In-situ Mud-Concrete as a material for load-bearing walls and sustainable building practices

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Declaration

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Abstract

The world is still struggling to find solutions for the increasing demand for housing with the growing population. To deal with this problem the greater importance has given in researching alternative materials and technologies which can cater sustainable solutions to these evolving demands. However, this materials and technologies must be suitable and appropriate to the local economy, social background and the cultural setting of that country. In the context of innovating sustainable building materials, ‘soil’ receives great attention as an environmental-friendly material, due to its economic affordability, low embodied energy and enhanced natural moisture buffering capacities.

Self-compacting Mud-Concrete load-bearing walling (MCW) system is an in-situ cast walling system that combines well-graded soil, cement (stabilizer) and water in their correct proportions. It receives great attention due to its sustainable advantages such as less raw material wastage, low-cost methods, quick construction technology and the low embodied energy consumption. This research presents a detailed analysis of mix design development, system development, thermal performances, long-term performance and cost-effectiveness of self-compacting Mud-Concrete load-bearing walls (MCW).

Results demonstrate that optimum usable gravel range is 4.75-32mm in MCW technology. Further, the mix design was finalized as fine - 5% (≤ sieve size 0.425mm), sand - 50 % (sieve size 0.425mm ≤ sand ≤4.75 mm) and gravel - 45% (sieve size 4.75mm ≤ gravel≤ 32mm) with 4% minimum cement of the total dry mix. In addition, optimum 20% of water can use to keep the self-compacting quality of the mix. Grading curves were developed constantly at 4%, 6%, 8% and 10% cement produced the best mix design with standardized methods. Also, the methods were introduced to predict the exact strength of MCW prior to construction. Accelerated erosion tests were conducted to determine the durability of MCW cast of the best mix design and the results satisfied the standard durability requirements under SLS1283. In addition, MCW can be listed as one of the excellent moisture buffering materials according to NORDEST classification system.

Optimum lifting height of a wall segment was found as 1200mm which can cast at once without proposing any joints. In every 1200mm height, the proper horizontal joint should be introduced in in-situ cast process and the introduced joint should keep the maximum continuity in between the wall segments. In addition, the results show maximum horizontal shrinkage is 0.23% and maximum vertical shrinkage is 0.22% within 07 days of curing period. Increasing the curing period from 07 days to 14 days, the shrinkage strain was reduced from 0.23% to 0.15%. It depicts that shrinkage strain can reduce in 65% by increasing the curing period for 14 days. Thus 14 days proper curing procedure was recommended to in-situ cast MC wall and the curing should start soon after dismantling the formwork of the wall segments. MCW has 1.2 W/m.K of conductivity, 1440 J/kg.K of specific heat capacity, 1540 kg/m^2 of density, 0.366 m^2.K/W of R-value and 2.17 W/m^2.K of U-Value. MCW acts as a good thermally resistive material due to its thermal mass and insulation characters. Comparatively, MCW has a low embodied energy and life-cycle cost due to the less material wastage, high reusability, fewer labour consumption and quick in-situ construction technologies. Ultimately the research invented a self-compacting in-situ cast load-bearing walling system through Mud-Concrete, which can highly cater to sustainable demands in the construction industry.

Keywords: Sustainability, Construction industry, Soil-based technologies, Mud-Concrete, Self-compaction, in-situ cast walling, load-bearing characteristics

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List of abbreviations

Symbol	Description
CB	Cement Block
CSCB	Compressed Stabilized Earth Block
C_u	Coefficient of uniformity
C_k	Coefficient of gradation OR Coefficient of curvature
EE	Embodied Energy
GSD	Grain Size Distribution
LCC	Life cycle costing
MC	Mud-Concrete
MCB	Mud-Concrete Block
MCW	Self-compacting in-situ cast Mud-Concrete load-bearing wall
MBV	Moisture Buffering Value
$MBV_{practical}$	Practical Moisture Buffering Value
MBV_{ideal}	Ideal Moisture Buffering Value
RE	Rammed Earth
USCS	Unified Soil classification system

1. INTRODUCTION

1.1. Need of the Study

After the “Industrial revolution”, most of established agricultural and commercial societies were replaced by modern and industrial societies with complex technologies. As a result, “Energy” became the most significant aspect when dealing with these highly multifaceted modern methods, procedures and activities. Therefore, due to high demand for “energy use”, the global concentration was focused towards the “energy conservation”, while establishing the sustainable built environment as a new concept. The idea of a sustainable built environment was introduced to safeguard scarce resources that became highly demanded, due to complicated technologies and developments. As such the careful consideration must be given to the suitability and adoptability of such methods and technologies; due to the reason that, most “modern and highly sophisticated” methods and technologies can create economically adverse conditions in developing countries by draining their resources to procure sophisticated technology from developed countries.

It is important that any, “methods or technologies”, always must be suitable and appropriate to the local economy, social background and the cultural setting of that country. As such, research work was carried out to find out and understand the existing technologies in the local context. During the study, it was identified that ‘soil’, as an ideal construction material. Before, the advent of cement and concrete, it was the mortar and, more often the material of which entire buildings were made. Then series of questions were raised; - If ‘soil’ is a sustainable material, why soil or earth is not popular in the current construction industry? - Or is it due to the lack of knowledge in disruptive technologies and applications? - And importantly does ‘soil’ using in a sustainable way in existing soil based technologies? - These questions were changed our research direction towards a novel soil-based research path that resulted in inventing the Mud-Concrete technology.

As we identified, the current soil-based technologies are not popular mainly due to the strength and durability issues. These issues are adversely affecting on popularizing the technology among the local people. Further, the common social misbelieve about earth as a low-cost housing solution which fulfils the need of poor has resulted in creating prejudice against earthen construction. Thus, the initial concept of developing Mud-Concrete is to incorporate both strength and durability of concrete to unfired soil-based constructions and make such constructions popular locally while ensuring indoor comfort, a low-cost load-bearing walling system with easy construction technique which has the least impact on the environment.

