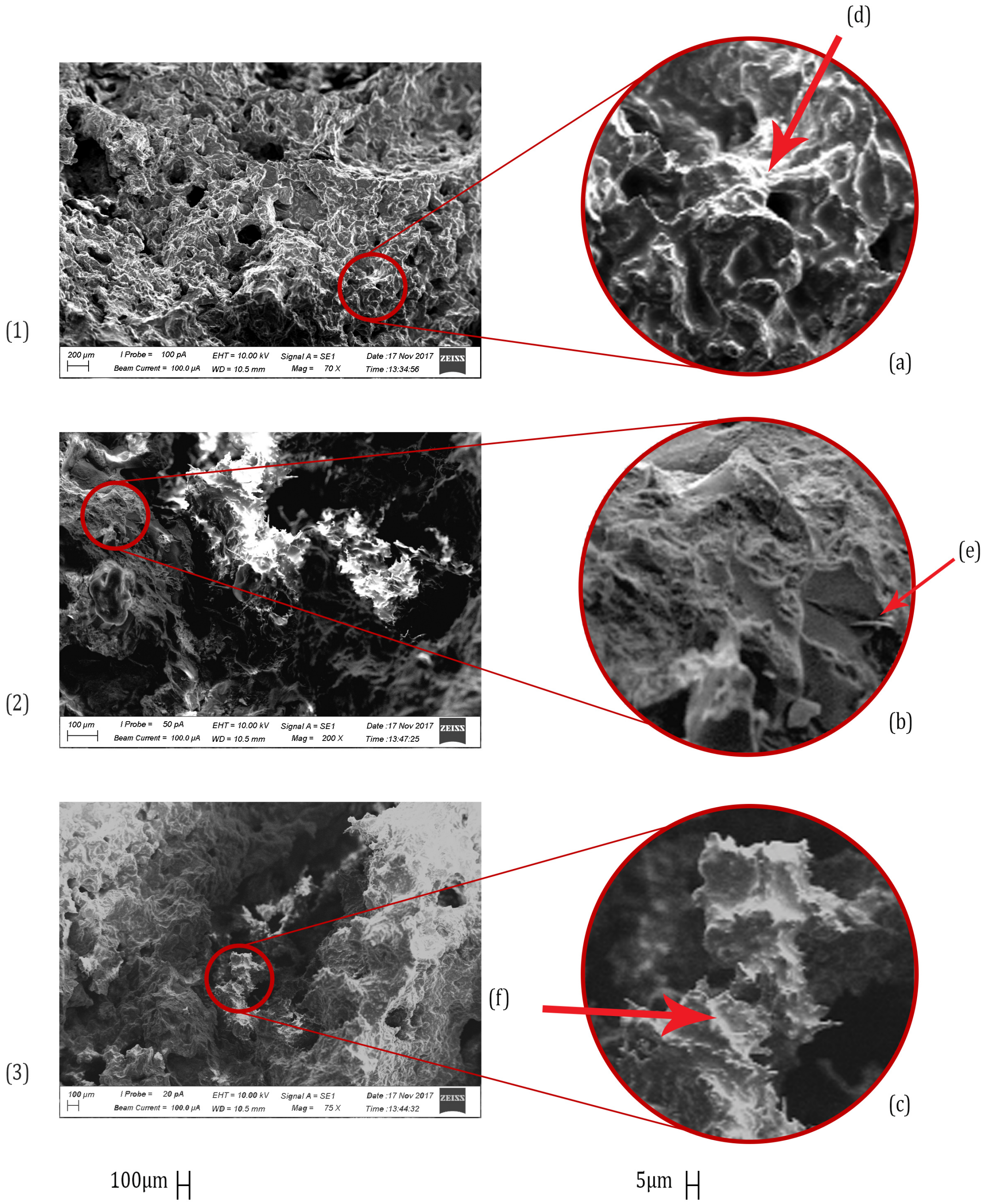



**Fig. 4.51** SEM images

ducted to understand the bonding pattern of the selected three different natural polymer stabilizers. The shown in Figure 4.51 on page 118 first section shows the PR stabilized mud concrete sample and its enlarged version shows the bonding pattern. However, the second image shows the Dawul Kurudu stabilized earth blocks and its fibrous polymers are visible even after drying. The third section showing sugarcane bagasse. Out of three selected natural polymers, PR shows some form of better binding. The polymer managed to bind soil particles and created different material.

## 4.5 Summary

Study of nature and vernacular technologies are the main points for the new innovative technologies. Finding secrets behind the nature scenarios and vernacular technologies were benefited to the development of the science. Sri Lanka is famous for its great construction technology. Most of the materials used in Sri Lanka are purely eco-friendly with a low carbon footprint.

This study was conducted to explore alternative stabilizers used in the Sri Lankan traditional construction technologies. The initial study was conducted by producing an inventory of natural materials used to stabilize walling materials. Then testing was conducted with the composition of waste, natural polymers etc. Several standard test methods were used to understand the strength improvement due to the addition of above-mentioned stabilizers. The study suggests that following stabilizers such as fly ash, rubber, rice husk ash, and pines resin can improve the strength in great extent. This stabilizer may improve some other quality of the earth block, but not the compressive strength as similar to the cement.

CHAPTER 5

# GEOPOLYMERIZING MUD CONCRETE

## 5.1 General

After conducting an initial experiment with selected stabilizers, the study has found that fly ash can stabilize the mud concrete mixture. Employing fly ash can improve the workability of the mixture. Therefore, the study was extended to understand a method to develop the cementitious properties of the fly to stabilize soil to build a walling material.Geopolymerizing mud concrete experiment was published in case studies in construction materials (Udawattha and Halwatura, 2018).

Fly Ash as a suitable alternative stabilizer was selected due to many reasons including its chemical composition shown in Figure 5.1 on page 121. In the original mud concrete mix design, cement is the main stabilizer. The cement chemical composition is Calcium oxide (lime), Silicon dioxide (silica), Aluminum oxide (alumina), Iron oxide and Sulphur (Andersson et al., 1989). Considerably, fly ash also has the same kinds of chemicals including Silicon dioxide (silica), Aluminum oxide (alumina) shown in Figure 5.1. Nevertheless, the clay in mud concrete has a great weakness of high water absorption (Choy et al., 2007; Salvador, 1995). Xu et al. (2001) stated that high water absorbing capacity is an engineering problem considering the liquid limit of a mix design. However fly ash does not absorb water, instead, it can reduce the water consumption and improve the workability of the mixture (Udawattha, Dilshan, and Halwatura, 2017).

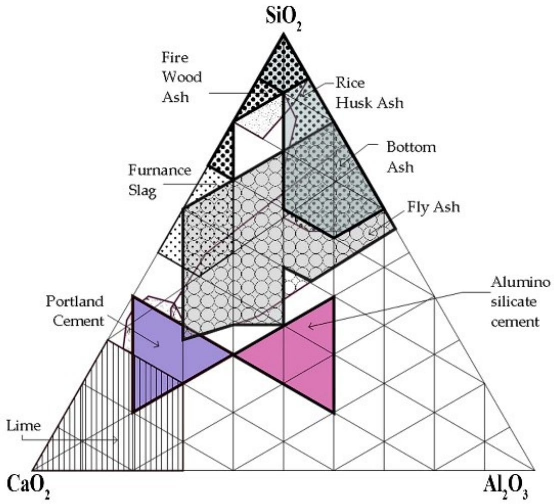



**Fig. 5.1** Comrades of cement

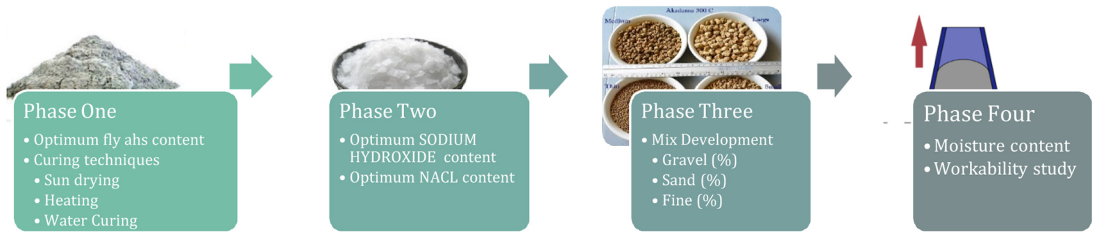



**Fig. 5.2** Experimental Phases

Also, fly ash is a waste produced in large quantities by the electric power plants. The production of fly ash has no use in Sri Lanka except for dumping it into a dumping yard next to the Indian Ocean. If this study can develop a method use fly ash as an alternative stabilizer the walling materials can utilize waste ash into useful walling materials to build affordable houses.

Therefore, the study was extended in order to improve fly ash as an alternative stabilizer according to the new experiment programme shown in Figure 5.3. Also, the extended literature survey shows that Joseph Davidovits from France has written a book "Why the pharaohs built the Pyramids with fake stones" and introduced the concept of alkaline activation of limestones to make stones for Egypt pyramids. Then many scholars developed the concept of geopolymer shown in the following table 5.1.

**Table 5.1** Previous studies of geopolymer

| Description | Source | Year |
|---|---|---|
| Introduced geopolymer | (Joseph A. Demkin, n.d.) | 1975 |
| Developed the concept of geopolymer | (Joseph and Tretsiakova-McNally, 2010) | 1976 |
| Study alternative activators | (Richard F. Heitzmann, Mark Fitzgerald, 1985) | 1984 |
| Developed geopolymer road stabilizer | (Shen et al., 2007) | 2007 |
| Coal fly ash geopolymer | (Komnitsas, 2011) | 2011 |
| Developed geopolymer with waste ash | (Bignozzi, 2011) | 2011 |
| Experiment with geopolymer rammed | (Cristelo et al., 2012) | 2012 |
| Experiment with geopolymer paving block | (Darius Vaz et al., 2012) | 2012 |
| Developed mortar for timber and soil | (Gouny et al., 2013) | 2013 |
| Geopolymer recycle concrete mix develop | (Posi et al., 2013) | 2013 |
| *Novel walling materials | (Lemougna et al., 2014) | 2014 |
| Geopolymer concrete mix development | (Vijaysankar et al., n.d.) | 2014 |
| Developed mortar for timber and soil | (Fouchal et al., 2015) | 2015 |
| *Geopolymer walling material | (Petrillo et al., 2016) | 2016 |
| Geopolymer concrete mix development | (Naskar and Chakraborty, 2016) | 2016 |
| Geopolymer ceramic product development | (Assaedi et al., 2016) | 2016 |
| Geopolymer concrete mix development | (Talakokula et al., 2016) | 2016 |

## 5.2 New experimental study

The idea of geopolymer is to use additives to develop the chemical composition to make a bond between soil particles. The definition of geopolymer is “the alumina-silica sources (fly ash, metakaolin and etc) are mixed with an activating solution (sodium hydroxide or potassium hydroxide ) that provides the alkalinity needed to liberate the Si and Al and possibly with an additional source of silica (sodium silicate is the most commonly used)”. This is not a brand new invention and the development of the geopolymer is shown in table 5.1. In order to find the possibility of making geopolymer mix, a blind mix was developed based on the literature shown in table 5.1.

**Table 5.2** Strength variation of different fly ash contents with time

| | Fly Ash 0% ($N/mm^2$) | Fly Ash 5% ($N/mm^2$) | Fly Ash 10% ($N/mm^2$) | Fly Ash 15% ($N/mm^2$) | Fly Ash 20% ($N/mm^2$) | Fly Ash 25% ($N/mm^2$) | Fly Ash 30% ($N/mm^2$) | Fly Ash 35% ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|
| 7 days | 1.2 | 0.9 | 1.1 | 0.97 | 2.04 | 1.3 | 0.7 | 0.8 |
| 14 days | 2.6 | 2.2 | 1.6 | 2.8 | 2.8 | 1.8 | 0.62 | 0.9 |
| 21 days | 2.8 | 2.3 | 2.9 | 3.4 | 3.6 | 1.96 | 0.98 | 0.8 |
| 28 days | 2.6 | 2 | 2.8 | 3.7 | 4.2 | 2.1 | 0.8 | 0.7 |

According to the previous experiment the optimum and required fly ash percentage


**Fig. 5.3** Casted geopolymer blocks

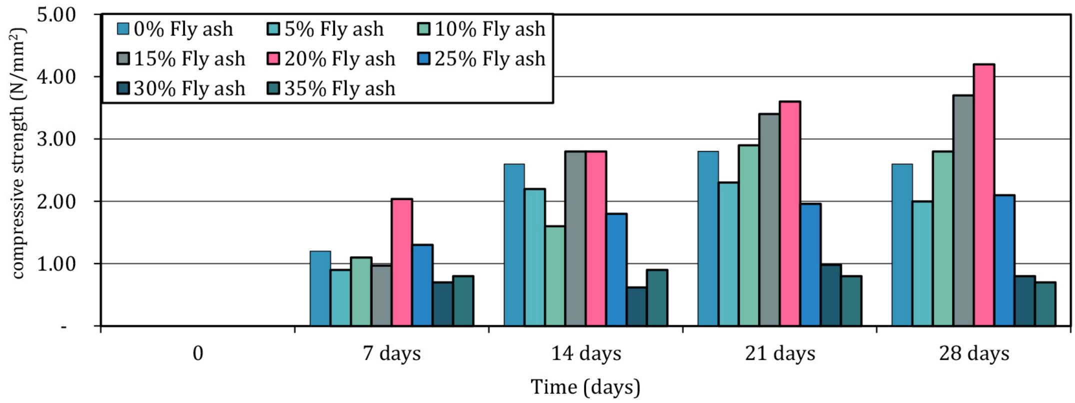



**Fig. 5.4** Graph Dry strength variation of different fly ash contents with time

is 20% of the dry mass of the total mix of the mud concrete block *(see the table 5.2 on page 122)*. A further literature study has shown that alkaline activation methods were systematically studied by changing the additive percentages. Therefore, a similar study was started to develop a fly ash stabilized mud concrete mix.

The idea of geopolymer is to use additives to develop the chemical composition to make a bond between soil particles. In order to find the possibility of making geopolymer mix, a blind mix was developed based on the literature shown in table 5.1 on page 122. The geopolymer experiment was started with the fly ash experiment conducted previously to find the suitable fly ash mixture to stable mud concrete block. According to the previous experiment the optimum and required fly ash percentage is 20% of the dry mass of the total mix of the mud concrete block. Then the literature shown alkaline activation methods were systematically studied by changing the additive percentages.

However, the literature did not show much information about the manufacturing method of fly ash stabilized geopolymer. Therefore, several blind mixes were tested according to the strength of the material. In order to freeze testing method, the curing method was finalized as seven-day curing. The curing method for mud concrete block mixture was developed by a sister research.

However, the studies show that there are many activators for fly ash such as potassium hydroxide, sodium hydroxide etc. Sodium hydroxide (NaOH) is a common cleaning material available in all the hardware stores in Sri Lanka. Recently the government

**Table 5.3** Optimizing activator contents

| Mix design | Soil | Fly Ash | Sodium hydroxide | Sodium chloride | Water | Mix design | Soil | Fly Ash | Sodium hydroxide | Sodium chloride | Water |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | 78% | 20% | 0% | 2% | 20% | M7 | 80% | 20% | 0% | 0.00% | 20% |
| M2 | 76% | 20% | 2% | 2% | 20% | M8 | 78% | 20% | 2% | 0.50% | 20% |
| M3 | 74% | 20% | 4% | 2% | 20% | M9 | 75% | 20% | 4% | 1.00% | 20% |
| M4 | 72% | 20% | 6% | 2% | 20% | M10 | 73% | 20% | 6% | 1.50% | 20% |
| M5 | 70% | 20% | 8% | 2% | 20% | M11 | 70% | 20% | 8% | 2.00% | 20% |
| M6 | 68% | 20% | 10% | 2% | 20% | M12 | 68% | 20% | 10% | 2.50% | 20% |

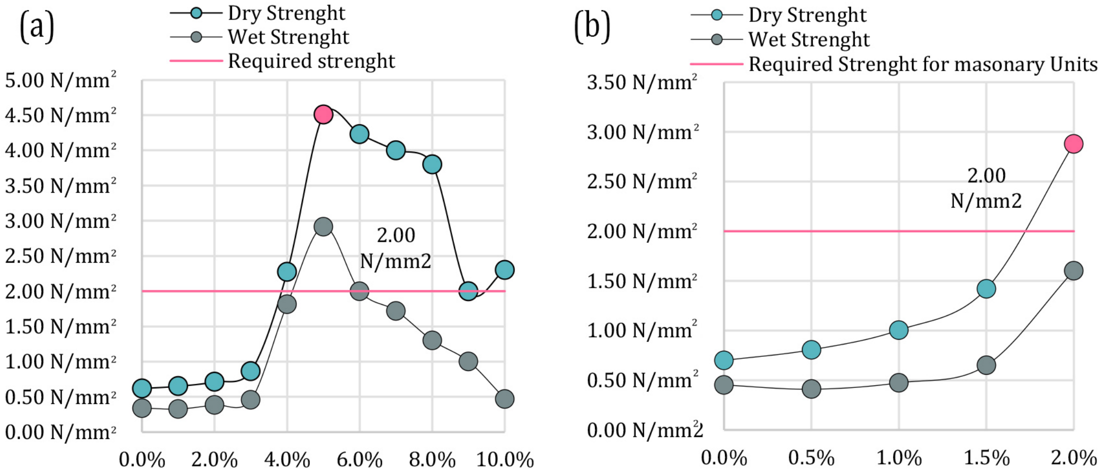



**Fig. 5.5** Results of activator content optimization

has plans to start a caustic soda manufacturing factory in Jaffna. Therefore, the study focused on developing geopolymer mud concrete by using caustic soda as an activator for fly ash stabilized mud concrete block. The sodium hydroxide content was changed starting from 0% to 10% of the dry weight of the mixture shown in table 5.3 on page 125. It was found that the most suitable strength optimized at the 5

Similarly, the use of sodium chloride helped to stabilize the mixture. Therefore, the salt was selected to develop the mixture considering the availability of salt water all around the country. The use of salt ratios starting from 0% to 2% varying it by 0.5% mixed with mud concrete fly ash mixture to study the most suitable salt content to build Geopolymerized mud concrete block mixture shown Figure 5.3 on page 123.

The results are shown in figure 5.5 on page 125. The optimum salt content of the make geopolymer mud concrete block is the 2% of the dry mixture of the mud concrete block. Then the study was extended to understand the suitable soil mix design for Geopolymerized mud concrete block.

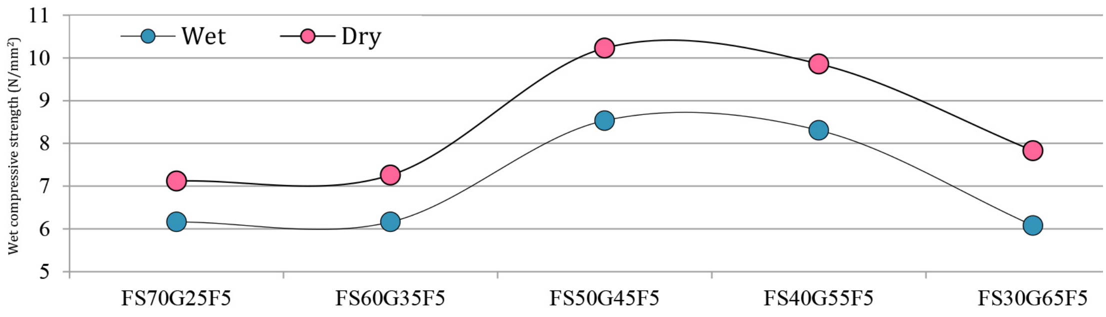



**Fig. 5.6** Soil Mix design for Geopolymerized mud concrete block

### 5.2.0.1 Soil Mix design for Geopolymerized mud concrete block

The method of soil mix design for specific stabilizer is clearly detailed in the methodology section explained to deal with the effect of aggregates grading on the strength of the mud concrete block. The optimized fly ash, caustic soda, and salt content were proportionately mixed with three different soil mix designs shown in Appendix B on page 206. The soil mix design was developed according to the table shown below. The mix design experiment results are shown in table 5.6. The suitable mix design for Geopolymerized mud concrete is FS50G45F5 *(see the figure 5.6 on page 126)*. Then another experiment was conducted to understand the suitable mixing method for the geopolymerized mud concrete block.

**Table 5.4** Soil mix design for geopolymer mud concrete

| | Existing Proportions | | | Proposed Proportions | | | Fly Ash | Activators | | | Added | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix Name | Gravel | Sand | Fine | Sand | Gravel | Fine | | NAOH | NACL | $H_2O$ | Gravel | Sand | Fine |
| FS70G25F5 | 54% | 41% | 5% | 70% | 25% | 5% | 20% | 5% | 2% | 20% | -29% | 29% | 0% |
| FS60G35F5 | 54% | 41% | 5% | 60% | 35% | 5% | 20% | 5% | 2% | 20% | -19% | 19% | 0% |
| FS50G45F5 | 54% | 41% | 5% | 50% | 45% | 5% | 20% | 5% | 2% | 20% | -9% | 9% | 0% |
| FS40G55F5 | 54% | 41% | 5% | 40% | 55% | 5% | 20% | 5% | 2% | 20% | 1% | -1% | 0% |
| FS30G65F5 | 54% | 41% | 5% | 30% | 65% | 5% | 20% | 5% | 2% | 20% | 11% | -11% | 0% |

### 5.2.0.2 Moisture content

The previous scholars shown in table 5.1 have experimented with geopolymer concrete shows that the optimum moisture content is 20% of the dry weight of the mix. However, since this is for mud concrete a new experiment was conducted to understand the suitable moisture ratio. In order to understand the suitable moisture content, different

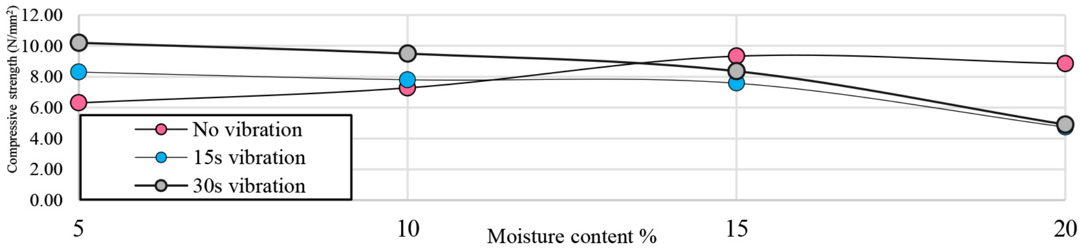



**Fig. 5.7** Finding optimum moisture content

moisture ratios were studied accordingly with geopolymer mix designed developed in the previous sections of this study shown in figure 5.6 on page 126. However, the moisture content should be optimized in accordance with the self-compacting nature of the mixture to reduce the manufacturing cost of the geopolymerized mud concrete block. Therefore, different mechanical soil stabilization techniques also introduced in order to develop such a suitable mix shown in figure 5.7 on page 127.