1.2. Research gap

It is important to study the most recent literature to understand the existing soil-based technologies while understanding the research gaps and generate the research question. The research reported in this thesis initiated with the Mud-Concrete block (MCB). The Mud-Concrete Block was the first invention done using Mud-Concrete (MC) technology. It is a sustainable masonry block product, which was patented on the year 2016 (17616, E04C 1/100, B28B, B28C, 2016). The need of the study arose with the question whether we could develop a self-compacting in-situ cast load-bearing walling system through Mud-Concrete. A detailed literature review was done to identify the existing soil-based technologies in the world. According to the summary of the literature presented under chapter one, the research gap was clearly identified as follows;

- There is no self-compacting in-situ cast load-bearing walling system introduced using soil-based materials.
- If the in-situ cast walling system is load bearing it always reduces the height to thickness ratio. (Ex; Rammed Earth walls – min.300mm thickness for load bearing wall) or the said walling system needs to be reinforced to increase the height to thickness ratio.
- Though the mix design of Mud-Concrete block was developed using the fraction of soil, the used gravel range (Fine gravel ranges = 4.75mm ≤ gravel≤ 20mm) was restricted due to the size of the block. Also, in MCB technology

mortar is used to block laying and considerably high labour power is needed in construction.

The research gap formed the main objectives of the research project of investigating the Mud-Concrete for self-compacting in-situ cast load bearing walls.

1.3. Aims and objectives

The main aim of this research is to investigate the Mud-Concrete technology for self-compacting in-situ cast load bearing walls. The specific objectives of this study can be listed as follows;

1. Develop the best practical mix; soil, sand, gravel, cement with water for the proposed self-compacting in-situ cast Mud Concrete load-bearing walls.
2. Analyse the structural performance of the self-compacting in-situ cast Mud-Concrete load-bearing walls.
3. Assess the thermal performance of the self-compacting in-situ cast Mud-Concrete load-bearing walls and structural optimisation according to the thermo-physical characteristics of the Mud-Concrete material.
4. Analyse the life cycle cost and embodied energy of self-compacting in-situ cast Mud-Concrete load-bearing walls.

1.4. Methodology

The following methodology was adopted to achieve the above objectives;

1. A literature survey was carried out to identify the existing soil based walling system, their benefits and drawbacks.
2. The detailed review of the Mud-Concrete technology was conducted and the research gap was identified. Then the necessity of finding the self-compacting in-situ cast Mud-Concrete load-bearing walling (MCW) technology was identified.
3. Laboratory testing methods were conducted to find the optimum gravel range which can be used in the mix design of MCW and using those the results best mix design of MCW was determined.

4. The optimum water-cement ratio was identified and grading curves of MCW was developed through the laboratory testing.
5. Durability test were conducted using the achieved best mix design to check the material suitability according to the SLS standards.
6. Moisture buffering capacity of MCW wall was analyzed using laboratory testing and the results were compared with other available contemporary walling materials in the market.
7. A questionnaire survey was performed to identify the comfortable lifting height of a wall segment of MCW. Further, the laboratory testing were carried to find out the optimum lifting height of a wall segment of MCW.
8. An optimum flexible modular formwork system was designed by computer simulation. An actual scale model was fabricated according to the identified components of the wall.
9. MCW segments were cast to check the values of drying shrinkage of identified best mix design. Further, the testing was extended to check the drying shrinkage with different curing periods of MCW and optimum methods were introduced.
10. Possible joint types between MCW segments were tested and recommendations were given to maintain the quality of construction.
11. A Small-scale MCW model house was constructed to measure the thermal performance of MCW walls. The results were analyzed and compared with computer simulations to find the thermos-physical characteristics of MCW.
12. In addition the walling thickness was optimized using quantitative and qualitative methods. The optimum walling thicknesses were used to the LCC and EE calculations.
13. Life cycle cost and embodied energy of MCW was analyzed and values were compared with other available contemporary walling materials in the market.

1.5. Main Findings

1. The effective gravel range of self-compacting in-situ cast load bearing wall is 4.75mm-32mm. Therefore, the soil which uses for the construction of MC walls must sieve through standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix. A minimum 4% of cement, 45% Gravel: 50% Sand ratio gives the maximum wet & dry compressive strength for the mix design of in-situ cast MC load bearing wall.
    a. Fine - 5% (≤ sieve size 0.425mm)
    b. Sand (fine aggregate) - 50 % (sieve size 0.425mm ≤ sand ≤4.75 mm)
    c. Gravel (course aggregate) - 45% (sieve size 4.75mm ≤ gravel≤ 32mm)

2. Increasing the water content reduces the compressive strength of the MC mix. However, the behaviour of water in MC was ambiguous as it is difficult to keep the exact water percentage of the dry mix even though the same volume of water was added to every sample while mixing. Therefore, data matrix was obtained through a series of testing procedures and a phenomenological equation was developed to plot the exact grading curves in identified water percentage of dry mix in MC walls. Developing grading curves of MCW helps to predict the grade strength of MCW with different cement ranges prior to construction. In addition, the gained data matrix helps to calculate the compressive strength with different moisture contents of MCW while achieving its self-compacting quality.

3. Durability of MCW was checked in laboratory conditions and the results confirmed the Achieved mix design of MCW (with minimum 4% cement) deemed to satisfy the SLS standards 1382. (Sri Lankan Standard Institute, 2009)

4. MCW is an excellent moisture buffering material according to the NORTDEST testing protocol. This buffering potential of the MC material can be developed with optimizing the surface exposure and walling thickness in a

given space while passively balancing the micro-climatic conditions. Increasing water content in the mix did not effectively increase the buffering potentials of the MCW material, because MC wall can crack with the high water content in the mix. Although the low water content has given a better moisture buffering value of MCW, it is difficult to keep the self-compacting quality of the material in practical construction. Thus, 20% optimum water content is recommended to be used in MCW construction and it always deemed to satisfy the self-compacting quality, required strength and excellent moisture buffering capacities.

5. The comfortable height of pouring concrete to formwork was found as 1200mm (approx.4’-0”) through the questionnaire survey conducted among 400 construction workers in different construction sites. Therefore, the formwork to cast a single wall segment was optimized up to 1200mm height. Since there is no height restriction, the total wall height (1200mm – height of a wall segment) can be cast at once without proposing any joints.

6. Seven (07) days of curing period was identified as an effective curing period for self-compacting load-bearing MC walls. Because 0.23% maximum shrinkage strain was recorded after 07 days of curing period and it is below than 0.5%, the value of maximum shrinkage for earth walls. However, the research was extended to check the behaviour of shrinkage patterns with different curing periods. When increasing the curing period from 07 days to 14 days the linear shrinkage strain reduced from 0.23% to 0.15%. So it is a considerably good solution to reduce the shrinkage strain more in practical constructions. With the 21 days curing period, the linear shrinkage strain reduced from 0.23% to 0.13%. Thus results depict that 14 days curing is much effective than the 21 days curing period. Therefore, to minimize the shrinkage cracks further, 14 days proper curing period is recommended for construction of in-situ cast MC load-bearing walls.

7. It is important to introduce a proper construction joint in between two MCW segments to reduce the crack development in walls. The results show that introduced joint should keep the maximum continuity in between the wall segments. In addition, the result confirmed that keeping a joint between the wall segments is not affecting the load bearing characters of the MC walling system.

8. Self-compacting in-situ cast Mud-Concrete load-bearing wall has 1.2 W/m.K of conductivity, 1440 J/kg.K of specific heat capacity, 1540 kg/m^2 of density, 0.366 $m^2.K/W$ of R-value and 2.17 $W/m^2.K$ of U-Value. The time lag of the MCW was proportionate to the thickness of the wall and decrement factor was inversely proportionate to the thickness. Thus, increasing the thickness will help to create a good thermally resistive material through Mud-Concrete.

9. Self-compacting in-situ cast Mud-Concrete load-bearing walling materials have the lowest embedded energy comparing to all other walling materials considered such as brick, cement blocks and Mud-concrete block (MCB) in testing. Further, it has the lowest life-cycle cost. The MCW has a comparatively low embedded energy content due to its self-compacting methods, in-situ construction and less-labour usage in the construction process (due to optimized formwork system). Not only that MCW is 96% reusable, but its ingredients can also also be crushed and produce the same walling material with an addition of cement ratio of 4%. Therefore, overall the MCW is one of the best alternative building materials suitable for a tropical climate condition like Sri Lanka.

1.6. Arrangement of the dissertation

The breakdown of the chapters in this thesis is as follows;

- Chapter 01 presents a detailed review of literature conducted to find out the background of the research.
- Chapter 02 presents the mix design development of MCW. This chapter elaborates the results of optimum usable gravel range, optimum gravel: sand: fine ratio, optimum water-cement ratio and grading curves of MCW.
- Chapter 03 presents the system development of MCW. This chapter includes the methods of modular formwork fabrications, the optimum lifting height of MCW, drying shrinkage capacities of MCW and possible joint formation of MCW.
- Chapter 04 presents the thermal performance analysis and the moisture buffering capacities of MCW with comparison to other conventional walling material in the market.
- Chapter 05 presents the life cycle cost analysis and the embodied energy analysis of MCW with comparison to other conventional walling material in the market.
- Finally, the dissertation presents the conclusion / recommendations and future works related to this research.

2. CHAPTER ONE – LITERATURE REVIEW

2.1. General introduction

This research focusses on developing a self-compacting in-situ cast load-bearing walling system using Mud-Concrete. Since the intention is to develop a soil-based technology, it was important to review the existing soil-based technologies around the world to identify the strength and the weaknesses of them. This chapter covers the literature survey of mud and its creations, existing soil based technologies (including MCB technology), soil classification system and soil stabilisation.

2.2. Mud and its production around the world

Mud is one of human’s oldest and most universally used construction materials (Houben & Guillard, 1994). Even at the dawn of humanity, people were building with mud, using it to form protective walls shielding the entrances to their caves. Even the first known cities constructed, closed to the river Tigris in the southern Mesopotamian kingdom of Sumer were built with mud. Mud construction occurs throughout the majority of the world’s different cultures, and for many, it continues to be the main method of construction in use today.

Mud construction is mainly found in places which are, relatively dry and have mud in abundance. At present, 1/3 of the world’s population lives in mud constructions, where developing countries alone are considered, this percentage increases to 50% (Maniatidis & Walker, 2003). Figure 1 shows how earth architecture has been practised throughout the world. Therefore, mud/earth house can be an ideal solution for many global issues. Collet et al, (2006) had further explained the advantages of mud houses are a reduction of energy consumption, reduction of greenhouse gases emission, reduction of water use and reduction of waste production and etc. Not only that but also earth has a high thermal capacity which could store much heat that is absorbed during the day. Thus, in the day time, the interior of the mud house is cooler relative to the outside (Eben, 1990). The ability to transmit heat strongly depends on the water content of clay and highly saturated clay has high thermal conductivity. When the outdoor temperature starts to go up, mud walls tend to heat and thus water in the clay is evaporated and heat loss occurred in the form of latent heat. Because of that, inside wall surface temperature is dropped and helps to maintain the indoor temperature in a lower value or in a steady state (Parra-Saldivar & Batty, 2006). Further, compared results between thermal behaviour of adobe house with a modern concrete house in Yemen shows, mud as a construction material has the potential of using in energy saving of passive houses (Algifri, Bin Gadhi, & Nijaguna, 1992).