The study suggests that the suitable moisture content for the mix is between 10%-20% *(see the figure 5.7 on page 127)*. The self-compaction study shows in figure 5.7 on page 127. According to results, a vibration does not make a colossal impact on the strength.The figure 5.7 [A] shows sand 70% gravel 25% mix, [B] shows sand 60% gravel 35% mix, [C] shows sand 50% gravel 45% mix, [D] shows sand 40% gravel 55% mix. Out of all four experiments, the results show that high gravel soil creates more strength than sand, fine soil mix. After concluding the total geopolymer mud concrete mixture, a sample wall was created to see the durability and practicality of this novel wall material shown in figure 5.9 on page 128. The figure 5.9 [a] shows casting process of this novel wall materials block, [b] shows curing process after removing the mould, [c] and [d] shows masonry construction of geopolymer mud concrete block.

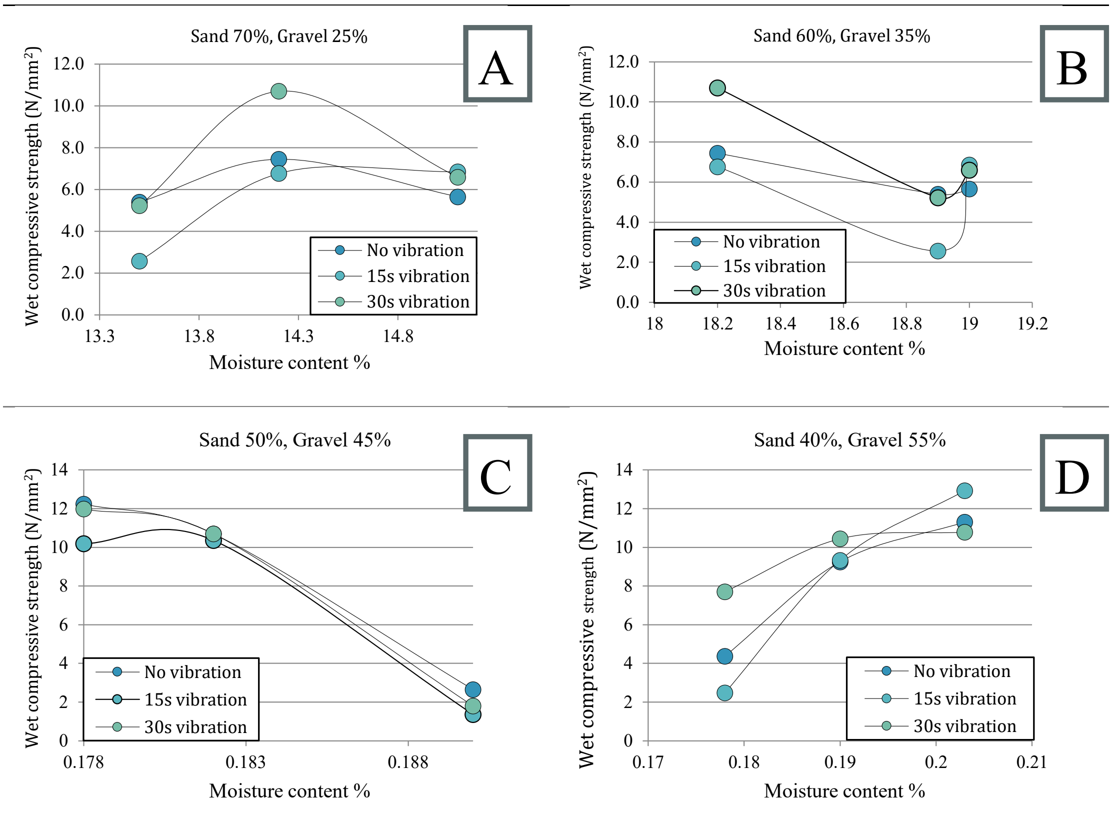



**Fig. 5.8** Finding optimum compaction method


**Fig. 5.9** Construction of geopolymer wall sample

**Table 5.5** Summary of best mix proportions

| | Average compressive strength | |
|---|---|---|
| Mix name | Wet | Dry |
| FS70G25F5 | 6.16N/mm$^2$ | 7.12N/mm$^2$ |
| FS60G35F5 | 6.16N/mm$^2$ | 7.26N/mm$^2$ |
| FS50G45F5 | 8.53N/mm$^2$ | 10.23N/mm$^2$* |
| FS40G55F5 | 8.31N/mm$^2$ | 9.86N/mm$^2$ |
| FS30G65F5 | 6.08N/mm$^2$ | 7.83N/mm$^2$ |

## 5.3 Chemical formulation in geopolymer mud concrete

Geopolymerization of mud mixture is an alternative method to alkaline activation of fly ash into the cementitious material. However, in this process, powdered aluminosilicate is combined with an alkaline activator such as NaOH and NaCL. The chemical reaction changes the properties of the fly ash and soil and creates a bond between soil particles. However, it is standard to check the water content of each and every mix after moulding them into moulds. The typical method was to over dry a sample of the mix. While this study was conducting, it was experienced that the sample has strengthened like a rock after a few hours inside the oven shown in figure 5.10 on page 131 in image section [c]. Therefore, another study was conducted to see the strength development of heated geopolymer mud concrete block mixture. The experiment programme is shown in table 5.6 on page 131.

A reaction between alumina silicate materials and alkali or alkali earth substances is known as alkaline activation. ROH, $R(OH)_2$, $R_2CO_3$, $R_2S$, $Na_2SO_4$, $CaSO_4.2H_2O$, $R_2(n)SiO_2$ are naturally occurring geopolymer materials on earth. In the formation of alkaline activated geopolymer, the R stands for an alkaline solution such as sodium (Na+) or potassium (K+), or an alkaline solution like calcium($Ca_{2+}$). The process of making alkaline bond is as follows. The polycondensation of silica ($SiO_2$) and alumina ($AlO_4$) tetrahedra interconnect and emit oxygen. Thus the release of oxygen begins hydroxyl (OH) high concentration within the mix. such medium breaks the bond between Si-O-Si, Al-O-Al, and AlOSi. Finally, silica and alumina are released to the mix and they create the bond between soil particles.

#### 5.3.0.1 Sodium Hydroxide

NaOH is an odourless, white chemical compound which absorbs moisture in the air easily when exposed to the environment. It is a base chemical and it shows a violent reaction with water and emits heat to the surrounding environment. The main benefit of using NaOH is that it gives a higher density of material when subjected to same compacting effort when it reacts with water (Assaedi et al., 2016; Cristelo et al., 2012; Darius Vaz et al., 2012). And also, NaOH is the major chemical used in the process of alkaline activation. It has shown that the concentration of NaOH affects the strength gain directly in such a way that a higher concentration of NaOH results in higher strength gain. According to a previous research, it was observed that there is an advance in soil-lime stabilization with an addition of sodium chloride (NaCL)(Cai et al., 2006; Cristelo et al., 2012; Galán-Marín et al., 2010; Latifi et al., 2015; Zhang et al., 2013).

The intention of this research is to determine the optimum fly-ash based alkaline binder that can be used to improve the Mud Concrete Block without using cement as a stabilizer. And then to find out the thermal curing to improve the engineering quality of the block. In addition to the engineering properties, the chemical structural formation and the morphological changes during or after the heat curing study is another objective of this study.

## 5.4 Heating and compressive strength development

The focus of this new study is to understand the chemical formation of the heated geopolymer mud concrete block. Therefore, the best method is to understand the chemical composition of the mixture before and after scenario. Three methods have been used in this study to understand the chemical formation of the heated geopolymer mud concrete block.

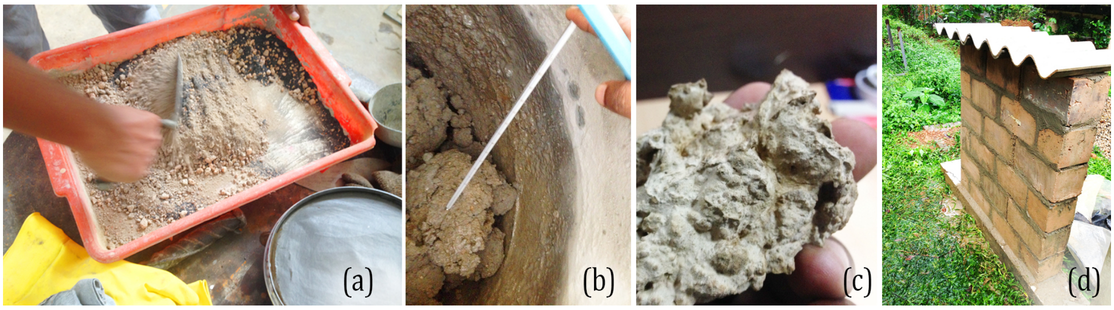



**Fig. 5.10** Geopolymer casting process

**Table 5.6** Casting schedule

| Experiment No. | Temperature | Heating Time (Minutes) | | | |
|---|---|---|---|---|---|
| EX1 | 50 C$^o$ | 60 | 120 | 240 | 480 |
| EX2 | 100 C$^o$ | 120 | 180 | 240 | 480 |
| EX3 | 150 C$^o$ | 120 | 180 | 240 | 480 |
| EX4 | 200 C$^o$ | 120 | 180 | 240 | 480 |
| EX5 | 800 C$^o$ | 120 | 180 | 240 | 480 |

The compressive strength is the best indicator of the quality improvement of the block (BS-EN 3921 (1985)). Considering single mixture, cast at single casting schedule was subjected to multi-time frame heating index. The idea is to use different heating indexes to understand the impact of thermal curing. However, the heated blocks were kept one day to release the heat and then tested in a compressive strength machine to check the compressive strength.

#### 5.4.0.1 Heating and compressive strength

The main objective of this study is to understand the strength development of heating. Therefore, the compressive strength development is a critical factor. However, the casted blocks were kept in the heating according to the heating schedule shown in table 5.6 on page 131. The results are shown in Figure 5.11 on page 134, astonishingly presents a contradicting idea about heating and geopolymer strength gain. The results show that maximum strength was gained in the low-temperature heating for a long time of 240 minutes. Suddenly heated blocks were cracked suddenly.

However, heated blocks developed cracks. This is due to available gravel particles inside the mixture. The mix consists of 35% of gravel. The gravel may expand in a different rate than sand and silt. This difference during the heating process will ultimately lead to cracking. In addition, very quickly heated blocks show series of air bubbles inside the block. However, the mixes 1 to 3 shows some form of good strength and good strength development during the strength testing process. The best results were shown in the 50 $C^o$ 480 minutes curing time. The maximum strength obtained was 3.9 N/mm in 50 $C^o$. This is adequate enough to build masonry walls and up-to-the standards of a masonry brick. Simultaneously to study the chemical formation of fly ash based geopolymer and to study the morphological changes of the fly ash based geopolymer. The chemical composition changes were studied by using XRD analyzing after heating and cooling the block into room temperature. The study wanted to understand the chemical formation of alkaline activation and chemical formation after the heating and cooling.

#### 5.4.0.2 Heating and chemical analysis using XRD

There have been many studies about the chemical formation of geopolymer. However, few studies were done in order to understand the phenomena of activators even after long time curing. This study presents a series of data on what will be the leftover scenario of NaOH in the geopolymer mud concrete block. The chemical formation of this study was conducted to understand how the heating has reacted upon the different mixes. The use of burner to heat the same according to the table 5.6 on page 131 and then most optimized mix was taken into XRD analysis. The study will help to understand how NaOH will react with fly ash and soil. The results show that there is no much difference between the non-heated mixture and the heated mixture. The only difference is the burning of the excessive carbon in the geopolymer mud concrete block mixture. The salt, of course, has been burnt off during the curing process. The XRD analysis was conducted to understand the pure soil chemical composition. The results shown in Figure 5.11 on page 134 clearly shows the highest number peaks were shown in

Dickite and Kaolinite. These are whitish lime types of mineral chemically composed of 20.90% aluminium, 21.76% silicon, 1.56% hydrogen and 55.78% oxygen. The different between Dickite and Kaolinite is the chemical bonding pattern. However, this XRD was conducted to understand the chemical composition of the selected soil sample. The series of XRD analysis was conducted to understand the mixed development and heat curing of mud concrete block. The results are shown figure 5.11 on page 134.

The results show that there is no significant difference between the non-heated mixture and the heated mixture. The unheated geopolymer mud concrete block mixture shown in figure 5.11 on page 134 shows the resulted mixture without heating. The Silicon oxide mixture which made the bond between particles and accelerated the geopolymerization results in the active action. The wavelength has started increasing when the heated time and heating temperature increased. However, the impact of the chemical formations results in similar to the non-heated Geopolymerized mud concrete block. The figure 5.11 [b], figure 5.11 [c], figure5.11 [d], figure 5.11 and figure 5.11 [e] show the similar kind of results. However, the active sodium content was increased and improved by the introduction of heating. White colour pigments were bubbled up on heated blocks. This is exclusive because of the removal of excess water from the mixture.

## 5.5 Morphology analysis

The most important study for this experiment is the morphological analysis. The morphological analysis will help to understand how the fly ash particles may dissolve after heat curing introduced. The figure 5.13 on page 135 shows the morphological study fly ash stabilized mud concrete and geopolymer mud concrete. There is a contrasting different between the figure 5.13 [a] and figure 5.13 [b]. However still there are some leftover particles *(see the figure 5.13 [b])*. The figure 5.14 [a] shows the heating temperature of 50°C at curing period of 8 hours. The leftover fly ash bubbles are clearly seen in the mixture. However, the increase of temperature has dissolved the fly ash carbon

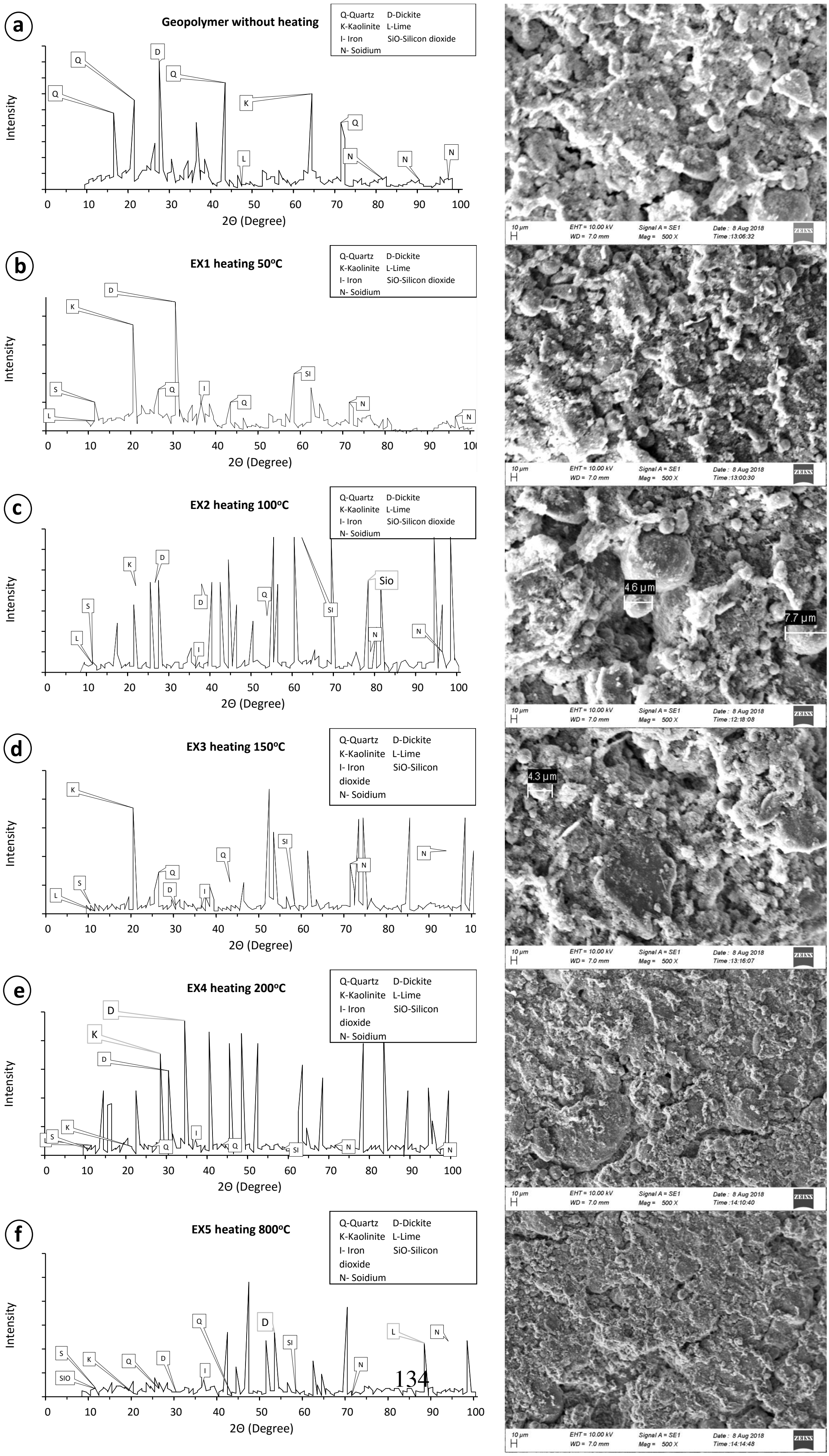



**Fig. 5.11** XRD analysis of heated geopolymer

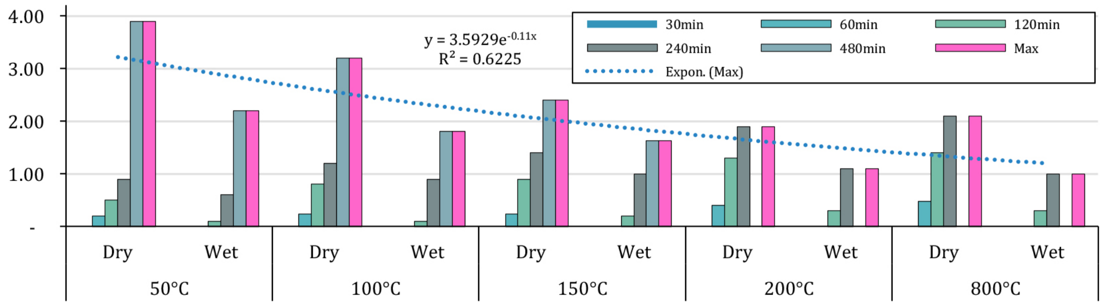



**Fig. 5.12** Heating and compressive strength results

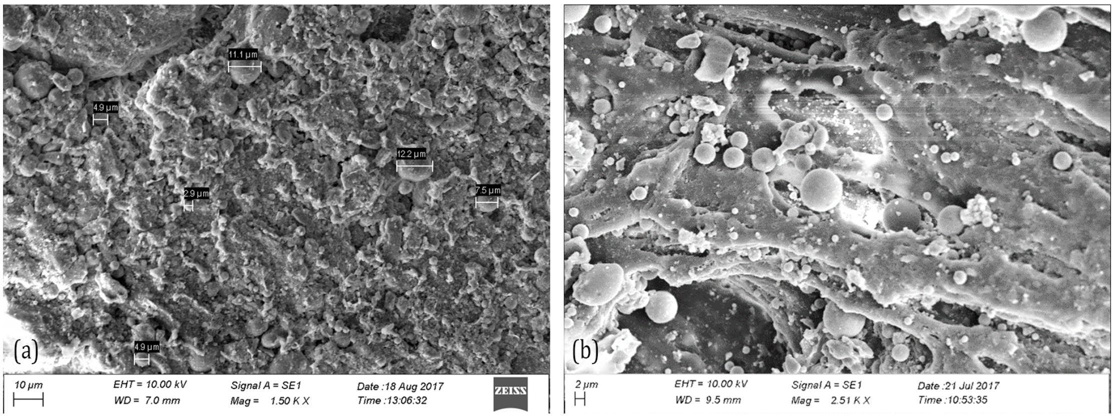



**Fig. 5.13** SEM image of geopolymer mud concrete

bubbles and melted with soil mixture while assuring a better bonding. The image e in figure 5.14 shows the formation of geopolymer links, most of the bubbles are dissolved and acts as **one unit**. Therefore, the strength is comparatively higher.

## 5.6 Summary

The study was started with a series of experiments to understand how the fly ash can be mixed with mud to make a self-compacting mixture. The results show that there are a significant strength gain and sudden strength gain during the heat curing process. However, heat curing to more than 200 degrees will give adverse effect to the Geopolymerized mud concrete. The introduction of heating will ended-up with a series of cracking within the block. It was noticed that the cracking occurred through the gravel particles. The chemical formation analysis shows that there is not much change after the heat curing.

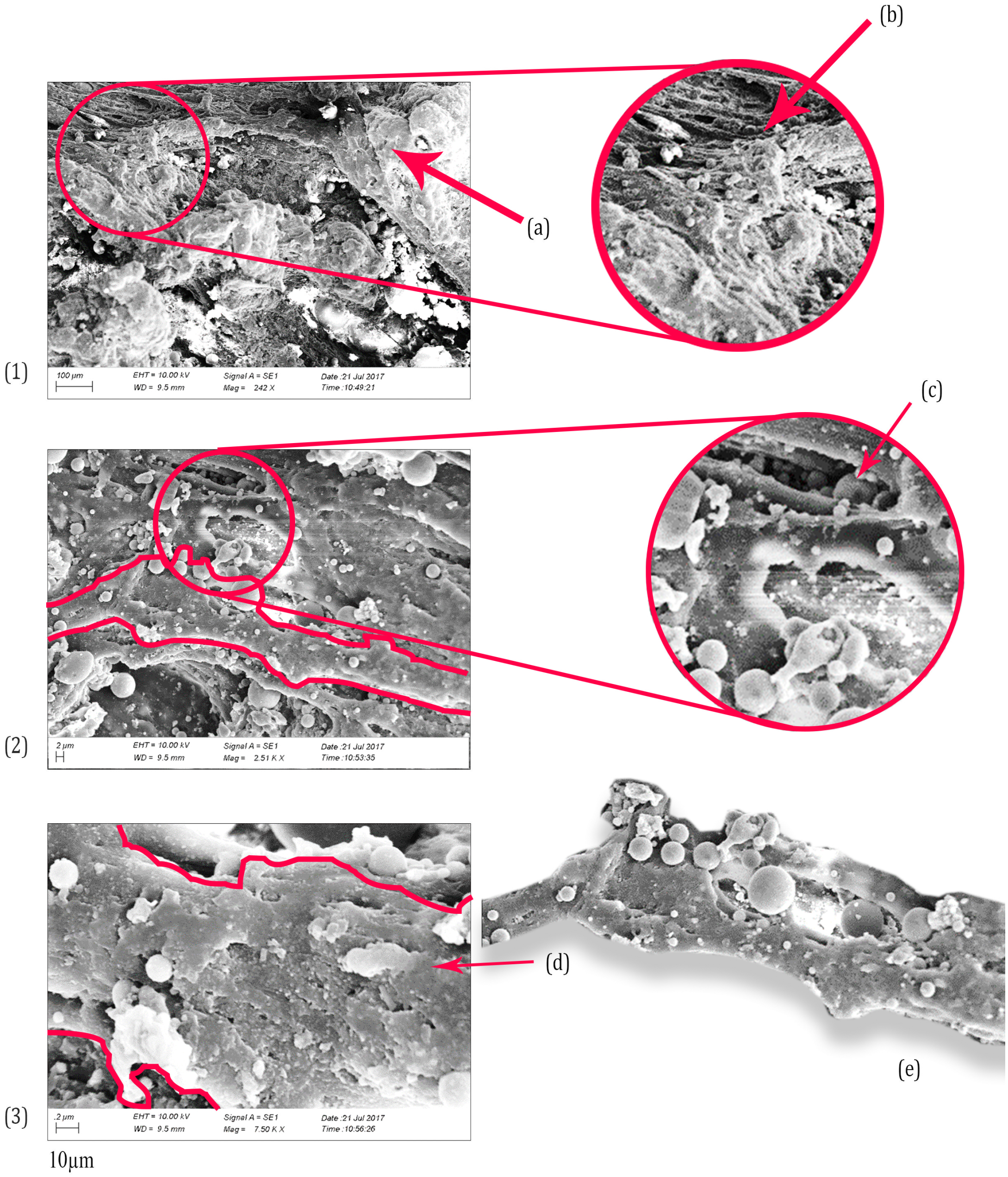



**Fig. 5.14** Detailed SEM image of geopolymer mud concrete

# CHAPTER 6

# ENVIRONMENTAL FITNESS AND LIFE CYCLE STUDY

## 6.1 General

After several studies, the mud concrete technology was optimized with several stabilizers as well as a manufacturing method. But it is important to understand cradle to grave life cycle analysis of this novel walling material comparing exiting walling materials. Therefore, the overall life cycle analysis of the newly developed geopolymer stabilized mud concrete block, cement stabilized mud concrete block shall be subjected to a comparative study with other existing wall construction masonry units such as cement blocks (CB), Brick(BB), cement stabilized earth blocks (CSEB), Cabook (CAB) *(see table 6.1 on page 138)*. The suitability of newly developed walling materials was studied starting from the durability test, moss growth study, Mould growth study and thermal performances prior to the life-cycle cost studies.

The durability study was carried on to substantiate the durability of new walling materials against natural circumstances especially the natural rain. Because that is the most critical condition for walling materials in Sri Lanka. Then the moss growth moss growth and mold growth was studied along with similar walling materials palette.Finally, the manufacturing frame work was optimized to produce Mud concrete block. Then the developed technology was transferred to low income communities to build their houses in Sri Lanka.

**Table 6.1** Specimen identification

| Walling material | Specimen code |
|---|---|
| Cement Block | CB |
| Brick | BB |
| Cement Stabilized Earth Block | CSEB |
| Cabook Block | CAB |
| Mud Concrete Block | MCB |
| Fly Ash Stabilized Earth Block | FSEB |
| Rough Cement Plaster | RCP |
| Cement Plaster | CP |

## 6.2 Intrinsic property comparison

Prior to the study, the environmental fitness of different walling materials developed by this study, the intrinsic properties of the walling materials were studied. The adaptable surface decay was studied by using accelerated weather testing.

### 6.2.1 Porosity

Results of the porosity measures show in figure 6.1 on page 139. Mud concrete block has the highest porosity comparing to other wall construction materials. Interestingly Mud concrete block porosity is higher than the porous materials such as Cabook. However, CSEB is the second highest porous materials and the next is the BB. BB Is interesting, because, microscope images shown in figure 6.21 explains that BB is having smaller scale porous spaces created after evaporation of water in the brick mud mixture. CB, CAB, FSEB, CP, and RCP are not highly porous materials and FSEB is the lowest porous material. FSEB has low porosity because of the addition of fly ash. Fly ash is a tiny particle which can spread within small porous spaces within the block. However, lowe porous materials are not good at thermal conduction, since fly ash contains carbon, the heat may transfer through the block. Therefore, If the walling materials are having adequate strength, the results of high porous show somewhat advanced materials. Because porous can enhance the structural cooling capacity. Such porous may cool the

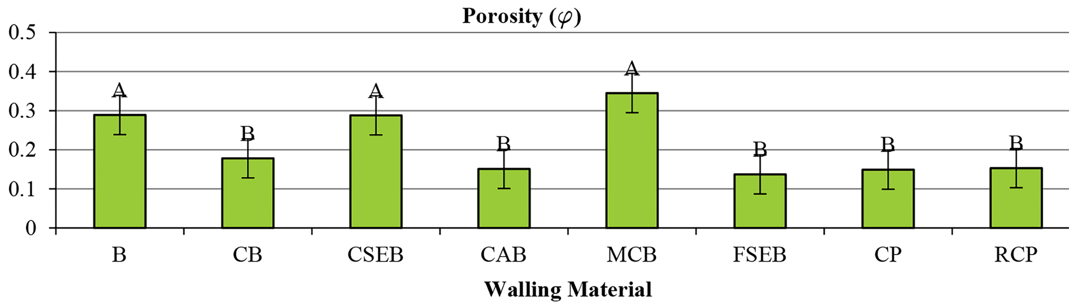



**Fig. 6.1** Porosity of walling materials

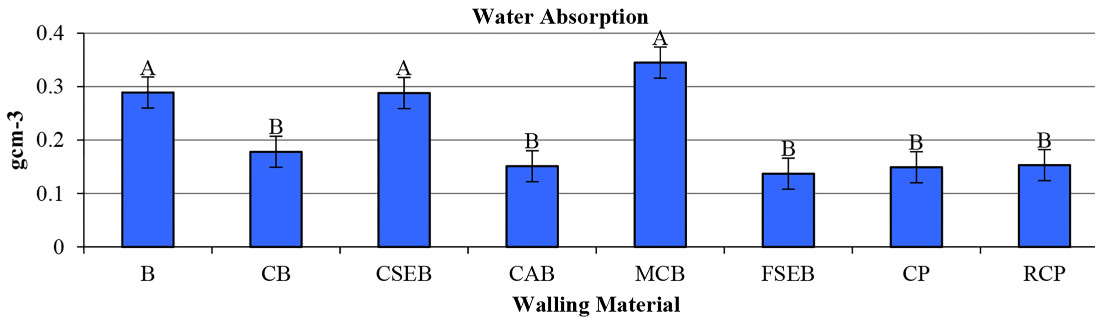



**Fig. 6.2** Water absorption of walling materials

space.

### 6.2.2 Water absorption

Water absorption results are following similar results of porosity results shown in figure 6.2, because high porous spaces can retain water. The water retains capacity is calculated in water absorption test. Therefore, MCB has the highest water absorbing capacity. Then brick and CSEB shows the second highest water absorbing capacity. However, overall results show that new wall masonry units such as mud concrete and fly ash stabilized masonry units fail to waterproof. An introduction of a waterproofing coating is needful to reduce the water absorbing capacity.

### 6.2.3 Capillary Action

Capillary action shows the speed of moisture absorption. This study is very important to analyze the suitability of a wall construction material for a tropical country like Sri Lanka. Because, if the foundation is not damp proof, the water may come into the wall masonry units and finally reduce the strength of the wall *(see the figure 6.3)*. The results of this experiment show that BB has the highest capillary action. The MCB is the second highest capillary action. Following FSEB, CSEB, CAB and CB have moderate capillary water absorption. However, smaller particle composed wall construction materials such as CP and RCP have the lowest capillary water absorption results. To conclude result of capillary action, better wall construction materials can be manufactured by covering low-cost high water absorbing materials with low capillary water absorbing materials such as CP and RCP.

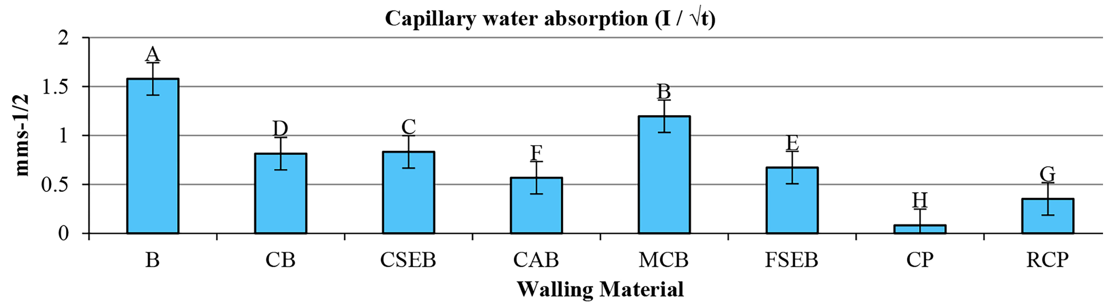



**Fig. 6.3** Capillary water absorption of walling materials

### 6.2.4 Surface roughness

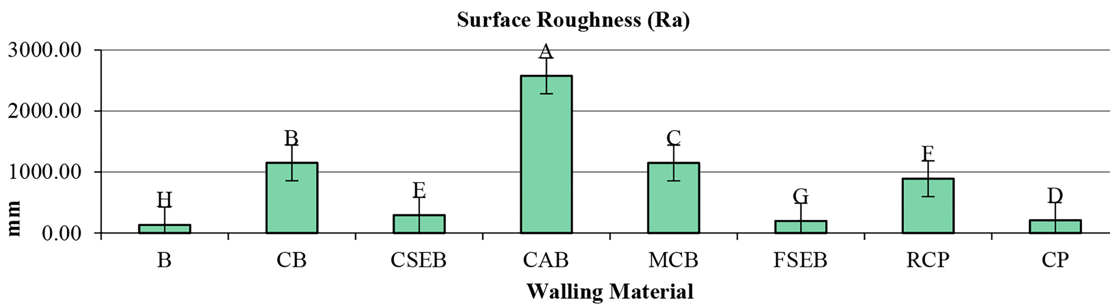



**Fig. 6.4** Surface roughness study results

Surface roughness is not an engineering property. But, the surface roughness directly affects the durability of the wall. Rough wall masonry units receptive to many environmental constraints such as rain, moss growth, and even surface decay (D'Orazio et al., 2014; Pranjic et al., 2015; Tran et al., 2014). According to the results of this experiment shown in the figure, 6.4 CAB is the roughest wall constriction material. Then

**Table 6.2** Surface roughness results

| Material | Roughness values (Ra) micrometers (um) |
|---|---|
| B | 133.03 |
| CB | 1149.17 |
| CSEB | 292.10 |
| CAB | 2575.65 |
| MCB | 1147.67 |
| FSEB | 197.46 |
| RCP | 890.62 |
| CP | 208.71 |

CB, MCB and RCP have moderate surface roughness. CSEB, FSEB, BB and CP has the lowest surface roughness. The novel wall construction materials developed in this study, made by using smooth steel surfaces. Therefore, the surface supposed to be very smooth. But, MCB composed with high gravel, the surface roughness was comparatively increased. However, FSEB is manufactured by using 20% of fly ash. Fly ash is a fine and makes FSEB surface smooth.

### 6.2.5 pH value

pH value was measured to calculate hydrogen ions ($H^+$) in the wall material. The pH value is stately on a negative logarithmic scale of hydrogen solution. pH values vary from 0 to 14; pH values between 0 – 7 referred as acidic, values between 7-14 referred to as basic or alkaline and pH 7 referred as neutral. Results of this study are shown in figure 6.5. The CAB has the lowest pH value. This is because CAB has been buried inside the earth for a long time and CAB is complete natural earth substances. Then CSEB made of the earth has the second lowest pH value. Mud concrete block and FSEB has moderate high pH content. However, CP, RCP and CB the highest pH content because of the addition of cement, cement is a high alkaline material.

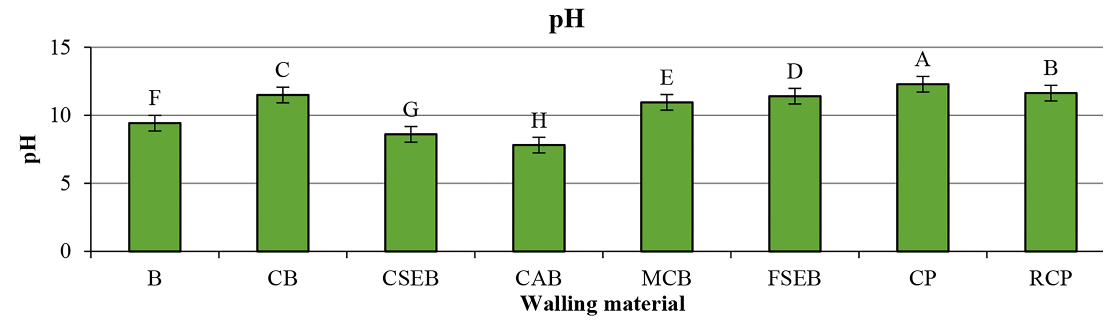



**Fig. 6.5** pH value of walling materials

6.2.6 Organic matter content

Organic matter refers to the number of natural substances available with a particular material (figure 6.6). High organic materials are bio receptive and finally decay due to natural causes such as moss, mould and rain. Therefore, understanding organic content is a very important factor. According to the results, the CAB and CP have the highest organic matter and brick and CB shows the lowest organic content. MCB, CSEB and FSEB have a moderate amount of organic content. Brick has the lowest organic matter because of brick produced by burning. The burning process removes all the organic matter or converts them to dust during the burning process. Therefore, Brick shows the lowest. Wall construction materials such as CAB raw materials of soil used to make MCB and FSEB was buried inside the earth for a long time. They are prone to biological activities. As a results CAB, MCB, FSEB and even CSEB have the highest organic matter content.

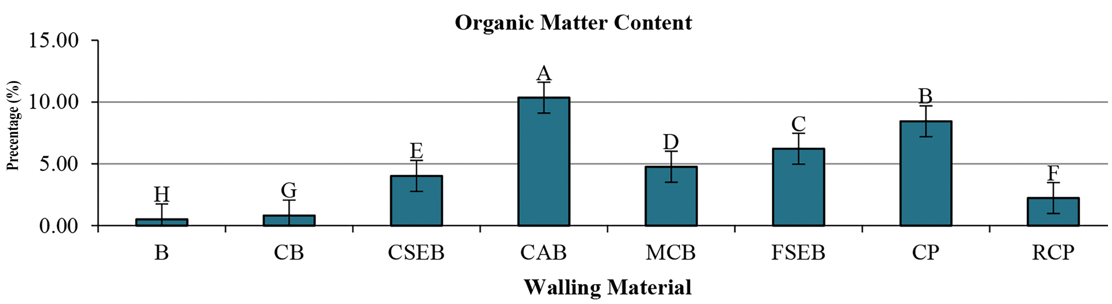



**Fig. 6.6** Organic mater content of walling materials

### 6.2.7 Intrinsic property study comparison

Overall results of intrinsic property study comparison shown in table 6.3. According to the result, novel wall materials such as MCB and FSEB are having advanced qualities over existing wall construction materials used to compare for this study. FSEB porosity is comparatively lower than other wall construction materials. FSEB and MCB have the comparatively lowest surface roughness. But the water absorption and capillary action are comparatively higher. The organic matter content also very low in MCB and FSEB. The pH content is comparatively higher in MCB and FSEB. However, overall results are positive to use MCB and FSEB as a wall construction material in Sri Lankan tropical climatic condition *(see the table 6.3)*. In order to understand the impact of the intrinsic properties of selected wall construction materials, a durability study was conducted.

**Table 6.3** Intrinsic property study comparison

| | Porosity (f) | Surface Roughness (Ra) (m) | Capillary Action (I) (mms-1/2) | Water Absorption (gcm-3) | Organic Matter Content (%) | pH Value |
|---|---|---|---|---|---|---|
| BB | 0.289 | 133.03 | 1.578 | 0.289 | 0.51 | 9.42 |
| CB | 0.178 | 1149.17 | 0.814 | 0.178 | 0.82 | 11.49 |
| CSEB | 0.288 | 292.1 | 0.832 | 0.288 | 4.02 | 8.6 |
| CAB | 0.151 | 2575.65 | 0.568 | 0.151 | 10.36 | 7.81 |
| MCB | 0.345 | 1147.67 | 1.196 | 0.345 | 4.76 | 10.95 |
| FSEB | 0.137 | 197.46 | 0.672 | 0.137 | 6.22 | 11.4 |
| CP | 0.149 | 208.71 | 0.082 | 0.149 | 8.45 | 12.28 |
| RCP | 0.153 | 890.62 | 0.352 | 0.153 | 2.23 | 11.63 |

## 6.3 Natural weather durability

Rainwater surface decay is a combination of intrinsic properties and the impact of the rain. There are two types of rain impact on a wall surface. The first is the direct rain coming straight away from the sky. However, walls are not directly affected by direct rain since wall constructed parallel to the direction of the rain. But the rain created by the wind impact on the wall surface. The wind-driven rain (WDR) decay wall surface. The second rain impact is the bouncing drop rain. The bouncing drop rain decays the lower part of the wall. To study the natural rain surface decay, a surface erosion test was conducted.

The surface erosion test was conducted using a spray test method. In the spray test, high-pressure salt water mix sprayed on to the wall surface for a period of ten hours. The pitting depth was measured at intervals of ten minutes. The pitting depth is compared by using a 3D scanner. A detailed experiment to study the durability and surface decay of six different wall types and two walls covering were published in the article named A Study on Natural Rain Surface Erosion of Different Walling Materials in Tropics. According to experiment results, CSEB and FSEB prone to the highest surface decay. CP, RCP, CB, and MCB has the lowest surface decay. However, the scaled off factor shows that most of the earth materials are subjected quick surface decay and then settled. It was observed that CAB doesnt erode by water. Instead, loose particles in the wall blocks tend to decay during the surface decay test (Udawattha, Galkanda, and Halwatura, 2018).

The surface erosion test was conducted according to ASTM C744. Three different samples were subjected to this study shown in figure 6.7 . The results of this study and comparison of spray test shown in figure 6.8. According to results CAB and FSEB has the highest surface erosion. The new wall material FSEB eroded more than all the other wall materials. But MCB did not erode. Results of the MCB is better than all the other wall construction materials. However, CP and RCP have the lowest surface

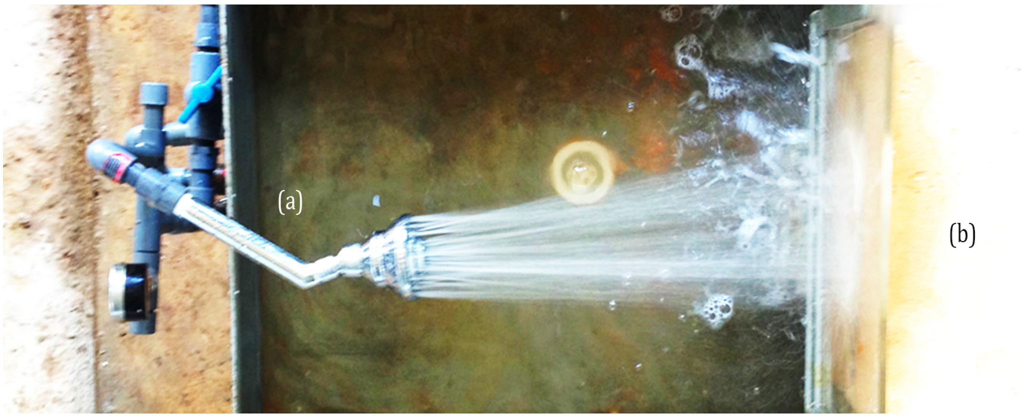



**Fig. 6.7** Surface erosion test

**Table 6.4** Surface erosion test results.

| | Pit depth (mm) | | | | Scale off |
|---|---|---|---|---|---|
| | 15 mins | 30 mins | 45 mins | 60 mins | ($g/mm^2$) |
| CAB | 2.0 | 2.9 | 4.0 | 7.9 | 0.00305 |
| FSEB | 5.0 | 9.2 | 18.0 | 23.1 | 0.00115 |
| CSEB | 2.1 | 2.5 | 3.1 | 3.2 | 0.00179 |
| CB | 0.0 | 0.0 | 0.0 | 2.1 | 0.00000 |
| MCB | 0.1 | 0.5 | 0.6 | 1.1 | 0.00000 |
| Brick | 0.2 | 0.6 | 0.8 | 1.1 | 0.00058 |
| CP | 0.2 | 0.8 | 1.6 | 2.1 | 0.00000 |
| RCP | 0.0 | 0.0 | 0.0 | 0.0 | 0.00000 |

erosion results. CB and BB have moderate surface decay results.