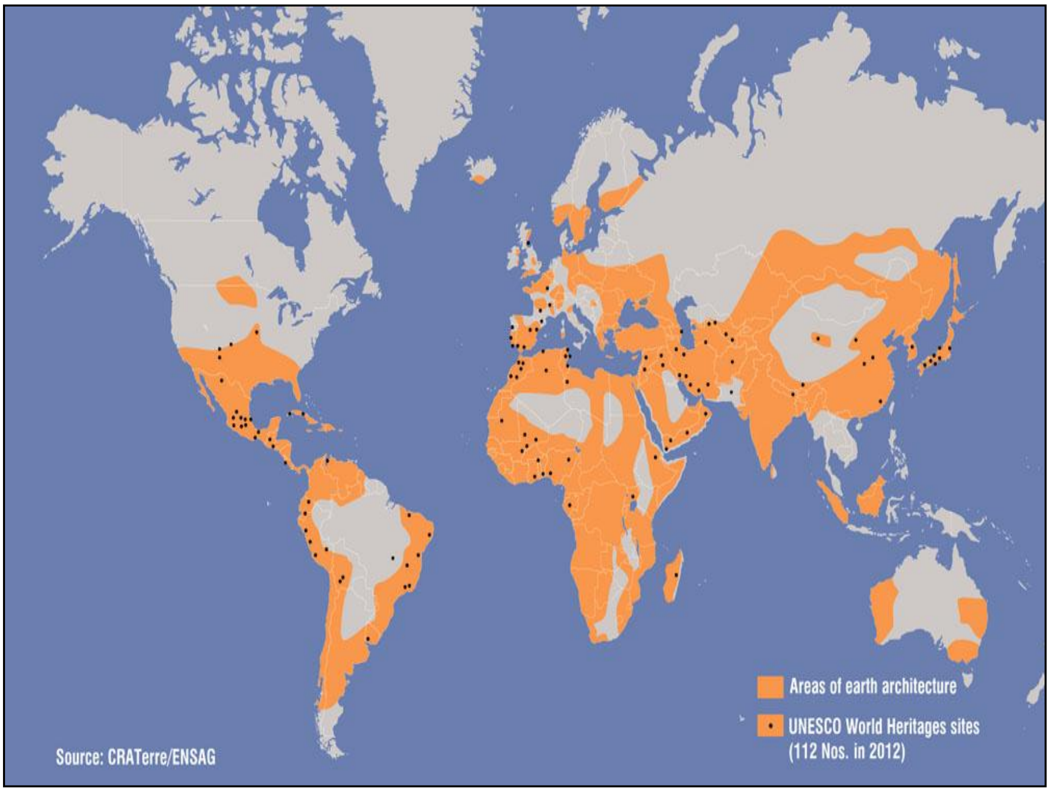


Figure 1: Locations where earth architecture practiced in the world (Source CRATerre/ENSAG)

Hence, based on literature it was proved that earth/soil/mud is a sustainable construction which we have used from the ancient eras. However, then again there is a counter-argument that could be made as to ‘why mud is not considered as a modern material though it is proved as a sustainable material for eras? At that point series of questions were created as for why earth-based building materials are not popular as so-called conventional composite materials (ex: concrete) in the construction industry. Unfortunately, most of the earthen constructions across the world are suffering from cracking and degradation (Omar Sore, Messan, Prud’homme, Escadeillas, &

Tsobnang, 2018a ; Heathcote, 1995 ; Guettala, Abibsi, & Houari, 2006 ; P. J. Walker, 1995a ; Woyciechowski, Narloch, & Cichocki, 2017 ; Türkmen, Ekinci, Kantarcı, & Sarıcı, 2017) which led to question the strength and durability parameters of soil-based constructions. Not only that, but the variability of the soil characteristics according to the context also becomes a great difficulty in application of earthen material in construction (Q.-B. Bui, Morel, Hans, & Walker, 2014a). Although there are several empirical techniques exist in soil based constructions (ex: compressed stabilized earth blocks (CSEB), rammed earth (RE)) (P. Walker, Keable, Martin, & Maniatidis, 2005 ; Burroughs, 2001 ; Gupta, 2014 ; Sitton, Zeinali, Heidarian, & Story, 2018) there is still a lack in terms of scientific base for vital understanding. Therefore, when developing a novel earth-based material, the challenge was to develop standards which require to keep the strength and durability parameters while enhancing the quality of construction. Hence, before inventing a novel material a comprehensive review was done to understand the research gap.

2.3. The existing soil based technologies

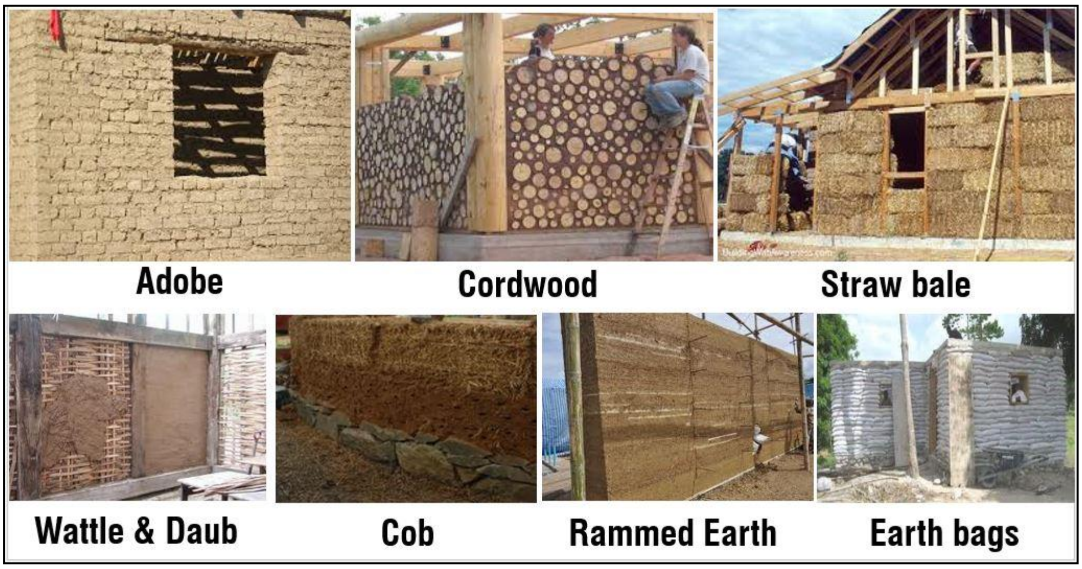


Figure 2: Available soil based technologies in global context

Mainly there are seven (07) types of soil based construction methods available globally such as Adobe, Wattle and daub, Rammed earth, Straw bale, earthen bags, Cob and Cordwood (Figure 2). Figure 3 shows the available soil based technologies in Sri Lanka. These technologies differ from context to context according to the availability of resources and raw materials. Existing soil based technologies were reviewed and the summary was recorded in Table 1 to Table 9.