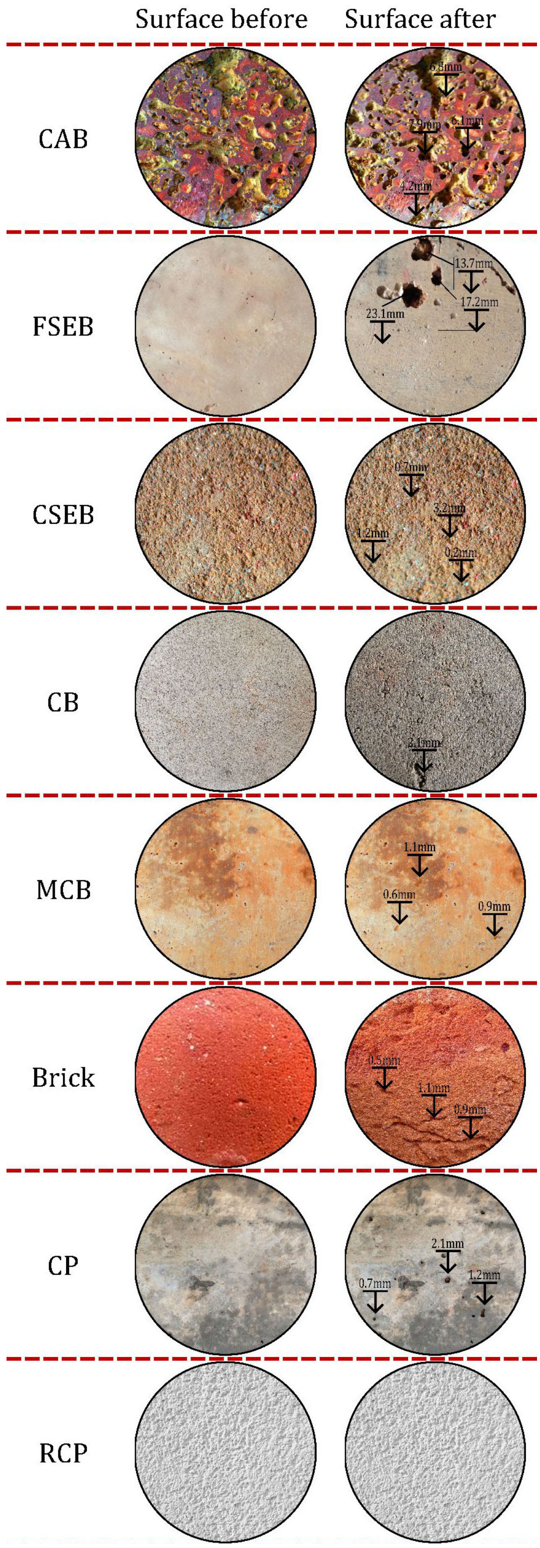



**Fig. 6.8** Surface roughness study comparison results

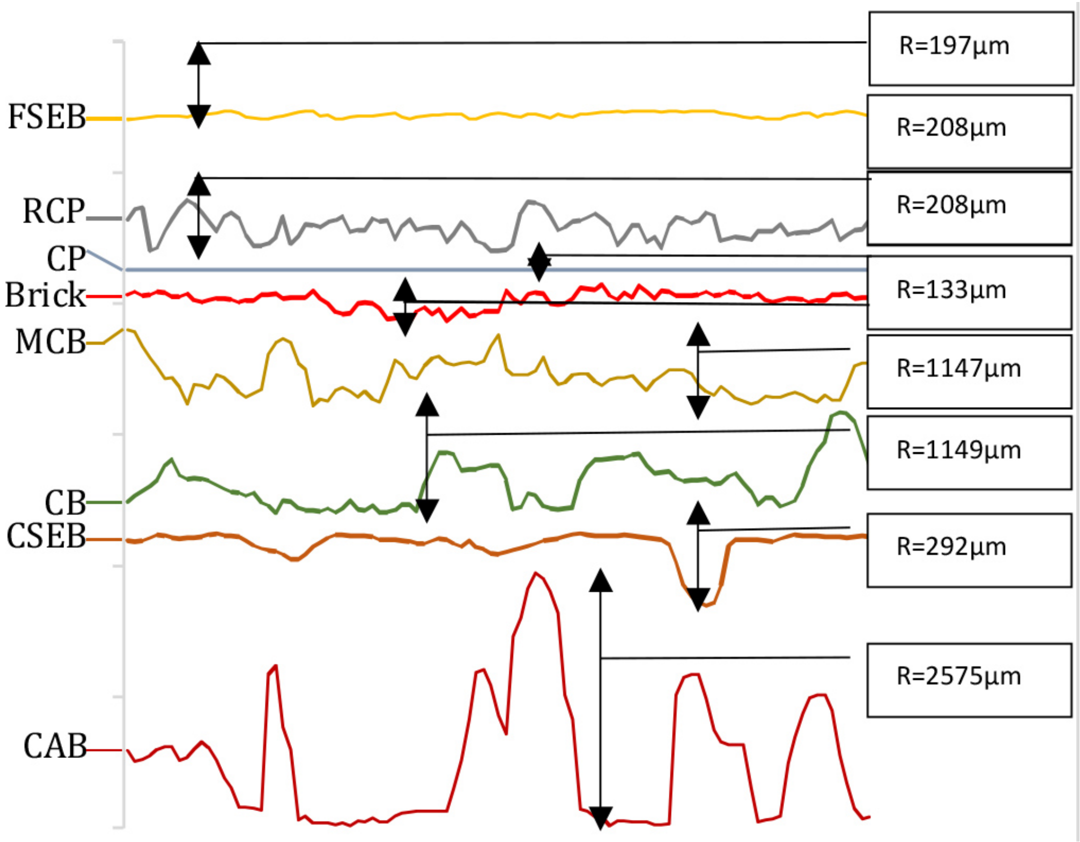



**Fig. 6.9** Surface roughness measurements

## 6.4 Moss growth test

Moss growth is a common phenomenon in tropical walls. Therefore, the growth rate and growth pattern were studied by using the systematic method.colorblueA a novel method of measuring moss growth was developed by this study and published in the Journal of Building and Environment in an article named Mold growth and moss growth on tropical walls (Udawattha, Galkanda, Ariyarathne, et al., 2018).

Eight different types of walls (1mX1m) including novel wall types such as MCB and FSEB were built and moss growth was studied. A sample walls constructed to study moss growth and durability shown in figure 6.12 on page 150. The photographic study was conducted on daily basis. Finally, colour variation was considered as the evaluation criteria shown in figure 6.13. The colour change was studied after conducting colour change shown in figure 6.12.

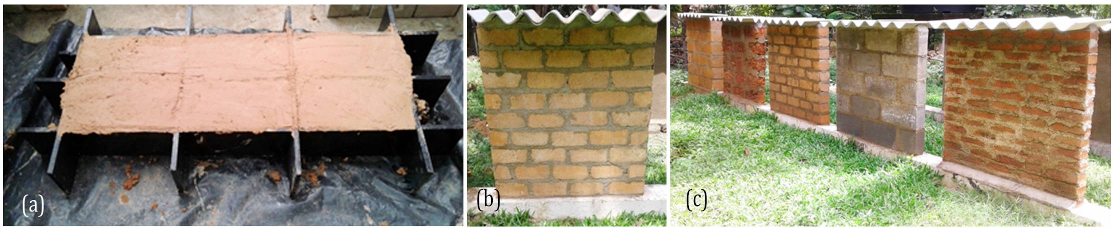



**Fig. 6.10** Wall samples

6.4.0.1 Comparison of moss growth area

Interestingly, novel water materials such as MCB and FSEB had comparatively less moss cover. Rough wall materials such as brick, cabook, and CSEB are prone to moss growth. Wall coverings of CP has the lowest moss growth. However, rough cement plaster also prone to somewhat significant moss growth. The conclusion of this study was that rough wall materials are receptive of moss growth irrespective to the materials type.

## 6.5 Mold Growth comparison

Fungus growth is the next important environmental parameter to be checked. The fungus growth test was conducted according to ASTM D3273-94. Total study of fungus test and comparison of different fungus growth rates were published in Journal of Building and Environment in an article named Mold growth and moss growth on tropical walls. The study has found that some of the intrinsic properties such as pH value and surface roughness have a co-relationship with fungus growth. Similarly, to moss growth, rough surfaces are receptive to mold and fungus (Udawattha, Galkanda, Ariyarathne, et al., 2018).

The figure 6.16 shows the connection between fungus growth and intrinsic properties. In order to accelerate the mold growth, the mold needs moisture. The moisture must be given by the atmosphere or wall materials. If the wall materials are high water absorptive, if the capillary action is better, the wall can retain water and feed mold. This study also found that high water absorptive materials such as CSEB, BB, and MCB have

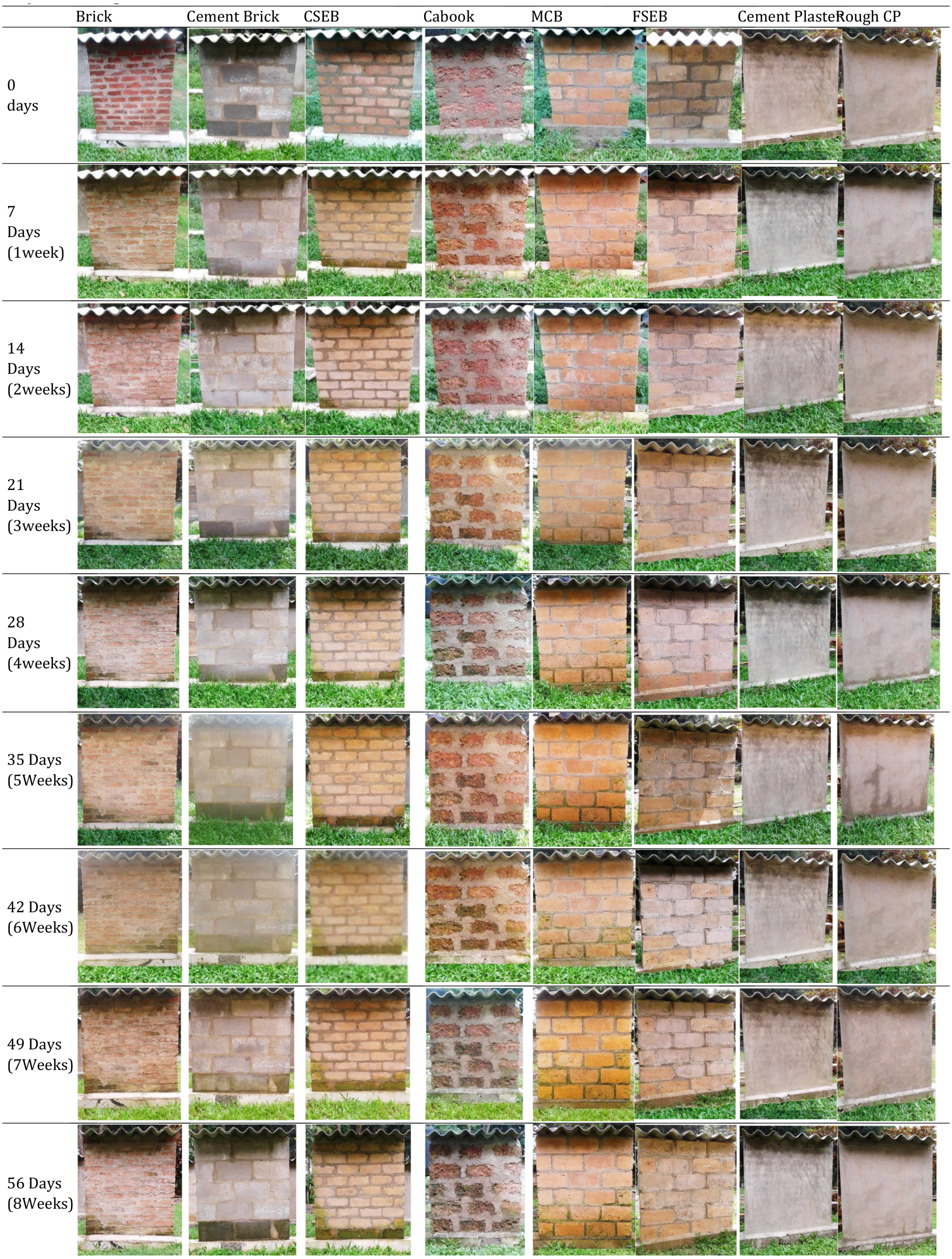



**Fig. 6.11** Moss growth study after 8 weeks

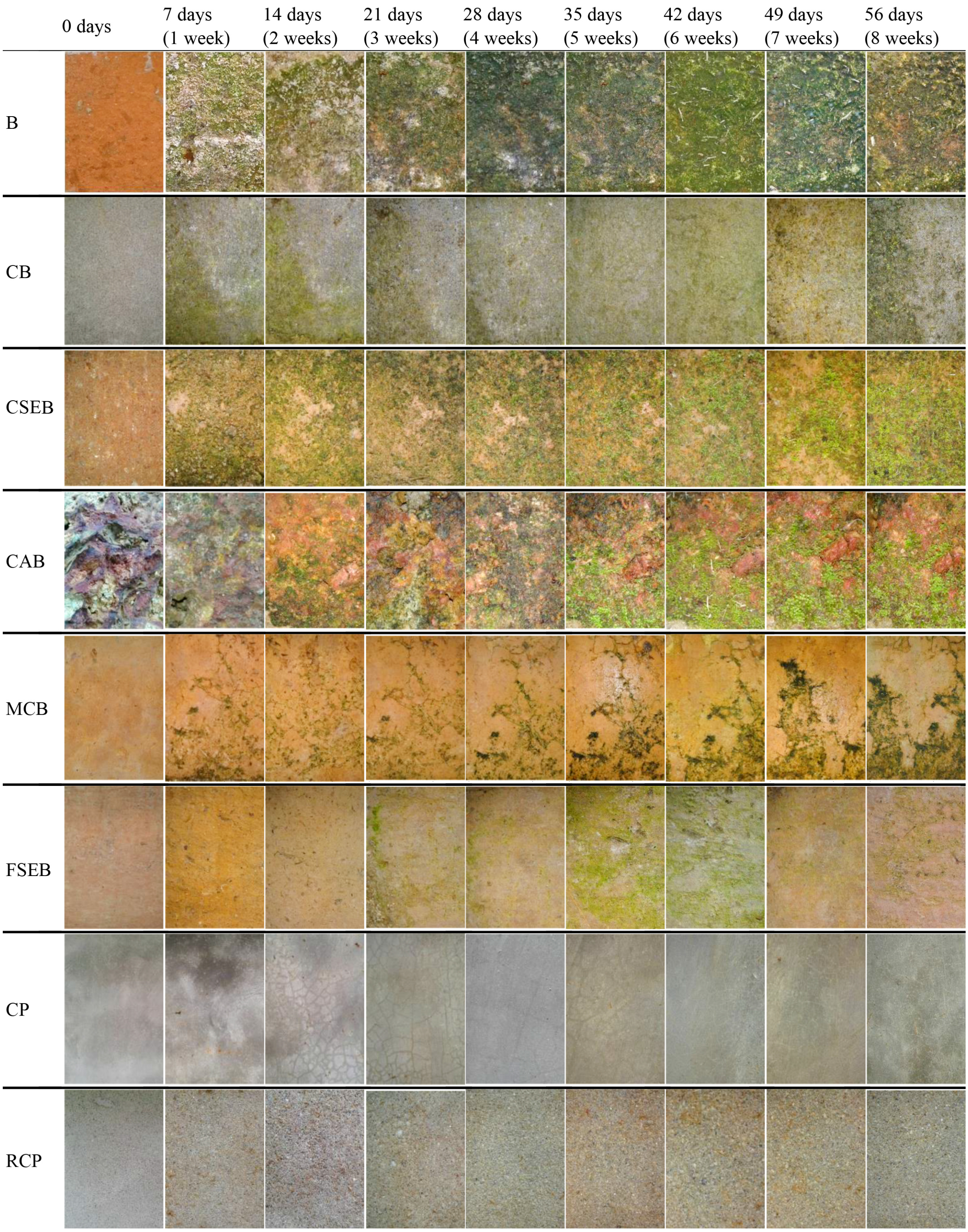



**Fig. 6.12** Comparison of moss growth

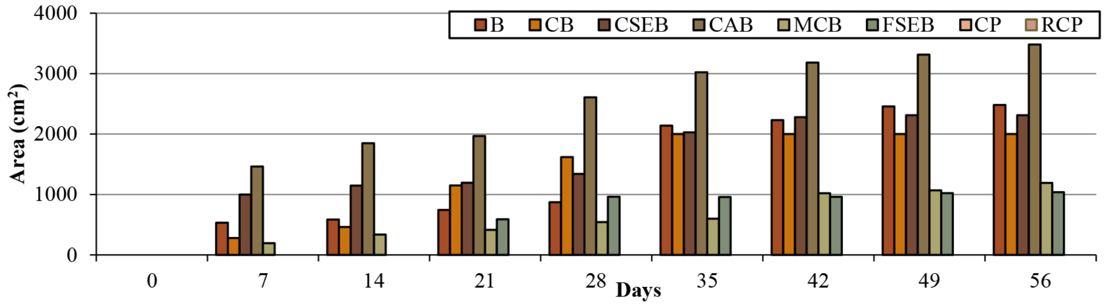



**Fig. 6.13** Moss growth rate of walling materials

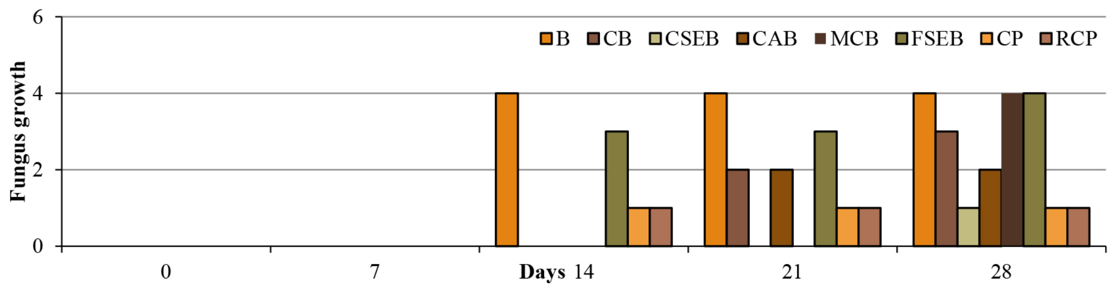



**Fig. 6.14** Fungus growth rate of walling materials

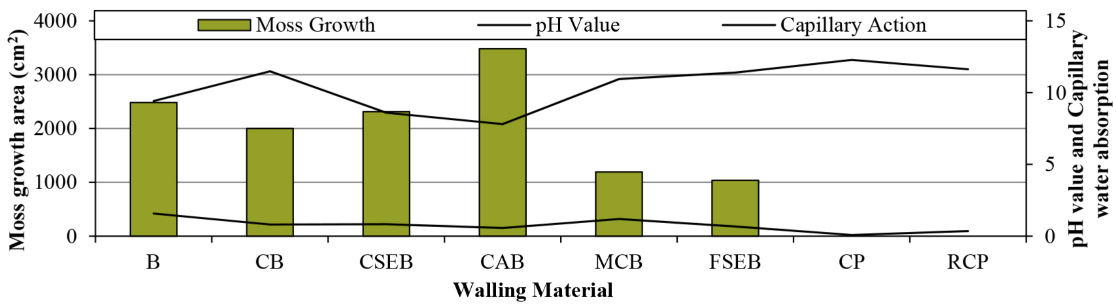



**Fig. 6.15** Variation of fungus growth with intrinsic properties

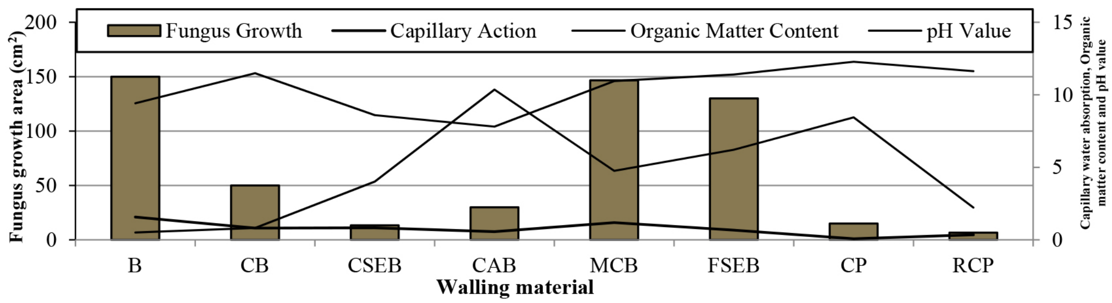



**Fig. 6.16** Fungus growth Vs. Significant intrinsic properties

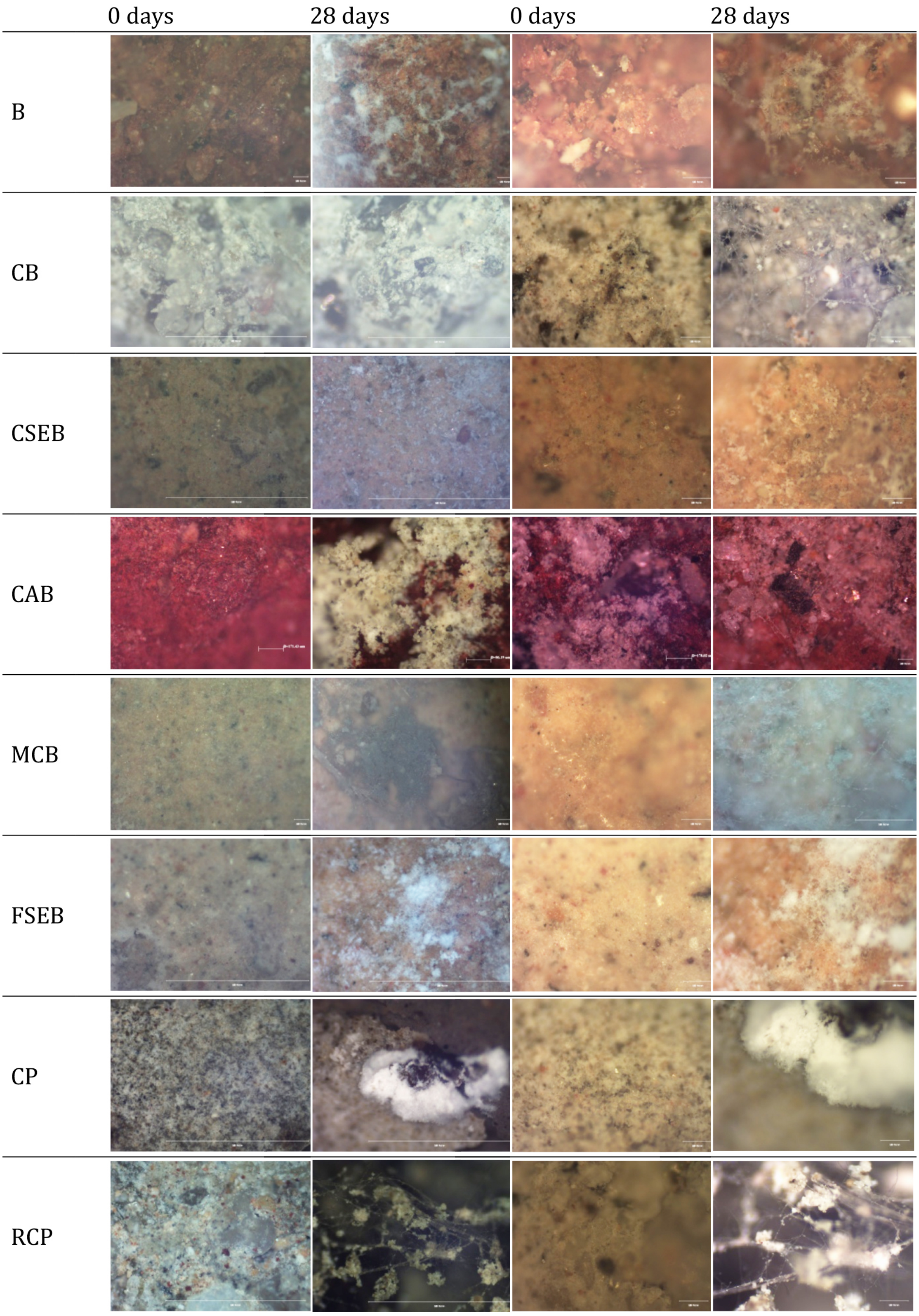



**Fig. 6.17** Microscope images of fungus growth on wall surfaces

**Table 6.5** Evaluation of fungus growth

| Days | B | CB | CSEB | CAB | MCB | FSEB | CP | RCP |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 4 | 0 | 0 | 0 | 0 | 3 | 1 | 1 |
| 21 | 4 | 2 | 0 | 2 | 0 | 3 | 1 | 1 |
| 28 | 4 | 3 | 1 | 2 | 4 | 4 | 1 | 1 |

high mold growth *(see the figure 6.16 and figure 6.17)*.