Figure 3: Available soil based technologies in Sri Lankan context

Table 1: Adobe: Understanding the research gap

Soil-based technology	Adobe
Block/ wall	Block
Raw materials & Construction Method	Sun-dried brick [soil & water & local fibre materials] bonded with clay mortar.
Stabilised/ Un-stabilised	Can be stabilized or un-stabilized
Formwork	Need a block formwork
Compaction method	Hand compaction
Reinforced/ Non-reinforced	Need fibrous material as reinforcement

Load-bearing/non-loadbearing	No specific mix design found for load bearing walls
Weaknesses of technology	▪ Need post-treatment (drying) is required after casting. ▪ Fibrous materials are needed to reinforce the block. ▪ No standard was developed specially for load bearing wall.
References	(Eben, 1990; Blondet & Garcia, 2011; Schroder & Ogletree, 2010; Doehne, 1990 ; Heath, Walker, Fourie, & Lawrence, 2009 ; Christoforou, Kylili, Fokaides, & Ioannou, 2016; Moevus, Anger, & Fontaine, 2012; Binici, Aksogan, & Shah, 2005; Vega et al., 2011; Martín, Mazarrón, & Cañas, 2010; Latha & Venkatarama Reddy, 2016; Miller, 1996; Parra-Saldivar & Batty,2006;Duffin & Knowles, 1984; Niroumand, Zain, & Jamil, 2013)

Table 2: Cob - Understanding the research gap

Soil-based technology	Cob
Block/ wall	Wall
Raw materials & Construction Method	Fresh lumps of mud [soil & water & local fibre materials] stacked on each other.
Stabilised/ Un-stabilised	Can be stabilized or un-stabilized
Formwork	No need a formwork
Compaction method	No need compaction
Reinforced/ Non-reinforced	Need fibrous material as reinforcement
Load-bearing/non-loadbearing	No specific standard found for load bearing walls
Weaknesses of technology	▪ Need post-treatment (drying) is required after casting. ▪ Fibrous materials are needed to reinforce the wall. ▪ No standard develop specially for load bearing wall.
References	(Lorenzo, Urs, Chiara, & Christof, 2012; McClellan, n.d.; "Natural Building Colloquium," n.d.; "Auroville Earth Institute," n.d.)

Table 3: Wattle and daub - Understanding the research gap

Soil-based technology	Wattle and daub
Block/ wall	Wall
Raw materials & Construction Method	Woven work of sticks intertwined with twigs or bamboo covered with mud; framework system

Stabilised/ Un-stabilised	Can be stabilized or un-stabilized
Formwork	No need a formwork
Compaction method	No compaction
Reinforced/ Non-reinforced	Need a frame to hold the daub of sticky soil.
Load-bearing/non-loadbearing	No specific standard found for load bearing walls
Weaknesses of technology	▪ Need post-treatment (drying) is required after casting. ▪ No standard develop specially for load bearing wall.
References	(Péfau, 2017; Karmowski, 2018; Shaffer, 1993; Speciale, Mylona, et al., 2017 ; Speciale, Aprile, Caruso, & Peinetti, 2017 ; Giannitrapani, Iannì, & Speciale, 2017; says, 2017; Marina, 2013; Graham, 2013)

Table 4: Cordwood or stone - Understanding the research gap

Soil-based technology	Cordwood or stone
Block/ wall	Wall
Raw materials & Construction Method	Leftover materials like a slender shoot of a tree or tiny stone bonded with mud [soil & sand & paddy husk]
Stabilised/ Un-stabilised	Un-stabilised
Formwork	No need a formwork
Compaction method	No need mechanical compaction
Reinforced/ Non-reinforced	Reinforced with fibre materials
Load-bearing/non-loadbearing	No specific standard found for load bearing walls
Weaknesses of technology	▪ Need post-treatment (drying) is required after casting. ▪ Fibrous materials are needed to reinforce the wall. ▪ No standard develop specially for load bearing wall.
References	(Rob, 2016; Kerin, 2016 ; Jaroslaw, 2007; Linda, 2000 ; Gore & Lane, 1963; R, Jean-Claude, Victor, & Frederic, 2016; Gregoire, 1983)

Table 5: Earthen Bag - Understanding the research gap

Soil-based technology	Earthen Bag
Block/ wall	Wall
Raw materials & Construction Method	Stacking the bags of damp earth hooked up with a thorn or barbed wire.
Stabilised/ Un-stabilised	Un-stabilised
Formwork	No need a formwork

Compaction method	No need mechanical compaction
Reinforced/ Non-reinforced	Non-reinforced
Load-bearing/non-loadbearing	No specific standard found for load bearing walls
Weaknesses of technology	▪ No standard develop specially for load bearing wall.
References	(Santos, 2012 ; Hunter & Kiffmeyer, 2004 ; Geiger & Zemskova, 2015; Santos, 2017; Sho, 2014; Shinkre, n.d. ; Tyler, 2013; Stouter, 2016; Tyler, 2014; Barnes, Kang, & Cao, 2006; Schwartz, 2013)

Table 6: Strawbale - Understanding the research gap

Soil-based technology	Strawbale
Block/ wall	Wall
Raw materials & Construction Method	Plastering the bundle of hay with mud
Stabilised/ Un-stabilised	Un-stabilised
Formwork	No need a formwork
Compaction method	No need compaction
Reinforced/ Non-reinforced	Non-reinforced
Load-bearing/non-loadbearing	No specific standard found for load bearing walls
Weaknesses of technology	▪ Need post treatments to prevent the dampness. ▪ Less fire resistance ▪ No standard develop specially for load bearing wall.
References	(Larisa & Peggi, 2014; Sutton, Black, & Walker, 2011; Peter, 2004; Bruce, 2003; Ashour, Georg, & Wu, 2011; G, M, & R, 2009; Jafferji, Raczka, & Wang, 2011;Bhattarai, Dhakal, Neupane, & Chamberlin, 2012; Fatelrahman & Salah, 2015 ; Kelly & Kevin, 2003)