## 6.6 Thermal performances comparison

A wall is our third skin. The purpose of the wall is to absorb heat and heat proof the interior space. Therefore, the comparison of thermal performance is an important factor to evaluate the suitability of novel wall materials. A detail thermal performance study was conducted and published in Advances in Building Energy Research in journal paper named Thermal performance and structural cooling analysis of brick, cement block, and mud concrete block (Udawattha and Halwatura, 2016c).

To study thermal performance three different wall materials were constructed a same plan in the same orientation in the same location three different buildings were built. The case study building are shown in figure 6.18. The wall construction materials which couldn't make real-world buildings such as CAB, CSEB and FSEB were simulated by using computer-based thermal simulation shown in figure 6.20. In order to simulate the thermal performances, the thermal conductivity was measured by using a thermal conductivity meter shown in figure 6.19.

(a) (b) (c)

**Fig. 6.18** Three different walling materials real scale buildings

**Fig. 6.19** Measuring thermal conductivity

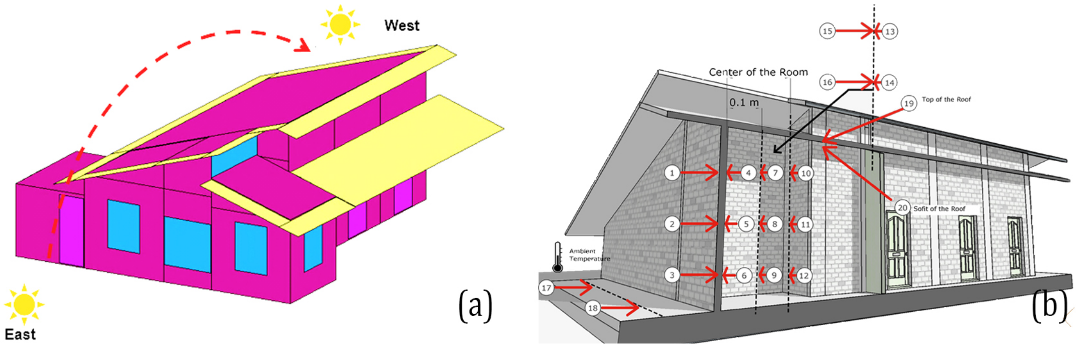



**Fig. 6.20** Simulated Derob Model and probe locations

Thermal performance is not an intrinsic property of a wall material. It is a combination of porosity and materials density. Further to this, there is a phenomenon of structural cooling and time lag during a heat transferring through a wall surface. The time lag refers to time take to transfer an outdoor heat into indoor. The decrement factors show the indoor and outdoor wall surface heat variation. Therefore, both porosity, time lag and decrement factor were studied. The thermal properties of the simulated data are shown in Appendix E on page 209.

According to results shown in table 6.6 on page 155 CAB, MCB and BB has the highest thermal performance, higher time lag and lesser decrement factor. FSEB shows moderate thermal performance because of addition of fly ash. Fly ash has high heat capacity. High heat capacity increase the decrement and reduce the time lag. Also, fly ash is fine and therefore reduce the porosity. The reduction of porosity lead to

**Table 6.6** Measure of porosity,structural cooling:time lag and decrements factor

| Days | BB | CB | CSEB | CAB | MCB | FSEB | CP | RCP |
|---|---|---|---|---|---|---|---|---|
| Porosity(f) | 0.289 | 0.178 | 0.288 | 0.151 | 0.345 | 0.137 | 0.149 | 0.153 |
| Time lag | 5.0hrs | 1.0hrs | 2.3hrs | 4.0hrs | 2.0hrs | 1.2hrs | 3.2hrs | 3.0hrs |
| DR | 0.99 | 0.966 | 0.924 | 1.1 | 0.947 | 0.897 | 0.941 | 0.982 |

quick heat gain. But overall, novel wall materials MCB and FSEB suitable for tropical climates, because they have good thermal performance comparing cement based wall construction materials such as CB and CSEB.

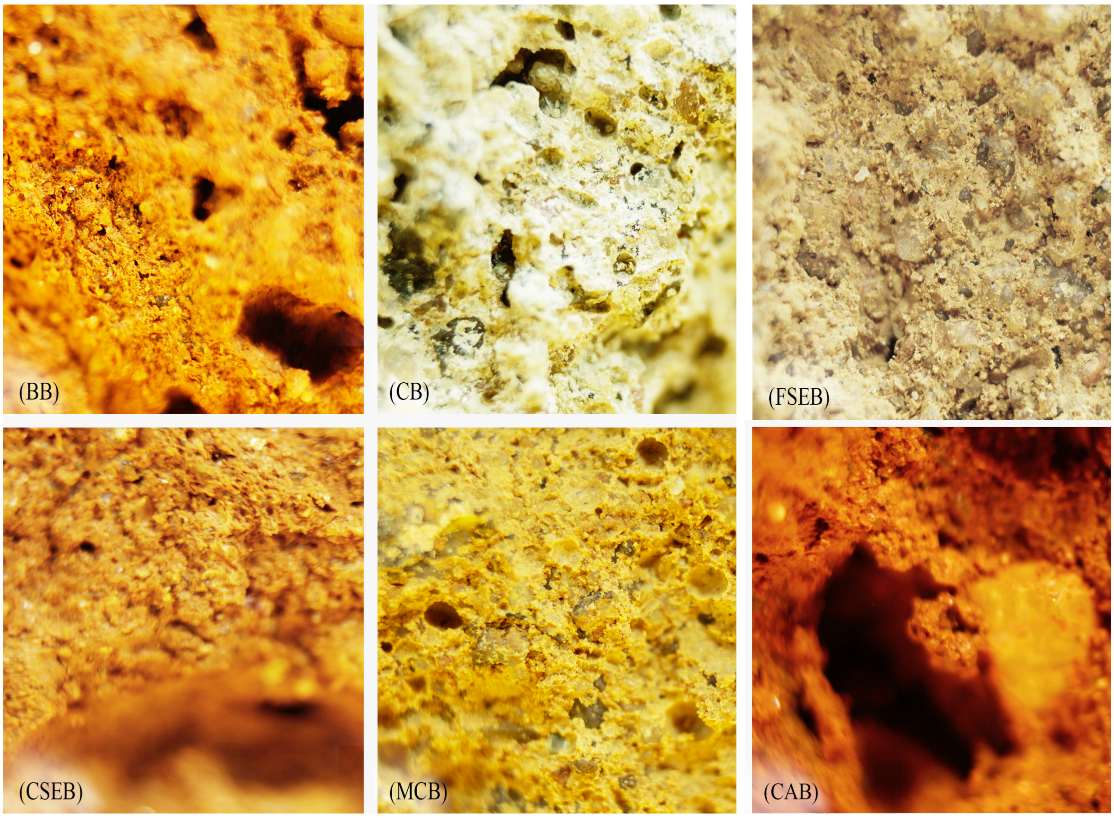



**Fig. 6.21** Photographic study of porosity

## 6.7 Embodied energy analysis

Calculating embodied energy is the first step to understand the environmental suitability. This study and novel method of calculating walling materials embodied energy were published in Energy and Building in journal paper named Embodied energy of mud concrete block (MCB) versus brick and cement blocks (Udawattha et al., 2016a,b; Udawattha and Halwatura, 2016a).

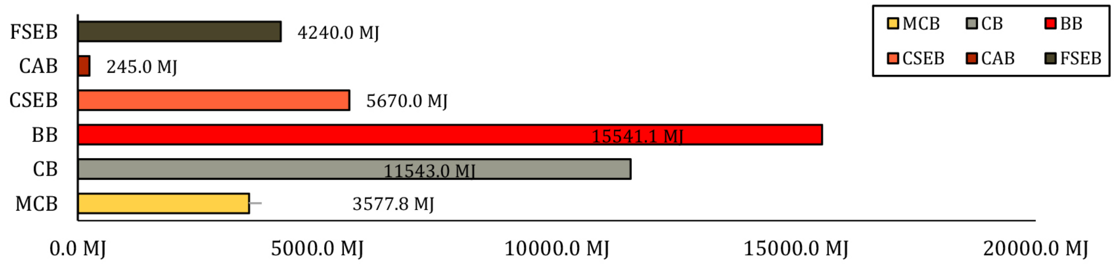



**Fig. 6.22** Energy content of building one square wall

A sample data set of embodied energy calculation is shown in Appendix F on page 211. The figure 6.22 on page 156 explains the energy consumption to build one square wall. The brick walls with many building units (1150 nos.) consume more energy than all the other walling materials (Udawattha and Halwatura, 2016a). In fact, brick wall per one square embodied energy content is 15541.1 MJ, and it is higher than mud concrete block energy content. Cabook consumes the lowest amount of energy because it is a natural walling material. However, the novel walling materials such as fly ash stabilized mud concrete block accounts comparatively lower embodied the energy and yet higher than MCB and CAB. Sample house models to calculate the thermal performances and cooling load is shown in figure 6.23. The figure 6.23 [a] shows a brick building, figure 6.23 [b] shows a plastered brick building and figure 6.23 [c] shows the mud concrete building.


**Fig. 6.23** Sample one square wall model house to compare wall properties

## 6.8 Life cycle cost

The life cycle analysis and total construction process calculation was published in the case studied in construction materials in journal paper named Life cycle cost of different Walling material used for affordable housing in tropics (Udawattha and Halwatura, 2017).

### 6.8.1 Initial cost

The initial cost of different walling materials was taken into consideration in respect to the total cost of the building. The cost of the walling materials, as well as the construction cost, was calculated after constructing one square meter wall at the backyard of the University. The cost comparison shows that brick is the most expensive walling material shown in figure 6.24 on page 158. Then the maintenance cost comparison shown in figure 6.25 on page 158. According to maintenance cost comparison, CAB has the highest maintenance cost.

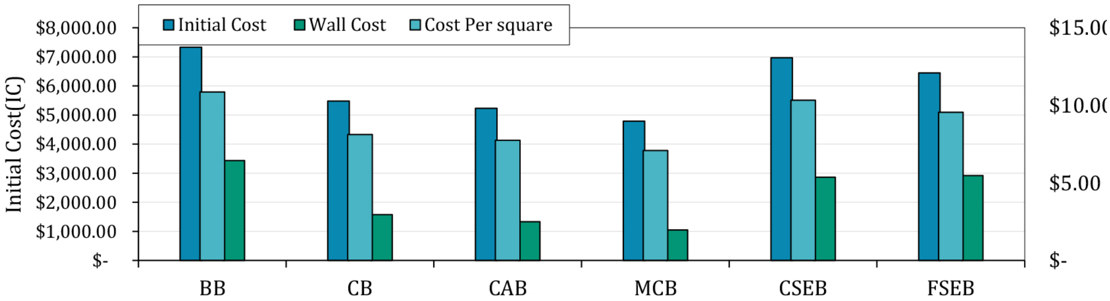



**Fig. 6.24** Initial cost comparison

### 6.8.2 Maintenance cost

Maintenance and operation costs represent the most significant part of the building life-cycle costs. Different types of wall construction materials need different types of maintenance, for an example, brick buildings are prone to moss growth. However, for this study, the maintenance cost was calculated by measuring the wall maintenance cost incurred for a period of sixty years. According to the results, the CAB has the highest maintenance cost. Then CSEB and FSEB have the second highest maintenance cost, due to the plastering repair cost during the longer period. The CB and MCB have the lowest maintenance cost due to use of non-plaster wall finishes.

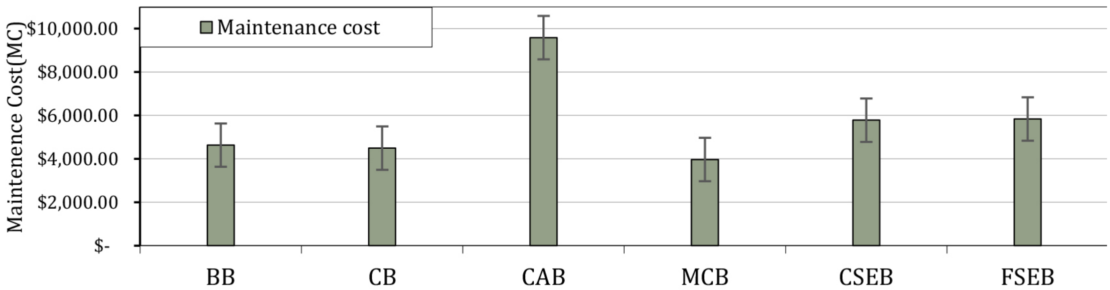



**Fig. 6.25** Maintenance cost comparison

### 6.8.3 Cooling load calculations

Cooling load is a result of a thermal performance. Not all tropical buildings are actively cooled by using air conditioners. But calculating the cost of air conditioners to achieve constant temperature is the only way to compare the cooling load and its monetary value. The cooling load was calculated by using design-builder simulation software. The simulation data sheet and construction details are shown in appendix D on page 208. According to results shown in the figure 6.26 on page 159, CAB has the highest cooling load. The cooling load was derived from the U value. New wall materials FSEB is the second highest energy consuming. CSEB and CB show some form or intermediate results. MCB and BB show the lowest cooling load.

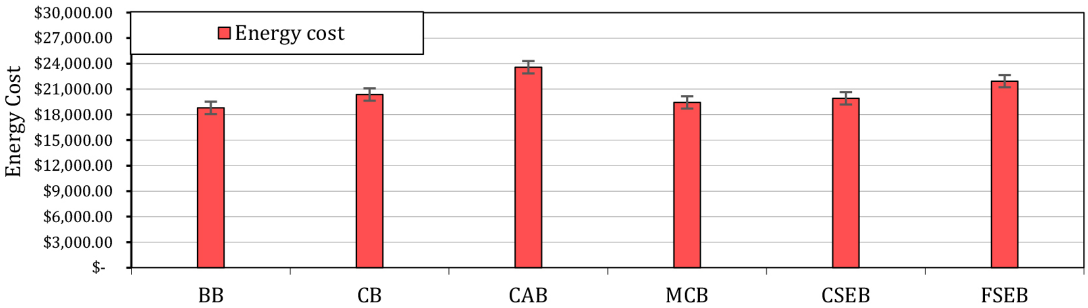



**Fig. 6.26** Cooling Load comparison

### 6.8.4 Re-usability and Resale value

Re-usability is a simple measure of the resale value of a masonry unit after the demolition of a building shown in figure 6.27 on page 159. For example, brick can be carefully removed from the wall and resale at a lower price. The resale value is depreciated by the material quality and appreciated by the money value. However, this is an important parameter to be considered when analyzing the life cycle cost. Re-usability and resell value indicates the resell value and reusability of different walling materials *(see the*

**Fig. 6.27** Measuring reusability of Mud concrete block

**Table 6.7** Comparison of re-usability and resale value

| | BB | CB | CAB | MCB | CSEB | FSEB |
|---|---|---|---|---|---|---|
| Re usability | 60% | 70% | 60% | 92% | 0% | 90% |
| Resale value | $ 1740 | $ 1106 | $ 800 | $r 969 | $ 0 | $ 2628 |

*Appendix G on page 212).* Usually, earth building does not have a second life. They all get back to earth after the demolition. However, MCB and FSEB have a second life. They can be demolished and used as a raw material to manufacture MCB and FSEB. According to the results shown in figure 6.28 on page 160 FSEB and BB has the highest resale value. Then CBA and CB can be sold at a similar price. Novel walling materials such as MCB has very low resale value. This is because MCB and FSEB cannot be removed from the constructed wall without damage to the block, unlike bricks, MCB and FSEB come in larger volume. Therefore, they cannot be used as the same application. Instead, they will be used as raw materials. The raw materials price is lower than a finished block.

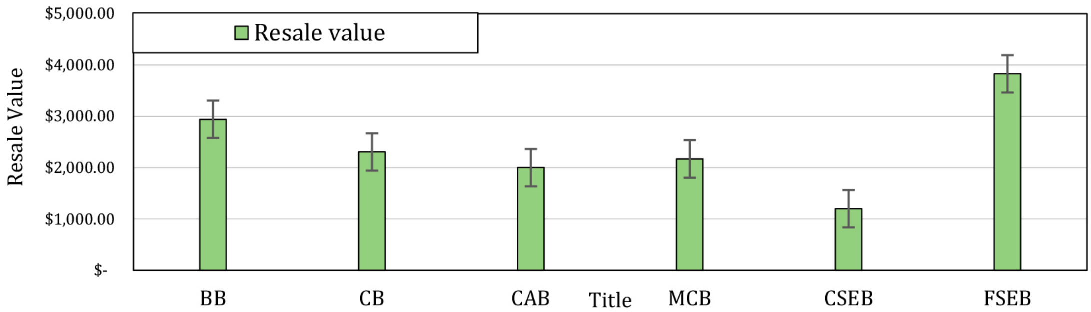



**Fig. 6.28** Re-usability and Resale value comparison

### 6.8.5 Carbon dioxide emissions

Carbon dioxide emission or the carbon footprint of selected walling materials were measured by converting the energy consumption into carbon shown in table 6.8 on page 161. The energy consumption included the embodied energy and operation energy consumption. According to the results, BB and MCB have the lowest carbon footprint. CSEB and CB show the second highest carbon footprint. FSEB consumes a lot of carbon since the production includes caustic soda. Caustic soda production itself consumes

**Table 6.8** Carbon dioxide emissions of different walling materials.

| Wall type | Energy MJ per blocks | Energy MJ per wall(10'X10') | Carbon (KgC) per block | Carbon (KgC) per wall(10'X10') |
|---|---|---|---|---|
| BB | 177871.71MJ | 178723.09MJ | 0.04kgC | 467.00kgC |
| HCB | 195220.58MJ | 132744.22MJ | 0.52kgC | 480.00kgC |
| CSEB | 33245.70MJ | 47810.49MJ | 0.05kgC | 170.81kgC |
| CABO | 31218.32MJ | 52750.50MJ | 0.10kgC | 244kgC |
| MCB | 28610.76MJ | 41145.00MJ | 0.04kgC | 147.00kgC |
| FSEB | 37880.65MJ | 54475.98MJ | 0.06kgC | 194.63kgC |
| CP | 318691.74MJ | 216700.96MJ | 0.85kgC | 783.59kgC |
| RCP | 223010.23MJ | 151640.36MJ | 0.60kgC | 548.33kgC |

a lot of carbon and waste environment. But the saving factor of utilizing fly ash cannot be included in the calculation, because, the carbon in the fly ash shall not go back to the source.

### 6.8.6 Environmental suitability of developed wall construction materials

Introduction of low-cost wall materials along shall not resolve modern day problems. The novel walling materials should be in line with environmental sustainability. Not only environmental but also should be in line with social economic sustainability. This study has introduced two new wall materials and a hand full of stabilizers. But the real suitable impact of those novel wall materials should be tested and evaluated. There is no straightforward method to evaluate the total sustainability. But the Emmanuel et al. (2005) has introduced a method of finding suitability index for wall materials. He has ranked several wall materials according to the total lifecycle.

### 6.8.7 Life cycle cost comparison

Life cycle cost comparison was done in order to understand the final impact of novel wall material against existing wall materials palette shown in figure 6.29 on page 162.. According to the results, CAB has the highest life-cycle cost. Because CAB has a very high cooling load, and reusability is very low. CB, BB, and FSEB show moderate LCC results. Interestingly, MCB has the lowest LCC. But the LCC does not give the large picture of application of these wall materials in a real-world context. Life-cycle cost

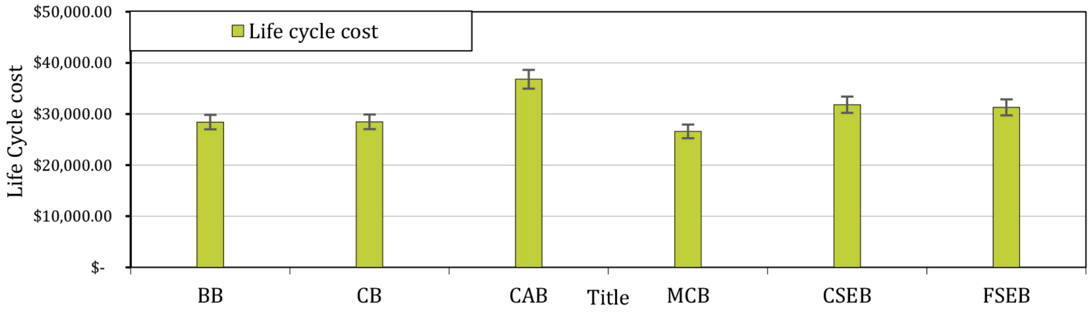



**Fig. 6.29** Life cycle cost comparison

analysis (LCC) is a method for assessing the total cost incurred during the total life of the building made of the above wall construction materials. It takes into account all costs of acquiring, owning, maintaining and disposing of reselling of a building or building system. But there are other features should be considered to make a conclusion such as surface decay mold growth and moss growth. Therefore, that para a mater should also be compared with other waling material prior to the conformity of novel wall material. It was assumed that the total lifespan of the building is sixty years and more than sixty-year lifespan building materials were multiplied by the reusability factor(*see the Appendix G on page 212*.

## 6.9 Suitability Index (SI)

The suitability index is a method of evaluating the suitability of a walling material. There is an important factor for wall materials such as strength etc. The strength is a basic parameter. Therefore, the strength was omitted and only string materials were taken into further consideration. The suitability rank was given considering all the aspects in a total life of a wall shown in table 6.9 on page 163. However, when it comes to real-world application, the weight of such indexing can be varied. For example, an architect may consider the aesthetic, features etc. rather than the initial cost. But for a low-income person, the initial cost and LCC could be an important parameter. For a housewife, mold growth and moss growth could be more important. Thus, there is a single method to generalize this suitability index and it will be another study. Nevertheless, this study uses only a single weight index was given. Where all the parameters such as surface erosion, moss growth, moss growth thermal performance, embodied energy carbon footprint and the life-cycle cost has equal value. The suitability index was developed by following equation (6.1) Then ranked all the wall materials against new wall materials introduced by this study.

$$Suitability\ Index = \frac{The\ value}{The\ value\ of\ the\ best\ case} \times 100 \tag{6.1}$$

**Table 6.9** Suitability index for new wall material

| Hierarchy of indexes | | BB | CB | CAB | MCB | CSEB | FSEB |
|---|---|---|---|---|---|---|---|
| 1 | Surface Erosion | 2 | 3 | 5 | 1* | 4 | 6 |
| 2 | Moss Growth | 6 | 3 | 5 | 2 | 4 | 1* |
| 3 | Thermal Performance | 1* | 6 | 2 | 4 | 3 | 5 |
| 4 | Initial cost | 6 | 3 | 2 | 1* | 4 | 5 |
| 5 | Embodied energy | 5 | 6 | 2 | 1* | 3 | 4 |
| 6 | Carbon foot print | 5 | 6 | 4 | 1* | 2 | 3 |
| 7 | Life cycle cost | 2 | 3 | 6 | 1* | 5 | 4 |
| | Overall Rank | 4 | 6 | 2 | 1* | 3 | 5 |

*The best case

The summary of the total study shows in table 6.9. This thesis has investigated for novel wall materials and novel stabilizer to build mud concrete block. Then to evaluate the suitability of using the mud concrete technology and alternative stabilizer technology in real-world applications. The overall results of this experiment show that MCB is a good alternative solution to replace expensive wall materials such as BB and CB. According to results shown in the table, 6.9 MCB has the lowest surface erosion, FSEB has the highest surface erosion. Surface erosion is a critical factor. Therefore, comparing other wall materials MCB is the best case. MCB and FSEB are the best against moss growth and mold growth. Therefore, they are suitable against bio receptivity. Obviously, brick is the best cooling wall materials and the CAB is the second. But MCB is in the third position next to CSEB. MCB and CAB have lowest embodied energy and carbon footprint. The overall all LCC shows that MCB is the lowest. However, the total study shows that MCB is much better wall material with cement as an alternative stabilizer. The new stabilizers such as geopolymerization need many improvements including cost optimization.

This part of the thesis and the study was launched to study against more generically from the base of the existing wall construction material palette. Therefore, the environmental fitness and life cycle cost study was conducted to understand the overall quality of novel wall materials. Finally, overall rank was given considering the best case scenario and found that mud concrete block is a suitable substitute for tropical wall construction. More studies need to be conducted to develop the mud concrete technology. The materials source and the environmental fitness should be taken into consideration in order to define the sustainability of a walling material. In addition, the social acceptability of the long-term use of mud concrete technology should be studied. This might need more than ten-year research and a real-world study must be conducted. The other limitation of the practicality of the walling materials were neglected.

This study was launched to develop an alternative wall construction masonry unit that is durable in tropical climate cost effective and practically manufactured. So far, this study has claimed that many stabilizers can replace cement. However, the focus should be to select the suitable stabilizer to build mud concrete block and improve the mud concrete technology. Mud concrete block has its own unique manufacturing process. This governs the final cost and the efficiency of the mud concrete block manufacturing process. The amount of labour (man hour) governs the speed of the production output. Manufacturing framework and Cost optimization of mud concrete block was developed and presented in the conference of science for people (Udawattha et al., 2016b).

In some cases, the by increasing labour can increase the production. But sometimes the increase in labour may decrease the efficacy of output. This is defined as labour depreciation. A number of moulds also define the total output per session. The number of devices can bring a number of blocks at a single time. Therefore, the number of moulds directly govern the efficiency of the Mud concrete block production. A number of sites are a variable factor whereas the number of sites per one mould can define the total cost of a block in terms of the mould cost.

## 6.10 Optimizing mud concrete block technology and technology transfer process

This study was launched to develop an alternative wall construction masonry unit that is durable in tropical climate cost effective and practically manufactured. So far, this study has claimed that many stabilizers can replace cement. However, the focus should be to select the suitable stabilizer to build mud concrete block and improve the mud concrete technology. Mud concrete block has its own unique manufacturing process. This governs the final cost and the efficiency of the mud concrete block manufacturing process. The amount of labour (man hour) governs the speed of the production output. Manufacturing framework and Cost optimization of mud concrete block was developed and presented in the conference of science for people (Udawattha et al., 2016b).

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#### 6.10.0.1 Mud concrete mould optimization

The mould is one of the key decision while programming for the optimum combination for the manufacturing mud concrete block. The main series of decision can be made according to a flowchart shown in chapter 1 figure 1.1. Figure 6.30 explains how the mould was optimized by considering the property of materials to the most of efficient combination of making a number of blocks from one mould. The number of blocks per one mould and number of blocks from one sheet was stimulated by using the optimization model by changing a number of moulds and numbers of sheet input-output scenario. The material, of course, decided by considering available technology. A general survey was conducted in order to understand the capability of each and every material in the market. Their pros and cons were analyzed accordingly.

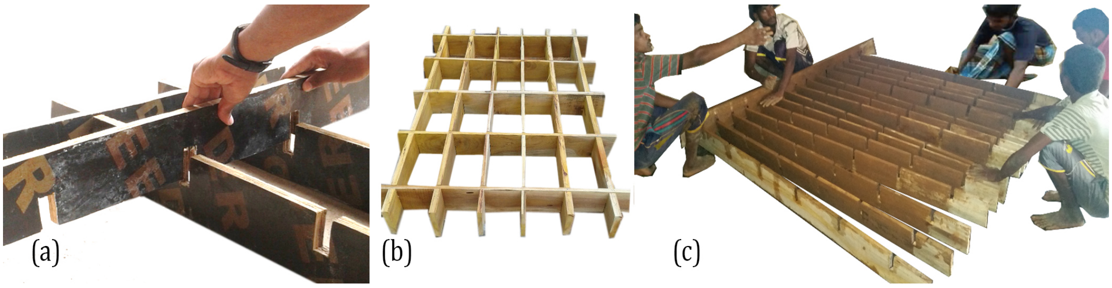


**Fig. 6.30** Experiments wooden Block mould

Steel was finalized as the best material for manufacturing Mud concrete block shown in figure 6.31. Suitable size width dimension was finalized after conducting a survey done within the construction community. The figure 6.31 explains how the material decision was done according to their pros and cons analysis. The most efficient method of manufacturing the mould was designed by using the 3d software in order to understand how this would look like in the real world and the practicality of it. The optimum size was measured by the optimum number of blocks (block efficacy) and the wastage of steel sheet.

One mould per one sheet was optimized by considering its ability to build mud concrete block with a minimum number of sheets. But the other combinations such as two moulds from one sheet, two moulds from two sheets and three moulds from two sheets was stimulated by using an excel programme made by the user. Finalizing mould was done by using sketch-up 3d model and cut-list plus for measuring cutting methodology and wastage of steel sheet. The price per one mould was measured considering the available market condition in the country. However, a mould manufacturing method and the process was carefully designed by considering the Sri Lankan Labour skills.

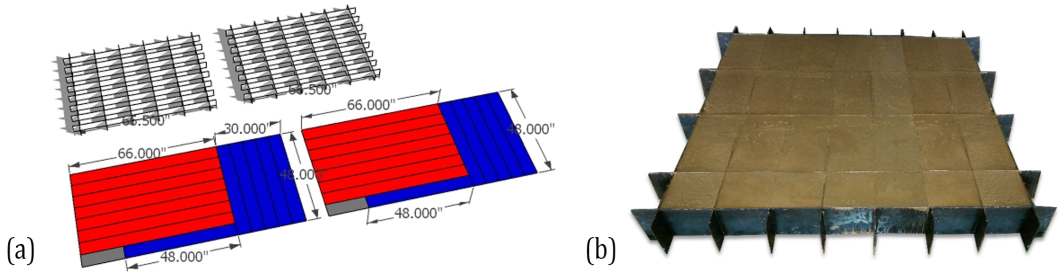


**Fig. 6.31** Optimized steel mould

Sri Lankan is not very much skilled with machinery based manufacturing. Therefore, a simple cut and joining system was used in order to build the mould.

Nevertheless, the final design for Mud concrete block size was optimized after conducting a questionnaire survey. The survey form is shown in Appendix D. Finally, the size of the mud concrete block was confirmed as 6X6X12 inches. Mud concrete block manufacturing was tested with a real-world scenario by producing the mould in a workshop. The design was changed slightly after understanding the practicality of the mould manufacturing as well as the block manufacturing process.

#### 6.10.0.2 Optimizing labour composition in manufacturing mud concrete block

Labour is a crucial factor for the manufacturing mud concrete block. Thus the manufacturing process of mud concrete block may not require skilled Labour but labour with firsthand experience would be better. The labour combination for the manufacturing mud concrete block was measured and optimized by using the scenario-based method as explained in the methodology section.

Linear optimization method was used to understand how the labour, the number of moulds and the number of the cycle can be optimized. The table 6.10 shows how the experiment was done in a real-world scenario. All the data were collected by a quantity surveyor and analyzed by using excel data sheet shown in Appendix D.

It was found that the effect also can be increased by employing more number of moulds and number of man hours into the scenario shown in table 6.10 on page 168. But the increase in labour and moulds always do not provide results. Because labour can

**Table 6.10** Labour composition optimization

| No of mould | labour | Total Labour Cost | Labour Cost Per Molt | No of Cycles | No of Blocks Per Day | No of days Needed | Total Labour Cost |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 1800 | 1800 | 4 | 128 | 20 | $234.37 |
| 2 | 2 | 1800 | 900 | 4 | 256 | 10 | $117.19 |
| 3 | 3 | 2700 | 900 | 1 | 96 | 26 | $468.75 |
| 4 | 3 | 2700 | 675 | 1 | 128 | 20 | $351.56 |
| 5 | 5 | 4500 | 900 | 4 | 640 | 4 | $117.19 |
| 6 | 5 | 4500 | 750 | 1 | 192 | 13 | $390.63 |
| 7 | 6 | 5400 | 771 | 1 | 224 | 11 | $401.79 |
| 8 | 6 | 5400 | 675 | 1 | 256 | 10 | $351.56 |
| 9 | 7 | 6300 | 700 | 1 | 288 | 9 | $364.59 |
| 10 | 7 | 6300 | 630 | 1 | 320 | 8 | $328.13 |

be idle in such a condition. However, the final optimum combination of manufacturing MCB if scenario one practice number four.

Table 6.10 explains the optimum number of the mould into labour combination. The mud concrete block manufacturing process can be increased by increasing the number of labour into a number of the mould by using the table five, such one mould per ten sites with two cycles per day employing three labours per cycle. Then, however, it was found that labour requires an enormous cost when manufacturing mud concrete block. Therefore, the efficiently managing labour is important when optimizing manufacturing process for mud concrete block. Thence the labour cost into total production was optimized by stimulation another process of calculating the total cost of two thousand five hundred mud concrete blocks.

The labour combination after increasing the number of moulds are five into five into four cycles per day. The cost can be minimized in large number in case of a mass production. Mass production is important for manufacturing mud concrete in mass scale. The experimental programme was conducted in Batticaloa shown in figure 6.32 on page 169.

However, as the table 6.11 on page 169 explains; the best combination of manufacturing mud concrete block in mass scale is the two labours per two mould and using

**Fig. 6.32** Manufacturing mud concrete block

five moulds per cycle. After understanding how labour response in increasing number of mould, the methodology of the manufacturing mud concrete block was finalized. The extended presentation of the mud concrete block manufacturing process was developed into a one-page document whereas the entire process can be identified. The whole concept of this development is to illustrate this idea of the low-cost mud concrete block manufacturing process to the general public.

**Table 6.11** Scenario base study to optimize MCB manufactruing process

| Senario | No. of moulds | No. of labours per site | Production cost for a block ($) | Possible saving compared to the current practice ($) |
|---|---|---|---|---|
| Current practice | 1 | 2 | $0.21 | |
| Senario 01 | 2 | 2 | $0.18 | $80.00 |
| | 2 | 2 | $0.13 | $200.00 |
| | 2 | 2 | $0.09 | $296.00 |
| Senario 02 | 3 | 2 | $0.20 | $26.67 |
| | 3 | 2 | $0.13 | $206.67 |
| | 3 | 2 | $0.07 | $344.00 |
| Senario 03 | 3 | 3 | $0.22 | $(40.00) |
| | 3 | 3 | $0.15 | $140.00 |
| | 3 | 3 | $0.09 | $284.00 |

### 6.10.0.3 Manufacturing mud concrete block

After optimizing the best labour combination for the manufacturing mud concrete block, the methodology of building mud concrete block was optimized. The previous research was used to optimize the best sieve size and cement combination for building mud concrete block. The process starts with extracting suitable soil for the manufacturing mud concrete block. Not all the soil suitable for the manufacturing mud concrete block. The soil can be tested by using a sieve test and should be done in a lab by doing some sample testing. The University of Moratuwa has the capacity of testing soil and inform its suitability of the soil for manufacturing Mud concrete blocked concrete block. Then the extracted soil was mixed with cement in order to process. The proper mixture was added with water and pour to the mould made of steel sheets or wooden sheets. Using steel sheets 28 number of blocks can be made at once.

After moulding mud concrete it should dry another six days. It should be in a dry place where the drying process plus chemical reactions should happen at the same time. Within this period of time, as same as the concrete water ratio should be poured into the mud concrete blocks. Mud concrete block is an obvious low-cost product that could replace the existing use of brick and cement block. The cost optimization was done after doing a series of experiments using scenario-based optimization techniques. The experiments were done in a real-world context by using real man hours and real materials in order to understand how the "economics of scale" work.

The manufacturing mould was optimized by using a series of optimization linear calculations. It proved that 28 blocks can be made by using one steel sheet. Two blocks per two sheets are the best combination for building a mould. After optimization the mud concrete block moulds, the manufacturing framework was introduced. The process was simulated and optimized into seven step diagram of the manufacturing mud concrete block. It can be simple as building cement blocks or Bricks. But the cost saving is greater in value considering less complicated process added into the mud concrete block production process. A proper costing calculating sheet was developed by using stimulation and optimization data collected. In addition, it was found that mud concrete block size of (200mmX150mmX300mm) can be manufactured at a price of 0.07$ while the same size of cement block is 0.23$ [1]. It's a 70% cost saving for construction of the wall in similar calibre.

[1]One dollar (1$ is equal to Rs.150.00) based on the time of the study

### 6.10.1 Innovation and mass production of mud concrete block

After the development of mud concrete technology, an experiment yard was located to understand the technical issues. In this study, a real-world experimental method was used to identify and rectify issues of the mud concrete manufacturing process. First, a shed was fixed at the location to start manufacturing if mud concrete block. Then the mould was developed according to mould development made by the previous study. Even though the study shows that mould size should be optimized according to sheet cutting. The real-world manufacturing was done considering the transportable quality of the mould. This was an interesting solution given by the real-world manufacturing that the mould should be 4 feet by 4 feet to transport the mould by using a three-wheeler.

Then untrained workers have explained the task of manufacturing mud concrete by the given technology. Instead of using hand mixing, concrete mixture and fan mixture was introduced to the experiment yard. Found that fan mixture does not suit to mixing mud mixture because of the swell properties of the mud mixture. The mud mixture was attached to the pan mixture. Then a concrete mixture was introduced to the site and found that the mixing with concrete mixture needs more time than hand mixing. Therefore, for small-scale manufacturing, it was concluded to manufacture by using hand mixing at the site.

After manufacturing mud concrete by using a typical steel mould and found that mould dismantling process cost and time. People those who have participated in the manufacturing optimization process complained that the mould removing takes time and delay the total manufacturing time. Therefore, another study was conducted to develop a machine for manufacturing mud concrete blocks. This was started with a series of literature showing experimental machines to build bricks in India. After studying many machines, this study has come up with a new machine for building mud concrete. Block. The use of steel and single mould to manufacturing mud concrete block shown in figure 6.33.

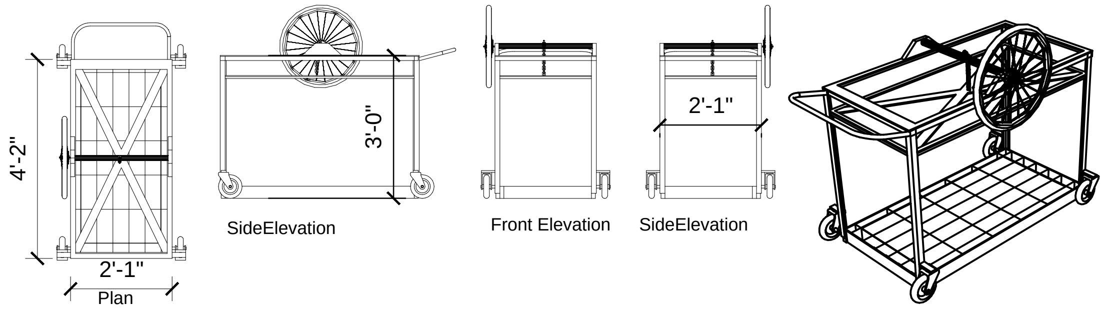


**Fig. 6.33** Single mould and small scale machine developed to manufacturing mud concrete block


**Fig. 6.34** Technology transferring to Sri Lankan community

### 6.10.2 Technology transferring to Sri Lankan community

After optimizing the mud concrete block technology, several campaigns were conducted with the help of UN-Habitat to transfer the knowledge to low-income people in the country. The knowledge transferring was conducted at the centre of the village shown in figure 6.34 on page 172 to build an affordable house for poor people in the country. First, need villages in need of houses were selected to transfer the knowledge to poor people. The series of presentation and workshops were conducted to transfer the knowledge of manufacturing mud concrete blocks.

At the same time, feedback from community craftsmen was noted down to develop the technology more. After conducting workshops, villagers started manufacturing mud concrete blocks by using the mould given by us. An average village manufactured around a thousand blocks per day.

**Fig. 6.35** Technology transferring to villagers to build their houses

## 6.11 Summary

Mud concrete block technology is a demonstrable low-cost product that can replace the existing wall construction technology. The cost optimization was done after doing a series of experiments using scenario-based optimization techniques. The experiments were done in a real-world context by using real man hours and real materials in order to understand how the economics of scale work. The manufacturing mould was optimized by using a series of optimization linear calculations. With the help of University and another organization, the study has launched several public awareness campaigns to build low-income people houses out of mud concrete. Both author and the supervisor visited village centres and demonstrated the way to manufacture mud concrete block shown in figure 6.35 on page 173.

## CHAPTER 7

# CONCLUSIONS

Earth constriction had been practised since prehistoric time. In earth construction, the main raw material is soil. The soil has this weakness of fragile, shrink-swell etc. A stabilizer is needed to convert geotechnical properties into engineering property. Mud concrete an engineering wall construction block invented by the University of Moratuwa. In mud concrete, the precise gravel percentage governs the strength. Cement in this mud concrete used as a stabilizer. Using cement as a stabilizer for this concrete has abounding issues including its cost, availability, embodied energy etc. Therefore, this study was conducted to find an alternative stabilizer for mud concrete and to replace cement. Secondary, this study was extended to develop the mud concrete technology by looking at the industrial scaled wall construction materials. The production method and manufacturing framework were optimized.

A literature survey has found that there are a series of alternatives. They were subjected and categorize into three sections based on literature such as mechanical soil stabilization, chemical soil stabilization and polymeric soil stabilization. However, mechanical soil stabilizers such as manual compaction, machine compaction and self-compaction; chemical soil stabilizers such as cement soil stabilization, fly ash, rice husk ash, bottom ash etc. and polymeric soil stabilizers such as latex rubber soil stabilizer, resin stabilizers etc. In addition, the literature showed that fibre soil stabilization could be implemented only if the fibres mixed with soil properly.

After the literature survey, an inventory of soil stabilizers were selected for experiments based on the availability, practicality and the cost. For further experiments, self-compaction from mechanical stabilization, waste ashes such as fly ash, bottom ash and rice husk ash from chemical soil stabilizers and polymeric soil stabilizers such as natural rubber latex, pines resin, jack resin, beal resin dawulkurudu polymer and wood apple resins were selected. Then they were experimented to understand the strength gain after stabilizing selected red podzolic soil 600mm below the surface of the earth. A systematic approach and experimenting method were developed and used to identify a suitable soil stabilizer.

The study found that the self-compaction is a method of user-friendly soil compaction method categorized under mechanical soil stabilization. Waste ashes such as fly ash, bottom ash and rice husk ash do not stabilize earth. Polymer soil stabilizers such as natural rubber latex stabilize soil and gain the strength up to the standard. But the study found there are many drawbacks to use natural rubber latex. Pines resin, sugarcane bagasse and dawul kurudu also gain the strength.

However, based on the initial experiment, fly ash was selected for further experiment, because of the availability in Sri Lanka, fly ash is already a huge environmental issue in the country and fly ash has many similarities to cement. The study has found that alkaline activating fly ash can make stronger mud concrete unit than cement stabilized mud concrete. Fly ash cementitious property can be improved by developing its chemical reactivity called polymerization which is finally developed a geopolymerized mixture. Geopolymerization of mud mixture is an alternative method to alkaline activation of fly ash into the cementitious material. However, in this process, powdered aluminosilicate is combined with an alkaline activator such as NaOH.

The chemical reaction changes the properties of the fly ash and soil and creates a bond between soil particles. The bonding created to make mud earth blocks as load bearing wall construction unit. It was found that geopolymerized self-compacting mud block can be manufactured with 75 - 85% of soil, 15- 25% of fly ash, base chemical to improve the pH 10 -12; 2% of sodium chloride mixed with water and then by pouring the mixture into the moulds, without any compaction and then sun-dried or heat cured.