Table 7: CSEB - Understanding the research gap

Soil-based technology	CSEB (Compressed stabilised earth blocks)
Block/ wall	Block
Raw materials & Construction Method	Mixing soil and cement to a specified composition and compacted to achieve the specified strength
Stabilised/ Un-stabilised	Stabilized
Formwork	Need a block mould
Compaction method	Manual or mechanical compaction

Reinforced/ Non-reinforced	Non-reinforced
Load-bearing/non-loadbearing	Can be load bearing or non-load bearing
Weaknesses of technology	▪ Need proper compaction during block manufacturing ▪ This will cause to increase the embodied energy of the product
References	(Deboucha & Hashim, 2011; Chang, Jeon, & Cho, 2015; McGregor, Heath, Fodde, & Shea, 2014; Sitton et al., 2018; Galán-Marín, Rivera-Gómez, & García-Martínez, 2015; Moevus et al., 2012; Simons, Koranteng, & Adinyira, 2014; Bahar, Benazzoug, & Kenai, 2004; Nagaraj, Sravan, Arun, & Jagadish, 2014;Jayasinghe, 2016; Sri Lankan Standard Institute, 2009;Omar Sore, Messan, Prud'homme, Escadeillas, & Tsobnang, 2018b; P.J. Walker, 2004; Latha & Venkatarama Reddy, 2016; McGregor, Heath, Shea, & Lawrence, 2014)

Table 8: Rammed Earth - Understanding the research gap

Soil-based technology	Rammed earth
Block/ wall	Wall
Raw materials & Construction Method	Damp earth laid between formwork and moulded and compacted by ramming.
Stabilised/ Un-stabilised	Can be stabilised or un-stabilised.
Formwork	Need a formwork
Compaction method	Hand or mechanical compaction
Reinforced/ Non-reinforced	Can be reinforced. But reinforcing is difficult because wall needs to compact properly.
Load-bearing/non-loadbearing	Load bearing or non- load bearing walling system. Minimum 300mm thick wall for load bearing wall.
Weaknesses of technology	▪ Rammed earth needs heavy compaction which leads to increase the embodied energy of the technology ▪ Need post treatments to prevent the dampness. ▪ Reinforcing is difficult due to compaction.
References	(McGregor, Heath, Maskell, Fabbri, & Morel, 2016; Soebarto, 2009; Matthew Hall & Allinson, 2009; Kariyawasam & Jayasinghe, 2016; Gupta, 2014; Jayasinghe & Kamaladasa, 2007; Heath et al., 2009; Q.-B. Bui, Morel, Hans, & Walker, 2014b; Ma, Chen, & Chen, 2016a; Venkatarama Reddy & Prasanna Kumar, 2010; Fay, Owen, & Treloar, 2001; Daniela Ciancio & Gibbings, 2012; T. –. Bui, Bui, Limam, & Maximilien, 2013; Corbin & Augarde, 2014; Allinson & Hall, 2012; Moevus et al., 2012; Allinson & Hall, 2010a; Lombillo, Villegas, Fodde, & Thomas, 2014; Arrigoni, Beckett, Ciancio, & Dotelli, 2017; Venkatarama Reddy, Leuzinger, & Sreeram,

	2014; D. Ciancio, Beckett, & Carraro, 2014; Burroughs, 2001; Matthew Hall & Djerbib, 2004; Serrano et al., 2017; Peter Walker, Keable, Marton, & Maniatidis, 2010a; Arrigoni, Grillet, et al., 2017; Jayasinghe, 2016; Woyciechowski et al., 2017; Latha & Venkatarama Reddy, 2016; Bernat Masó, Gil Espert, & Escrig Pérez, 2016; Thuysbaert, 2012; Gomes, Gonçalves, & Faria, 2014; Ma, Chen, & Chen, 2016b; Niroumand et al., 2013)

Table 9: MCB - Understanding the research gap

Soil-based technology	Mud Concrete Block (MCB)
Block/ wall	Block
Raw materials & Construction Method	The proper mixture of Soil, cement and water (using the fraction of soil) needed to prepare the mix. Gravel helps to achieve the strength of the block
Stabilised/ Un-stabilised	Stabilised
Formwork	Need a block mould
Compaction method	Self-compaction
Reinforced/ Non-reinforced	Non-reinforced
Load-bearing/non-loadbearing	Load bearing
Weaknesses of technology	▪ The usable gravel range is restricted up to 4.75mm to 20mm. ▪ Raw material wastage.
References	(Arooz, Udawattha, & Halwatura, 2017; Udawattha, Arooz, & Halwatura, 2016b;Arooz, Halwatura, & Ranasinghe, 2016; Arooz & Halwatura, 2017; Arooz, Ranasinghe, & Halwatura, 2015; Arooz & Halwatura, 2016; Udawattha, Arooz, & Halwatura, 2016a)

After reviewing all these existing earth-based technologies, weaknesses and potentials of developing the technology were noted. In addition, most recent literature of RE technologies and MCB technologies were focused in order to invent in-situ cast load-bearing walling system through Mud-Concrete. Table 10 shows the minimum performance specification of rammed earth walls. As recorded by Hall and Djerbib (2004) rammed earth walls are free-standing, load-bearing walls typically with 300mm -600mm thickness. Further, they have confirmed 1800 -2200 kg/m^3 of dry density of rammed earth in 1.3 N/mm^2 of minimum characteristic unconfined dry compressive strength. Though these values are comparatively lower than bricks or concrete, a typical downward thrust of a single storey house is only 0.1 Nmm^{-2}. The compressive strength of a block or wall has become the basic and universally accepted unit of measurement for specifying the quality of masonry units as it is an indirect measure of the durability of the blocks or walls. Therefore, the minimum requirement achieved in RE can be regarded as a justifiable benchmark to be followed for the research. According to the specifications compiled for RE, the minimum requirement of 28 days dry compressive strength of a wall/block should be 2.0 Nmm^{-2} with a minimum of 4% cement. Further, proper grading of soil mix, proper compaction and proper stabilization using admixture would help to increase density, reduce water absorption and increase frost resistance in RE technology (Corbin & Augarde, 2014;M Hall & Djerbib, 2004;Serrano et al., 2017; Venkatarama Reddy & Prasanna Kumar, 2010; Woyciechowski et al., 2017 and Matthew Hall & Allinson, 2009).