Novel wall construction technology and stabilizers were subjected to a comparative study against more generically from the base of existing wall construction material palette. Found that environmentally irresponsible, scarce, extravagant and labour-intensive wall construction technologies such as brick, cement block, and compressed earth block technology can be replaced with mud concrete technology. But there are several drawbacks in the novel wall construction technology. The first is the surface decay and high-water absorption. Fly ash stabilized mud concrete block should only have manufactured by using machines. The effect of chemicals used to manufacture fly ash stabilized mud concrete block are harmful.

The study has found that the cost of the novel wall units is comparatively lower. Not only the cost but also the total life-cycle cost is comparatively low. The genesis of mud concrete technology and the optimized mud concrete block manufacturing process have established a new wall construction technology in Sri Lanka. This has already accommodated a new technology transformation in the country.

## 7.1 Limitations

The reaction mechanism of geopolymerization is still not clear. There are a few experimental facilities to study the chemical formation of geopolymer. Most of the life cycle and durability studied were tested by using accelerated tests and simulations. There is a limited time to understand the durability of this novel wall construction materials.

## 7.2 Recommendation and future research

Many different expensive stabilizing technologies, tests, and experiments have been left for the future due to lack of time, super expensive and exorbitant (i.e. chemical enhancement of soil, synthetic polymeric soil stabilization). Future work concerns to develop the geopolymer mud concrete block into the industrial scale manufacturing process. There are some ideas to use machines to do the total manufacturing process of the geopolymer mud concrete block. A deeper analysis of particular practical uses, new proposals to try different methods following ideas could be tested and explored:

- 3D printing geopolymer mud concrete mixture
- In-situ casting or rammed earth geopolymer structure to build a wall.
- To build internal confined structures by using geopolymer technology

Further research should discover potential applications of geopolymer mud concrete technology. For an instant, the same mix can be used to make rammed earth structures. This would lead to research areas that are specifically oriented towards applications such as low-cost house construction. The geopolymer mud technology has the potential to go beyond making houses, this can be used in road construction and many other infrastructure developments. However, there are other stabilizing technologies tested in this study. The polymeric soil stabilization should be further studied. Natural rubber latex is a good stabilizer for the soil to build earth blocks. The tensile quality of earth blocks can be enhanced by using natural rubber latex.

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# LIST OF PEER-REVIEWED JOURNAL PROCEEDINGS

JOURNAL PROCEEDINGS


1. Udawattha, C., De Silva, D. E., Galkanda, H., Halwatura, R. (2018). Performance of natural polymers for Stabilizing earth blocks. Materialia. doi.org/10.1016/j.mtla.2018.07.019

2. Udawattha, C., Galkanda, H., Ariyarathne, I. S., Jayasinghe, G., and Halwatura, R. (2018). Mold growth and moss growth on tropical walls. Building and Environment. doi: 10.1016/j.buildenv.2018.04.018

3. Udawattha, C., and Halwatura, R. (2018, may). Geopolymerized Self-Compacting Mud concrete masonry units. Case Studies in Construction Materials. doi: 10.1016/ j.cscm.2018.e00177

4. Udawattha, C., and Halwatura, R. (2017b). Life cycle cost of differentWalling material used to build affordable housing in tropics. Case Studies in Construction Materials, 7(November 2016), 1529. doi: 10.1016/j.cscm.2017.04.005

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CONFERENCE PROCEEDINGS

1. A Study on Natural Rain Surface Erosion of Different Walling Materials in Tropics in Moratuwa Engineering Research Conference.
2. Fly Ash-based Geopolymer Mud Concrete Block in Moratuwa Engineering Research Conference.
3. Character of Lime as an Alternative Stabilizer to Improve the Long-Term Strength of Mud Concrete Block, in 8th International Conference on Structural Engineering and Construction Management, ICSECM2017, 2017.
4. Use of fly ash as alternative stabilizer for Mud Concrete Block. International Conference on Sustainable Development
5. Comparative Study of Embodied Energy in Different Walling Materials. In Proceedings of the International Forestry and Environment Symposium in Department of Forestry and Environmental Science, University of Sri Jayewardenepura
6. Investigation on Elements and their Fraction of Building Construction Cost, in Moratuwa Engineering Research Conference
7. New Earth Walling Material: Integrating Modern Technology into Ancient Mud Wall
8. The Energy content of walling materials- A comparison of Mud-Concrete Blocks, Bricks, Cabook and Cement Blocks on tropics,
9. Life cycle cost and energy analysis of an Affordable house in Sri Lanka

10. The embodied energy and life cycle costing: A case study on basic dwellings in Sri Lanka, in National Green Conference 2016 at University of Kelaniya

11. Manufacturing framework and Cost optimization for Building Mud concrete Blocks MCB, in Mobilization Modern Technologies for Sustainable Development in Asia

BOOK PUBLICATIONS

1. Chameera Udawattha and Rangika Halwatura (November 5th 2018). Alternative Stabilizer for Mud Concrete, Cement Based Materials, Hosam El-Din M. Saleh and Rehab O. Abdel Rahman, IntechOpen, DOI: 10.5772/intechopen.76065.

PATENTS

1. Fly Ash stabilized mud concrete block for load-bearing walls - Patent Number 19495.

2. Rubber stabilized earth blocks for load-bearing walls - Patent number 19379.

3. Geopolymerized self-compacting mud block - Patent number 19567.

RESEARCH AWARDS

1. 2018 Elsevier Foundation Green and Sustainable Chemistry Challenge Top 50 No 13 in the world.

2. 2018 First author younger than 35 years old who has been accepted for publication in Building and Environment.*C. Udawattha, H. Galkanda, I.S. Ariyarathne, G.Y. Jayasinghe, R. Halwatura, Mold growth and moss growthmoss growth on tropical walls, Building and Environment*

3. 2017 Best Research Paper Award Udawattha, C., Dilshan, P., and Halwatura, R. Use of fly ash as alternative stabilizer for Mud Concrete Block. International Conference on Sustainable Development, (August), 8—12.

4. 2016 The Presidents Awards for Scientific Publication are given to Sri Lankan scientists with a local institutional affiliation who achieve a publication in the top 15% of Science Citation Index Expanded journals (ranked on their Impact Factor under each journal category based on SCI categorization of journals) *C. Udawattha, R. Halwatura, Embodied energyEmbodied energy of mud concrete block (MCB) versus brick and cement blocks, Energy and Buildings*

# Appendices

# Appendix A

# Inventory of possible soil stabilizers

| | Name of stabilizer | Chemical Formula | Available sources | Uses and properties | Production Method |
|---|---|---|---|---|---|
| **Mechanical soil stabilizers** | Manual soil compaction E.g. Rammed earth | Mechanical soil stabilization doesn't change the chemical composition of the soil. Instead the particle distribution and the morphology of the soil changes. | The compaction can be made by using timber post on soil mixture poured into a wooden structure. | Manuel soil compacting technology has many applications in the world. 1. Rammed earth 2. Cement stabilized earth blocks(CSEB) 3. Compressed earth blocks |  |
| | Mechanical soil particle vibration | | The mechanical vibration can be introduced and the vibration can improve the density of the soil mixture. | Engineering bricks are produced after introducing mechanical vibration to improve the density of the block. |  |
| | Self-compaction method | | The self-compacting technology is to optimize the soil moisture mixture to make self-compacting nature to improve the density to gain the strength. | Self-compacting soil stabilization has a rare application such as road construction etc. However, the Mud concrete block mixture with cement was developed along with this idea of self-compacting soil mixture. |  |
| **Chemical soil stabilizers** | Lime | $CaCO_3$ | Industrial and natural | Use as construction and food source. | The limestone is burnt in a rotary or shaft kiln and produce lime |
| | Fly Ash | pulverized fuel ash | Any coal combustion plant | Land Fill, dump | Coal combustion process produces tons of fly ash per day even in Sri Lanka |
| | Bottom Ash | SiO2 Al2O3 Fe2O3 CaO K2O TiO2 MgO SO3 - Na2O P2O5 BaO | Ash that falls in the bottom of the boiler is called bottom ash. In modern coal-fired power plants | Bottom ash is part of the non-combustible residue of combustion in a furnace or incinerator | Stuck in the furnace and taken out more than four lorries per day in Lakvijaya power plant |
| | Rice husk Ash | $SiO_2$,$Al_2O_3$,$Fe_2O_3$ CaO, MgO,$K_2O$ $Na_2O$,$P_2O5$ | Rice husk ash is a by-product of rice production process. Rice husk ash is available in large quantize. | Increases the electrochemical stability of the film, uses as a filler for the earthling process. | Rice husk is produced after firing rice husk into burning temperature. Fired rice husk ashes are spread into the paddy field without any use. |
| | House fire Ash | SiO2 Al2O3 Fe2O3 CaO K2O TiO2 CaO, MgO,$K_2O$ MgO SO3 - Na2O P2O5 BaO | House fire ash is available at any house to use dry wood as a source of heat for their cooking. | There are no essential uses for house ash except use to develop fertilizers for the garden | House fire ash is a by production after the cooking process. Thus there are many other methods of house ash production such as bakeries, many industries used firewood as a heating source. |
| | Industrial sludge | Sleds are industrial wastes composed with many chemical formations. | Industrial sludge is available in many industries such as rubber, farm oil, food industries etc. | Most of the there is no particular use for these industrial sludge except use them as landfills and garbage dumps. | There are many production methods for sludge in Sri Lanka. Most of the sludge production is due to using of additional chemicals. |

**Fig. A.1** Inventory of mechanical and chemical soil stabilizers

| Name of stabilizer | Chemical Formula | Available sources | Uses and properties | Production Method |
|---|---|---|---|---|
| Rubber Latex (Muhammad & Ismail, 2012) | Polyisoprene | Can be collected from rubber plants | Used in many applications and products in combination with other materials | Can be used with Sulphur to stable and create longer bonds between the rubber materials. |
| Pines Gum | Pinene | obtained from pines | Used as stabilized in many civilizations | Pines resins are generally produced as stem secretions |
| Lignin | carboxymethyl lignin | sugarcane bagasse | Stabilizing agent in aqueous ceramic suspensions | Using ethanol-water as the solvent and sulfuric acid with 70c for 30 mints. |
| Molasses | $C6H12NNaO3S$ | sugarcane bagasse | Soil Stabilization | Molasses made from sugar beets differs from sugarcane molasses. Only the syrup left from the final crystallization stage is called molasses |
| Dawul Kurudu (Neolitsea cassia) | | Mixed with silt/clay/ lime and used as a plaster material and a paint material | | Leaves were collected from trees and then squeezed by a compressive to collect the resin. |
| Bael Resin (Aegle marmelos) | | Used as a polymer to stabilizer painting walls, mixed with lime and build ancient putty. | | Fruits are collected from the trees and then their core is collected as a polymer. |
| Jack Resin (Artocarpus heterophyllus) | | Used as ancient paint mixture and used as adhesive in prehistoric time. Mixed with charcoal and painted. | | generally produced as stem secretions |
| Agarwood Resin(Aquilaria malaccensis) | | Applied as a varnish for ancient woodwork and temple carvings in front of god statues | | Produced from dried timber wood |
| Wood Apple Resin(Limonia acidissima) | | Used as an earth stabilizer for temple paint walls. | (complex mixture of vitamins, polyphenols, esters, aldehydes, sugar, mineral salts, organic acids and amino acids) | generally produced as stem secretions |
| Sugarcane Bagasse (Saccharum officinarum) | | Stabilizing agent in aqueous ceramic suspensions | | Using ethanol-water as the solvent and sulfuric acid with 70c for 30 mints |
| Hydrophilic polymer | | Aegle marmelos | | concentrations used in the formulation were 2, 4, 6 & 8 \% w/w of cordial fruit gum |

Polymer soil stabilizers

**Fig. A.2** Inventory of polymer soil stabilizers

| | Name of stabilizer | Image | Availability | Cost per one Kg ($) | Remarks |
|---|---|---|---|---|---|
| Mechanical stabilization | Self-compaction method (SCM) |  | The idea is to make an optimum liquid ratio to compact the mix itself. | Self-compacting soil doesn't involve any cost except mixing with optimum water ratio. | self-compacting soil mixture (mud mixture) commonly call as SCM is an optimized mix design which has the optimum moisture ratio low yield, high deformability with good segregation |
| Chemical soil stabilizers | Lime |  | Lime is available in larger quantities, but the production cost to the environment. | 1.2$ | Lime is a by-product of limestone. Therefore, using limestone has similar carbon footprint as the cement. |
| | Fly Ash |  | Available in large quantities and waste product from Lakvijaya power plant (per day production is more than 1 ton) | There is no cost involved in fly ash except transport cost 0.1$ | Fly ash can be a suitable solution since fly ash is waste from the coal combustion process. Using fly ash as an alternative stabilizer can be a win-win study for the country. |
| | Bottom Ash |  | Available in larger quantities and bottom ash also produced by some other industries such as bakeries etc. | There is no cost involved in fly ash except transport cost 0.9$ | Bottom ash has a single weakness of changing properties of the bottom ash from one location another considering the coal combustion process. |
| | Rice Husk Ash |  | At the current situation, rice is grown over the hundred countries and produces more than 715 million tons of paddy rice annually (480 million tons of milled rice). | There is no cost involved in fly ash except transport cost 0.1$ | RHA, which is the main raw material, was collected from a bricks furnace located in Beliatta area (Mahalla). This RHA was sieved by using a 1.18mm sieve |
| Polymer soil stabilizers (Natural)[1] | Rubber Latex |  | Can be collected from rubber plants | 0.6$ / litre | Rubber latex is produced in large quantities. Therefore, the available materials. |
| | Pines Gum |  | Pines resins are generally produced as stem secretions | 1.8$ /litre | Pines resins are produced in larger quantities, pines resin uses to produce many chemicals. |
| | Jack Resin (Artocarpus heterophyllus) |  | Difficult produce in large quantities | 2.2$ | Rarely found in larger quantities except in Ayurveda productions. |
| | Wood Apple Resin |  | sugarcane bagasse | 5.7$ | Generally produced as stem secretions and its very rare materials to produce. |
| | Dawul Kurudu (Neolitsea cassia) |  | Leaves were collected from trees and then squeezed to collect the resin. | 0.5$ | Leaves were collected from trees and then squeezed by a compressive to collect the resin. |
| | Agarwood Resin(Aquilaria malaccensis) |  | Produced from dried timber wood | 35$ | Agarwood is a very expensive resin. Therefore, these are not suitable as a stabilizer. |
| | Bael Resin (Aegle marmelos) |  | Produced from Bael fruit, but very expensive to collect | 2.7$ | Fruits are collected from the trees and then their core is collected as a polymer. |

**Fig. A.3** Selected soil stabilizers for further studies

## Appendix B

# Soil sieve analysis and mix design

**Table B.1** Selected soil Sieve analysis

| | | | | | MIX A | | MIX B | | MIX C | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sieve Number | Diameter (mm) | Mass of Sieve (g) | Mass of Sieve and Soil (g) | Soil Retained (g) | Soil Retained (%) | Soil Passing (%) | Soil Retained (%) | Soil Passing (%) | Soil Retained (%) | Soil Passing (%) |
| 0 | 20.00 | 2750 | 3050 | 300.0 | 1.0 | 99.0 | 0.5 | 99.5 | 0.3 | 99.8 |
| 1 | 16.00 | 2850 | 3250 | 400.0 | 1.5 | 98.5 | 1.0 | 99.0 | 0.5 | 99.5 |
| 2 | 14.00 | 2550 | 2750 | 200.0 | 2.5 | 97.5 | 1.5 | 98.5 | 0.8 | 99.3 |
| 3 | 10.00 | 2500 | 2700 | 200.0 | 5.0 | 95.0 | 4.5 | 95.5 | 2.5 | 97.5 |
| 4 | 8.00 | 2700 | 3050 | 350.0 | 10.0 | 90.0 | 7.5 | 92.5 | 3.5 | 96.5 |
| 5 | 4.75 | 2950 | 3700 | 750.0 | 15.0 | 85.0 | 10.0 | 90.0 | 7.5 | 92.5 |
| 6 | 3.35 | 603.8 | 1093 | 489.2 | 15.0 | 70.0 | 11.5 | 78.5 | 10.0 | 82.5 |
| 7 | 2.80 | 578.2 | 759.3 | 181.1 | 13.0 | 57.0 | 12.0 | 66.5 | 12.5 | 70.0 |
| 8 | 1.70 | 528.8 | 953.1 | 424.3 | 12.0 | 45.0 | 13.0 | 53.5 | 15.0 | 55.0 |
| 9 | 1.18 | 509.7 | 809.1 | 299.4 | 8.0 | 37.0 | 16.5 | 37.0 | 20.5 | 34.5 |
| 10 | 0.710 | 483.9 | 900 | 416.1 | 12.0 | 25.0 | 17.0 | 20.0 | 22.0 | 12.5 |
| 11 | 0.600 | 467.9 | 620.4 | 152.5 | 0.0001 | 25.0 | 0.0001 | 20.0 | 0.0001 | 12.5 |
| 12 | 0.425 | 452.3 | 558.4 | 106.1 | 0.0002 | 25.0 | 0.0002 | 20.0 | 0.0002 | 12.5 |
| 13 | 0.355 | 442.4 | 483 | 40.6 | 0.0500 | 24.9 | 0.0500 | 19.9 | 0.0500 | 12.4 |
| 14 | 0.300 | 432.6 | 452.3 | 19.7 | 0.1000 | 24.8 | 0.1000 | 19.8 | 0.1000 | 12.3 |
| 15 | 0.250 | 422.8 | 449.5 | 26.7 | 0.2000 | 24.6 | 0.2000 | 19.6 | 0.2000 | 12.1 |
| 16 | 0.212 | 418.5 | 436.6 | 18.1 | 0.3000 | 24.3 | 0.3000 | 19.3 | 0.3000 | 11.8 |
| 17 | 0.150 | 406.3 | 436.1 | 29.8 | 0.4000 | 23.9 | 0.4000 | 18.9 | 0.4000 | 11.4 |
| 18 | 0.075 | 364 | 389.7 | 25.7 | 0.6000 | 23.3 | 0.6000 | 18.3 | 0.6000 | 10.8 |
| 19 | 0.050 | 362.73 | 383 | 20.3 | 0.7000 | 22.6 | 0.7000 | 17.6 | 0.7000 | 10.1 |
| 20 | 0.025 | 347.36 | 365.01 | 17.7 | 0.8000 | 21.8 | 0.8000 | 16.8 | 0.8000 | 9.3 |
| 21 | 0.010 | 331.99 | 347.02 | 15.0 | 0.9000 | 20.9 | 0.9000 | 15.9 | 0.9000 | 8.4 |
| Pan | | 541.8 | 544.6 | 2.8 | 0.9000 | 0.0 | 0.9000 | 0.0 | 0.9000 | 0.0 |
| | | | TOTAL: | 4485.1 | 100.0 | | 100.0 | | 100.0 | |
| | | | | % Gravel: | 35.0 | % Gravel: | 25.0 | % Gravel: | 15.0 | |
| | | | | % Sand: | 60.0 | % Sand: | 70.0 | % Sand: | 80.0 | |
| | | | | % Fines: | 5.0 | % Fines: | 5.0 | % Fines: | 5.0 | |

## Appendix C

# Rubber stabilized earth block experiment data

**Table C.1** NRL stabilized block weight loss

| Blocks | | Drying weight (g) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 d | 1 d | 2 d | 3 d | 4 d | 5 d | 6 d | 7 d | 8 d | 9 d | 10 d | 11 d | 12 d | 13 d | 14 d |
| 0% | 1548 | 1552 | 1524 | 1528 | 1532 | 1534 | 1525 | 1522 | 1519 | 1517 | 1514 | 1510 | 1507 | 1503 | 1500 |
| 1% | 1493 | 1499 | 1471 | 1475 | 1481 | 1483 | 1475 | 1473 | 1471 | 1469 | 1466 | 1463 | 1461 | 1459 | 1456 |
| 2% | 1525 | 1531 | 1504 | 1508 | 1515 | 1516 | 1509 | 1507 | 1506 | 1504 | 1502 | 1499 | 1497 | 1495 | 1493 |
| 3% | 1486 | 1495 | 1460 | 1471 | 1478 | 1474 | 1469 | 1466 | 1464 | 1461 | 1459 | 1456 | 1454 | 1451 | 1448 |
| 4% | 1494 | 1452 | 1426 | 1335 | 1341 | 1336 | 1283 | 1252 | 1220 | 1189 | 1157 | 1122 | 1089 | 1089 | 1089 |
| 5% | 1513 | 1522 | 1477 | 1468 | 1450 | 1492 | 1482 | 1478 | 1474 | 1470 | 1466 | 1459 | 1456 | 1456 | 1456 |
| 6% | 1548 | 1552 | 1524 | 1517 | 1505 | 1288 | 1282 | 1282 | 1281 | 1281 | 1281 | 1185 | 1150 | 1150 | 1150 |
| 7% | 1493 | 1499 | 1471 | 1465 | 1453 | 1246 | 1239 | 1238 | 1238 | 1237 | 1237 | 1145 | 1112 | 1112 | 1112 |
| 8% | 1525 | 1531 | 1504 | 1498 | 1488 | 1280 | 1275 | 1274 | 1273 | 1272 | 1272 | 1182 | 1148 | 1148 | 1148 |
| 9% | 1486 | 1495 | 1460 | 1454 | 1441 | 1319 | 1307 | 1303 | 1300 | 1296 | 1293 | 1232 | 1207 | 1207 | 1207 |
| 10% | 1494 | 1452 | 1426 | 1390 | 1356 | 1328 | 1313 | 1309 | 1304 | 1299 | 1294 | 1242 | 1222 | 1222 | 1222 |