Table 10: Typical minimum performance specifications for rammed earth walls

Parameter	**Specification**
Soil composition	Meet recommended and agreed specification for grading, plasticity, shrinkage, chemical composition, mineralogy, colour, texture, organic matter content and salt contents.
Minimum dry density	98% of heavy manual compaction
Maximum dry density	20 kN/m^3 for compaction levels
Compaction moisture content	± 1-2% of optimum moisture content (The optimum moisture content (OMC) for RE soils is critical in order to achieve maximum dry density through dynamic compaction, which will directly influence the strength and durability of the material.
Unconfined compressive strength	1.0 N/mm^2 (General) 2.0 N/mm^2 (load-bearing)
Finish	Boniness, efflorescence, colour variation, etc. to agree in advance In general no cracks wider than 3mm and longer than 75mm
Erosion resistance	Erosion rate greater than 1mm/min
Surface abrasion	No general specification
Maximum drying shrinkage	Not greater than 0.5% (composite load-bearing) Not greater than 1.0% (other)

Source : (Peter Walker et al., 2010a)

After identifying the qualities of rammed earth (RE) technology, it is required to analyze the Mud-Concrete block (MCB) technology, which provides the most relevant and recent literature on developing the MCW walls. MC is an earth-based material which introduces with self-compacting technologies (Arooz & Halwatura, 2017). Concrete is a composite construction material made out of cement, sand, metal and water. Here, metal (coarse aggregate) governs the strength, cement acts as the binder and sand (fine aggregate) reduces the porosity and water acts as the reactor for cement. In Mud-Concrete, sand and metal of concrete are replaced by fine and coarse aggregates of soil (Figure 4). The intended functions of sand and metal are obtained by varying the particle sizes of soil. In Mud-Concrete Block (MCB) experiment soil has been classified as shown in Table 11 (Patent: 17616) (Halwatura, 2016 ; Arooz & Halwatura, 2017).

Table 11: Soil classification and mix design of MCB technology

Particle type	Sieve sizes	Mix proportions
Gravel	Particle passes from 19mm (3/4”) and retained in 4.75mm (No.4) sieve	30%- 35%
Sand	Particle passes from 4.75mm (No.4) and retained in 0.425mm (No.40)	60% -65%
Fine (Sandy fine, silt and clay)	Particle passes from 0.425mm (No.40)	5%-10%

Source: (Arooz & Halwatura, 2017)

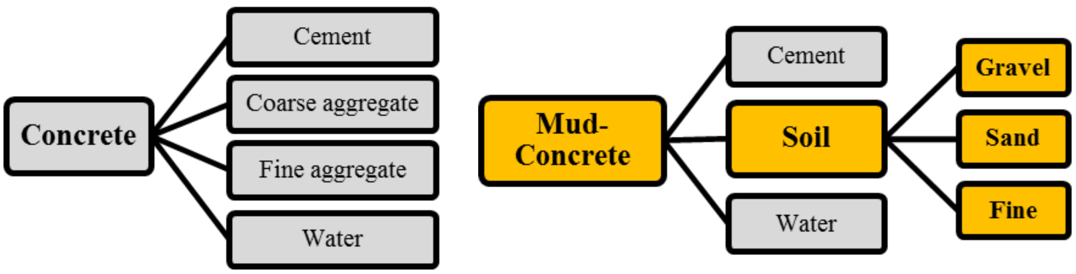


Figure 4: Similarities of developing the concept of Concrete and Mud-Concrete

2.4. Soil classification systems

Selected soil type and gradation of soil are most important in RE and MCB technology. In RE technology soil will be improved by either mechanical means such as compaction and vibration and/or chemical stabilisation by cement or other alternative stabilisers. In order to increase the mechanical strength and weathering resistance of soil, it is advantageous to minimise the voids ratio in order to increase the contact between soil particles. Theoretically, soils with no voids can be achieved if the soil particles are entirely spherical (Maniatidis & Walker, 2003). As stated by Jayasinghe et.al, the sandy laterite soils have shown the best behaviour in RE construction in Sri Lankan context (Jayasinghe & Kamaladasa, 2005). However in MCB technology gravelly laterite soil is recommended, because gravel governs the strength of the material (Arooz & Halwatura, 2017).

In soil mechanics, it is practically always useful to quantify the size of the grains in a type of soil. Since a given soil will often be made up of grains of many different sizes, sizes are measured in terms of grain size distributions. Grain size distribution (GSD) information can be of value in providing initial rough estimates of a soil's engineering properties such as permed− ability, strength, expansivity, etc. A subject of active research interest today is the accurate prediction of soil properties based largely on GSDs, void ratios, and soil particle characteristics (Figure 5). When measuring GSDs for soils, 02 methods are generally used (ASTM, 2016):

1. For grains larger than 0.075mm dry sieving is used;
2. For grains in the range of .075mm > D > 0.05mm, the hydrometer test is used.

In the MC technology, the hydro-meter level was not used due to the impracticality in construction procedures at the site. There are different types of soil classification systems are practising in the world. However, in the MCB technology Unified Soil classification system (USCS) is used to describe the texture and grain size of a soil (Arooz & Halwatura, 2017). Thus, the process of grading the soil is in accordance with the USCS systems. Gradation of a soil is determined by reading the grain size distribution curve produced from the results of laboratory tests on the soil.