**Table C.2** Weight loss during curing time

| | | | | A | | | | B | | | | C | | | | D | | | | E | | | | F | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (mm) | | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) |
| R4% | Initial | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 |
| | New | 92 | 93 | 96 | 821.4 | 92 | 93 | 94 | 804.3 | 93 | 94 | 94 | 821.7 | 95 | 94 | 97 | 866.2 | 93 | 94.5 | 93.5 | 821.7 | 93 | 95 | 93.5 | 826.1 |
| R6% | Initial | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 |
| | New | 91 | 92.5 | 91.5 | 770.2 | 94 | 91 | 94.5 | 808.4 | 94 | 93 | 91 | 795.5 | 94 | 94 | 96.5 | 852.7 | 93 | 93 | 92 | 795.7 | 96 | 94 | 97 | 875.3 |
| R8% | Initial | 98 | 106 | 101 | 1049.2 | 102 | 105 | 101 | 1081.7 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 | 100 | 100 | 100 | 1000.0 |
| | New | 91 | 91 | 92 | 761.9 | 91 | 91 | 93 | 770.1 | 91 | 91.5 | 87 | 724.4 | 90 | 89 | 90 | 720.9 | 90 | 90 | 89 | 720.9 | 90 | 92 | 91 | 753.5 |
| R10% | Initial | 101 | 101 | 101 | 1030.3 | 98 | 104 | 101 | 1029.4 | 100 | 104 | 101 | 1050.4 | 100 | 107 | 101 | 1080.7 | 100 | 106 | 101 | 1070.6 | 99 | 106 | 101 | 1059.9 |
| | New | 91.5 | 92 | 89 | 749.2 | 92 | 88 | 95.5 | 773.2 | 90 | 92 | 94 | 778.3 | 90 | 90 | 95 | 769.5 | 90 | 91 | 98 | 802.6 | 91 | 92 | 91 | 761.9 |
| | | A1 | | | | B1 | | | | C1 | | | | D1 | | | | E1 | | | | F1 | | | |
| (mm) | | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) | X | Y | Z | V (cm3) |
| S2% | Initial | 101 | 101 | 104 | 1060.9 | 100 | 102 | 104 | 1060.8 | 100 | 102 | 104 | 1060.8 | 101 | 102 | 104 | 1071.4 | 100 | 101 | 104 | 1050.4 | 100 | 103 | 104 | 1071.2 |
| | New | 89 | 92 | 92 | 753.3 | 92 | 91.5 | 89 | 749.2 | 89 | 91 | 90 | 728.9 | 90 | 92 | 92 | 761.8 | 91 | 93 | 90 | 761.7 | 94 | 92 | 91 | 787.0 |
| S4% | Initial | 98 | 102 | 101 | 1009.6 | 97 | 102 | 101 | 999.3 | 102 | 102 | 101 | 1050.8 | 98 | 102 | 101 | 1009.6 | 100 | 102 | 101 | 1030.2 | 97 | 102 | 101 | 999.3 |
| | New | 93.5 | 94 | 90 | 791.0 | 95 | 95 | 91 | 821.3 | 91 | 94 | 91 | 778.4 | 92 | 92 | 89 | 753.3 | 92 | 92 | 90 | 761.8 | 91.5 | 93 | 92 | 782.9 |
| S6% | Initial | 101 | 102 | 101 | 1040.5 | 102 | 101 | 101 | 1040.5 | 98 | 100 | 101 | 989.8 | 100 | 100 | 101 | 1010.0 | 100 | 101 | 101 | 1020.1 | 100 | 102 | 101 | 1030.2 |
| | New | 92 | 94 | 89 | 769.7 | 94 | 94 | 90 | 795.2 | 94 | 95 | 89 | 794.8 | 90 | 93.5 | 91 | 765.8 | 93 | 94.5 | 93 | 817.3 | 91 | 95 | 92 | 795.3 |
| S8% | Initial | 98 | 103 | 101 | 1019.5 | 100 | 102 | 101 | 1030.2 | 101 | 103 | 101 | 1050.7 | 100 | 102 | 101 | 1030.2 | 99 | 103 | 101 | 1029.9 | 101 | 102 | 101 | 1040.5 |
| | New | 92 | 94 | 91 | 787.0 | 92 | 95 | 95 | 830.3 | 94 | 95 | 94.5 | 843.9 | 94 | 95 | 93 | 830.5 | 93 | 94 | 94 | 821.7 | 93 | 96 | 94 | 839.2 |

# Appendix D

# MCB manufacturing process optimization

**Work study**

| | | | |
|---|---|---|---|
| Current practice | | | |
| Nos. of molds | | | 1 |
| labour requirement/ per day | | | 2 |
| Nos.of blcks per cycle | | | |
| Time taken | | | |
| Production | | Hr. | 1 |
| Waitng time | | Hr. | 2 |
| Total number of cycles per day | | | 4 |
| Total number of blocks per cycle | | | 25 |
| Total number of blocks per day | | | 100 |
| Cost analysis | | | |
| Labour cost | (Rs.1200.00 X 2) | Rs. | 2,400.00 |
| Mold cost | | Rs. | 18,000.00 |
| Number of blocks per community centre | | | 2500 |
| Number of days for the production | | | 25 |
| Total cost for the production | | Rs. | 78,000.00 |
| **Production cost/block** | | **Rs.** | **31.20** |

**Possible scenarios #1**

| | | | |
|---|---|---|---|
| Nos. of molds | | | 2 |
| labour requirement/ per day | | | 2 |
| Nos.of blcks per cycle | | | |
| Total number of cycles per day | | | 4 |
| Total number of blocks per cycle | | | 25 |
| Total number of blocks per day | | | 200 |
| Cost analysis | | | |
| Labour cost | (Rs.1200.00 X 2) | Rs. | 2,400.00 |
| Mold cost | | Rs. | 36,000.00 |
| Number of blocks per community centre | | | 2500 |
| Number of days for the production | | | 12.5 |
| Total cost for the production | | Rs. | 66,000.00 |
| Production cost/block | | Rs. | 26.40 |
| Possible saving | | | **12,000.00** |
| Concidering the sharing of mold cost for 2 sites................. | | | |
| Total cost for the production | | Rs. | 48,000.00 |
| Production cost/block | | Rs. | 19.20 |
| **Possible saving** | | | **30,000.00** |
| Concedering the sharing of mold cost for 10 sites................. | | | |
| Total cost for the production | | Rs. | 33,600.00 |
| Production cost/block | | Rs. | 13.44 |
| **Possible saving** | | | **44,400.00** |

**Possible scenarios # 2**

| | | | |
|---|---|---|---|
| Nos. of molds | | | 3 |
| labour requirement/ per day | | | 2 |
| Nos.of blcks per cycle | | | |
| Total number of cycles per day | | | 4 |
| Total number of blocks per cycle | | | 25 |
| Total number of blocks per day | | | 300 |
| Cost analysis | | | |
| Labour cost | (Rs.1200.00 X 2) | Rs. | 2,400.00 |
| Mold cost | | Rs. | 54,000.00 |
| Number of blocks per community centre | | | 2500 |
| Number of days for the production | | | 8.3 |
| Total cost for the production | | Rs. | 74,000.00 |
| Production cost/block | | Rs. | 29.60 |
| **Possible saving** | | | **4,000.00** |
| Concedering the sharing of mold cost for 2 sites................. | | | |
| Total cost for the production | | Rs. | 47,000.00 |
| Production cost/block | | Rs. | 18.80 |
| **Possible saving** | | | **31,000.00** |
| Concedering the sharing of mold cost for 10 sites................. | | | |
| Total cost for the production | | Rs. | 25,400.00 |
| Production cost/block | | Rs. | 10.16 |
| **Possible saving** | | | **52,600.00** |

**Possible scenarios # 3**

| | | | |
|---|---|---|---|
| Nos. of molds | | | 3 |
| labour requirement/ per day | | | 3 |
| Nos.of blcks per cycle | | | |
| Total number of cycles per day | | | 4 |
| Total number of blocks per cycle | | | 25 |
| Total number of blocks per day | | | 300 |
| Cost analysis | | | |
| Labour cost | (Rs.1200.00 X 3) | Rs. | 3,600.00 |
| Mold cost | | Rs. | 54,000.00 |
| Number of blocks per community centre | | | 2500 |
| Number of days for the production | | | 8.3 |
| Total cost for the production | | Rs. | 84,000.00 |
| Production cost/block | | Rs. | 33.60 |
| **Possible saving** | | | **-6,000.00** |
| Concedering the sharing of mold cost for 2 sites................. | | | |
| Total cost for the production | | Rs. | 57,000.00 |
| Production cost/block | | Rs. | 22.80 |
| **Possible saving** | | | **21,000.00** |
| Concedering the sharing of mold cost for 10 sites................. | | | |
| Total cost for the production | | Rs. | 35,400.00 |
| Production cost/block | | Rs. | 14.16 |
| **Possible saving** | | | **42,600.00** |

**Fig. D.1** Mud concrete block production work study

# Appendix E

# Thermal performance simulation data

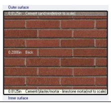
| Thermal properties of wall section | | | | | | | |
|---|---|---|---|---|---|---|---|
| **walling materials** | **wall section detail** | Plaster out resistance (Pro) | Plaster conductivity (PK) | wall material conductivity (Wk) | Plaster conductivity (PK) | Plaster indoor resistance (Pri) | U value |
| | **layer thickness** | 0.0000 m | 0.0125 m | 0.220 m | 0.0160 m | 0.0000 m | |
| **Brick** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 0.84 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.110 m2 K W -1** |
| **HCB** |  | 0.020 m2 K W -1 | 0.5 W m-1K-1 | 1.26 W m-1K-1 | 0.5 W m-1K-1 | 0.130 m2 K W -1 | **2.617 m2 K W -1** |
| **Cabook** |  | 0.020 m2 K W -1 | 0.5 W m-1K-1 | 0.80 W m-1K-1 | 0.5 W m-1K-1 | 0.020 m2 K W -1 | **2.688 m2 K W -1** |
| **MCB** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 1.00 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.315 m2 K W -1** |
| **WATTLE AND DAUBE** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 1.15 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.480 m2 K W -1** |
| **Brick** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 0.84 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.399 m2 K W -1** |
| **HCB** |  | 0.020 m2 K W -1 | 0.5 W m-1K-1 | 1.26 W m-1K-1 | 0.5 W m-1K-1 | 0.130 m2 K W -1 | **3.075 m2 K W -1** |
| **Cabook** |  | 0.020 m2 K W -1 | 0.5 W m-1K-1 | 1.30 W m-1K-1 | 0.5 W m-1K-1 | 0.020 m2 K W -1 | **4.779 m2 K W -1** |
| **MCB** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 0.00 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.315 m2 K W -1** |
| **WATTLE AND DAUBE** |  | 0.032 m2 K W -1 | 0.5 W m-1K-1 | 1.15 W m-1K-1 | 0.5 W m-1K-1 | 0.123 m2 K W -1 | **2.888 m2 K W -1** |

**Fig. E.1** Thermal properties of wall section

**Constructions Data**

Layers | Surface properties | Image | Calculated | Cost | Condensation analysis

| | |
|---|---|
| Inner surface | |
| Convective heat transfer coefficient (W/m2-K) | 2.152 |
| Radiative heat transfer coefficient (W/m2-K) | 5.540 |
| Surface resistance (m2-K/W) | 0.130 |
| Outer surface | |
| Convective heat transfer coefficient (W/m2-K) | 44.870 |
| Radiative heat transfer coefficient (W/m2-K) | 5.130 |
| Surface resistance (m2-K/W) | 0.020 |
| No Bridging | |
| U-Value surface to surface (W/m2-K) | 3.140 |
| R-Value (m2-K/W) | 0.469 |
| **U-Value (W/m2-K)** | **2.134** |
| With Bridging (BS EN ISO 6946) | |
| Thickness (m) | 0.2286 |
| Km - Internal heat capacity (KJ/m2-K) | 157.8662 |
| Upper resistance limit (m2-K/W) | 0.469 |
| Lower resistance limit (m2-K/W) | 0.469 |
| U-Value surface to surface (W/m2-K) | 3.140 |
| R-Value (m2-K/W) | 0.469 |
| **U-Value (W/m2-K)** | **2.134** |

**Fig. E.2** Simulation data series

| | |
|---|---|
| Inner surface | |
| Convective heat transfer coefficient (Btu/h-ft2-F) | 0.379 |
| Radiative heat transfer coefficient (Btu/h-ft2-F) | 0.976 |
| Surface resistance (ft2-F-hr/Btu) | 0.739 |
| Outer surface | |
| Convective heat transfer coefficient (Btu/h-ft2-F) | 7.902 |
| Radiative heat transfer coefficient (Btu/h-ft2-F) | 0.903 |
| Surface resistance (ft2-F-hr/Btu) | 0.114 |
| No Bridging | |
| U-Value surface to surface (Btu/h-ft2-F) | 0.223 |
| R-Value (ft2-F-hr/Btu) | 5.338 |
| **U-Value (Btu/h-ft2-F)** | **0.187** |
| With Bridging (BS EN ISO 6946) | |
| Km - Internal heat capacity (-) | 60.0000 |
| Upper resistance limit (ft2-F-hr/Btu) | 5.339 |
| Lower resistance limit (ft2-F-hr/Btu) | 5.339 |
| U-Value surface to surface (Btu/h-ft2-F) | 0.223 |
| R-Value (ft2-F-hr/Btu) | 5.339 |
| **U-Value (Btu/h-ft2-F)** | **0.187** |

**Fig. E.3** Simulation construction data sample

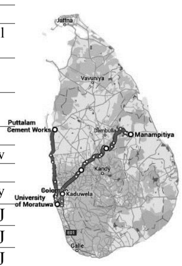
# Appendix F

# Embodied energy calculation

***A. Cement Block Energy Content***

| Requirement | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Material requirement for one hollow block (100X200X400mm)** | | | | | | | | |
| quarry dust | | sand | | cement | | | water | |
| 1.42 kg | | 4.92 kg | | 0.69 kg | | | 2.00 Liter | |
| | | | Material requirement for | | | 80 nos. | blocks | |
| 113.60 kg | | 393.60 kg | | 55.20 kg | | | 160.00 Liter | |
| Material requirement for hundred square feet wall construction | | | | | | | | |
| Nos Units | the mixture (kg) | Mortar (m³) | Cement (Kg) | Cement Bags | Sand (Kg) | | Sand Bags | Water (Lit) |
| **80** | **26.667** | **0.35** | **26.667** | **1** | **183.507** | | **5** | **6** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Distances** | **Transport distance** | | | | | | | |
| | Manufacturing Level1 | | Transporting to site (Level 2) | | | Construction of hundred square feet wall (level 3) | | |
| | quarry dust | Water | Blocks | Cement | Sand | blocks | Labor | Mortar |
| | 20.0 km | 0.15 km | 5.0 km | 152.0 km | 257.0 km | 0.000 km | 0.00 km | 0.00 km |
| **Method** | Soil | Water | Blocks | Cement | Sand | blocks | Labor | Mortar |
| | 36tractors | 100Pm | 1Lorry | 1Lorry | 1Lorry | 1Wheel barrow | on site | 1Wheel barrow |




| **Level one** (Manufacturing hollow cement blocks ) | Raw material | Biomass | Fossil fuel | Electricity | Total Energy |
|---|---|---|---|---|---|
| | Quarry Dust | 0.00 kg | 302.93 Liter | 0.00 MWh | 10883.4 MJ |
| | Sand | 0.00 kg | 8.03 Liter | 0.00 MWh | 288.3 MJ |
| | Cement | 0.00 kg | 5.66 Liter | 0.00 MWh | 203.1 MJ |
| | moulding | 0.00 kg | 0.00 Liter | 0.005 MWh | 20 MJ |
| | Total energy for Block production | | | | 11394.5 MJ |

| **Level Two** (Transporting materials to the site) | Method | Biomass | Fossil fuel | Electricity | Total Energy |
|---|---|---|---|---|---|
| | Uploading | 0.00 kg | 0.00 Liter | 0.00 MWh | 0 MJ |
| | Transporting | 0.00 kg | 0.03 Liter | 0.00 MWh | 1 MJ |
| | Unloading | 0.00 kg | 0.00 Liter | 0.00 MWh | 0 MJ |
| | Cement(for mortar) | 0.00 kg | 0.10 Liter | 0.00 MWh | 3 MJ |
| | Sand(for mortar) | 0.00 kg | 32.13 Liter | 0.00 MWh | 144 MJ |
| | Total energy for transporting materials to the site | | | | 11542.9 MJ |

| **Level Three** (Construction) | Method | Biomass | Fossil fuel | Electricity | |
|---|---|---|---|---|---|
| | Masonry | 0.00 kg | 0.00 Liter | 0.00 MWh | 0 MJ |
| | Mortar Mixing | 0.00 kg | 0.00 Liter | 0.00 MWh | 0 MJ |
| | Constructing | 0.00 kg | 0.00 Liter | 0.00 MWh | 0 MJ |
| | Total energy for hundred square feet block wall after Construction | | | | **11542.9 MJ** |

***List of assumptions for Block wall production

1. Quarry dust for block production was extracted from a quarry 20km away (nearest location to the site).
2. Water for block mixing was collected from a well 150m away using electric pump (125 liters per minutes)
3. No oil, engine oil was used while mixing and moulding bricks.
4. All the labor available within the site.
5. Mortar can be mixed at the same place where the brick wall is being built
6. Mortar mixings were done using human labor; no machinery was used whatsoever while building the brick wall.

| | |
|---|---|
| Blocks per 10Sq.Ft of single Skin Wall 225mm | 80 |
| Wheel Barrow Volume (l) | 65 |
| Weight of Cement Bag | 50 |
| Volume of Bag of Cement (l) | 33 |
| Volume of Mortar per brick laid | 0.00034 |
| Cement Bags per cubic meter of Class I Mortar | 9.5 |
| Volume of Sand per cubic meter of Class I Mortar | 1.23 |
| Weight of a bag of sand | 40 |
| Volume of 40kg sand bag | 30 |
| Liters in a Cubic Meter | 1000 |
| Joint width on Block Work | 10mm |

**Fig. F.1** Embodied energy calculation

# Appendix G

# Life cycle cost calculation

| Item and life span | Description | BB | CB | CAB | MCB | CSEB | FSEB |
|---|---|---|---|---|---|---|---|
| **Foundation** | Initial Cost | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 |
| **<60 years** | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| **100%** | Resale value | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 | $ 390.33 |
| **Wall (Square feet 1460)** | Initial Cost | $ 3,434.61 | $ 1,579.57 | $ 1,333.49 | $ 1,052.84 | $ 2,866.07 | $ 2,919.70 |
| **> 60 years** | Maintenance Cost | $ 1,717.31 | $ 1,579.57 | $ 6,667.47 | $ 1,052.84 | $ 2,866.07 | $ 2,919.70 |
| | | $ 0.00 | $ 0.00 | $ 0.00 | $ 0.01 | $ - | $ 0.01 |
| | Resale value | $ 1,739.79 | $ 1,105.70 | $ 800.10 | $ 968.61 | $ - | $ 2,627.73 |
| **Front Concrete Column** | Initial Cost | $ 70.00 | $ 70.00 | $ 70.00 | $ 70.00 | $ 70.00 | $ 70.00 |
| **> 60 years** | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Roof Work** | Initial Cost | $ 955.04 | $ 955.04 | $ 955.04 | $ 955.04 | $ 955.04 | $ 955.04 |
| **35 years** | Maintenance Cost | $ 64.59 | $ 64.59 | $ 64.59 | $ 64.59 | $ 64.59 | $ 64.59 |
| | Resale value | $ 744.93 | $ 744.93 | $ 744.93 | $ 744.93 | $ 744.93 | $ 744.93 |
| **Doors & Windows** | Initial Cost | $ 426.00 | $ 426.00 | $ 426.00 | $ 426.00 | $ 426.00 | $ 426.00 |
| **> 60 years** | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| | Resale value | $ 63.90 | $ 63.90 | $ 63.90 | $ 63.90 | $ 63.90 | $ 63.90 |
| **Floor concrete** | Initial Cost | $ 587.16 | $ 587.16 | $ 587.16 | $ 587.16 | $ 587.16 | $ 587.16 |
| **> 60 years** | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Bathroom** | Initial Cost | $ 40.00 | $ 40.00 | $ 40.00 | $ 40.00 | $ 40.00 | $ 40.00 |
| **30 years** | Maintenance Cost | $ 3.98 | $ 3.98 | $ 3.98 | $ 3.98 | $ 3.98 | $ 3.98 |
| | Resale value | $ 1.39 | $ 1.39 | $ 1.39 | $ 1.39 | $ 1.39 | $ 1.39 |
| **Electrical** | Initial Cost | $ 126.67 | $ 126.67 | $ 126.67 | $ 126.67 | $ 126.67 | $ 126.67 |
| **50 years** | Maintenance Cost | $ 2.70 | $ 2.70 | $ 2.70 | $ 2.70 | $ 2.70 | $ 2.70 |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Internal wall plastering** | Initial Cost | $ 375.05 | $ 375.05 | $ 375.05 | $ 375.05 | $ 375.05 | $ 375.05 |
| **only for paints** | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **External wall plastering** | Initial Cost | $ 284.91 | $ 284.91 | $ 284.91 | $ 284.91 | $ 284.91 | $ 284.91 |
| | Maintenance Cost | $ - | $ - | $ - | $ - | $ - | $ - |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Internal Painting** | Initial Cost | $ 337.33 | $ 337.33 | $ 337.33 | $ 337.33 | $ 337.33 | $ 337.33 |
| **6 years** | Maintenance Cost | $ 1,913.19 | $ 1,913.19 | $ 1,913.19 | $ 1,913.19 | $ 1,913.19 | $ 1,913.19 |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **External Painting** | Initial Cost | $ 161.33 | $ 161.33 | $ 161.33 | $ 161.33 | $ 161.33 | $ 161.33 |
| **6 years** | Maintenance Cost | $ 915.01 | $ 915.01 | $ 915.01 | $ 915.01 | $ 915.01 | $ 915.01 |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Septic tank** | Initial Cost | $ 146.67 | $ 146.67 | $ 146.67 | $ 146.67 | $ 146.67 | $ 146.67 |
| **30 years** | Maintenance Cost | $ 14.58 | $ 14.58 | $ 14.58 | $ 14.58 | $ 14.58 | $ 14.58 |
| | Resale value | $ - | $ - | $ - | $ - | $ - | $ - |
| **Total initial cost** | | $ 7,335.09 | $ 5,480.05 | $ 5,233.97 | $ 4,953.32 | $ 6,766.54 | $ 6,820.17 |
| | | $ 4,631.35 | $ 4,493.62 | $ 9,581.52 | $ 3,966.89 | $ 5,780.11 | $ 5,833.74 |
| **Total Resale value** | | $ 2,940.34 | $ 2,306.25 | $ 2,000.65 | $ 2,169.16 | $ 1,200.55 | $ 3,828.28 |
| **Energy cost** | | $ 18,799.49 | $ 20,359.55 | $ 23,569.68 | $ 19,444.52 | $ 19,924.54 | $ 21,939.13 |
| **Over heads** | | $ 586.81 | $ 438.40 | $ 418.72 | $ 396.27 | $ 541.32 | $ 545.61 |
| **Life cycle cost** | | $ 28,412.40 | $ 28,465.38 | $ 36,803.24 | $ 26,591.82 | $ 31,811.96 | $ 31,310.38 |
| ****** one kilo watt equals 0.26$** | | | | | | | |

**Fig. G.1** Life cycle cost calculation sample