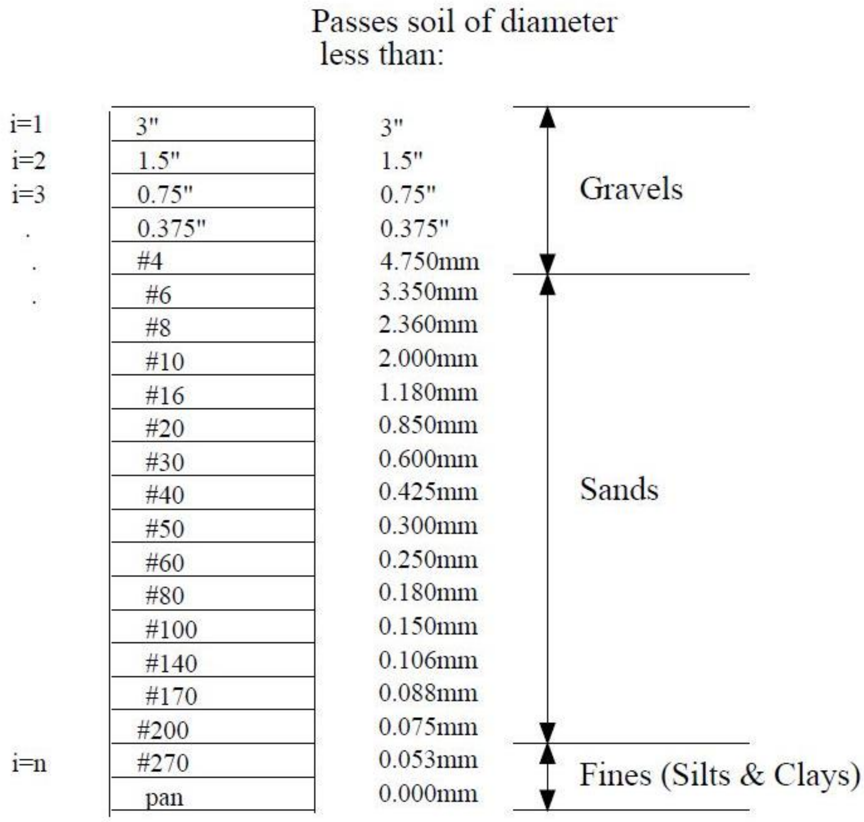


Figure 5: Grain Size Distribution – according to the diameter of Particle sizes

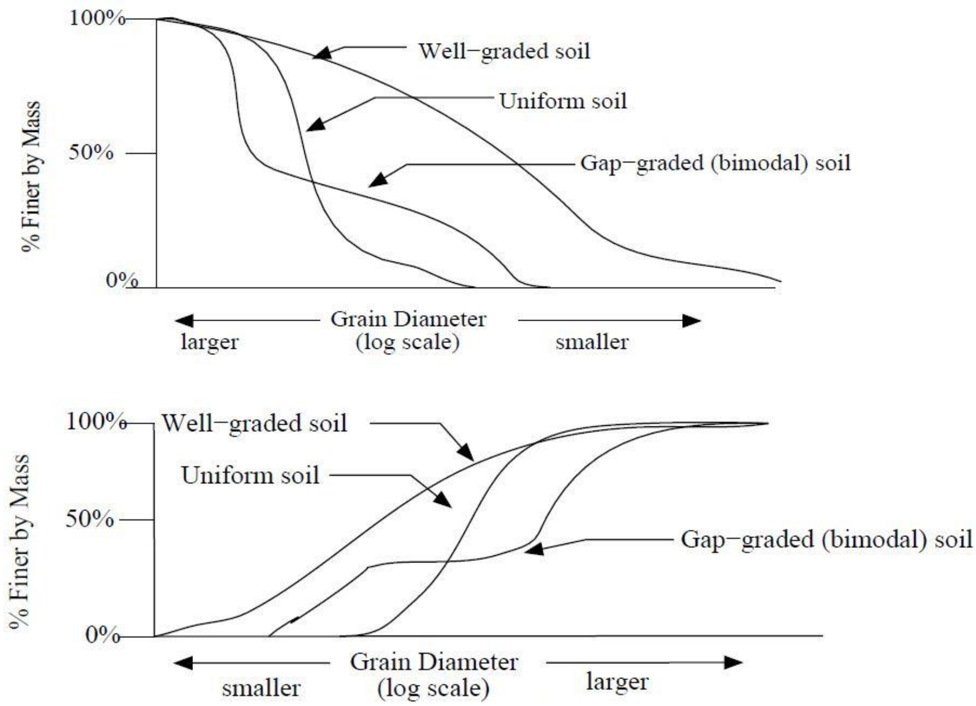


Figure 6: GSD are plotted on standard semi-log paper, they look different since the grain size will increase from left to right

Gradation of soil can also be determined by calculating the coefficient of uniformity (C_u) and the coefficient of curvature (C_k) of the soil and comparing the calculated values with published gradation limits (ASTM, 2016).

$$C_k = D_{30}^2/D_{10} - D_{60}$$

Where,

D_{10} is the diameter in the particle size distribution curve corresponding to 10% passing

D_{30} is the diameter in the particle size distribution curve corresponding to 30% passing

D_{60} is the diameter in the particle size distribution curve corresponding to 30% passing

In MCB technology, it is recommended to use a well-graded gravelly laterite soil (Arooz & Halwatura, 2017). A well-graded soil is a soil that contains particles of a wide range of sizes and has a good representation of all sizes from the No. 4 to No. 200 sieves (Figure 6 and Figure 7). A well-graded gravel is classified as GW while a well-graded sand is classified as SW. Ck between 0.5 and 2.0 indicates a well-graded soil (ASTM, 2016).

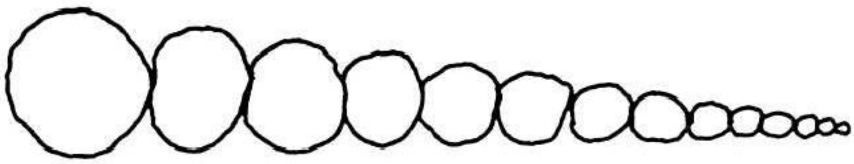


Figure 7: Grain distribution of a well-graded soil

2.5. Soil stabilization

Soil stabilization method is one of the several methods of soil improvement. Soil stabilization aims at improving soil strength and increasing resistance to softening by water through bonding the soil particles together, waterproofing the particles or combination of the two (Makusa, 2012). Usually, the technology provides an alternative provision structural solution to a practical problem. The simplest stabilization processes are compaction and drainage (if water drains out of wet soil it becomes stronger). The other process is by improving the gradation of particle size and further improvement can be achieved by adding binders to the weak soils (Afrin, 2017). Soil stabilization can be accomplished by mainly two methods such as mechanical stabilization and chemical stabilization. In MCB technology chemical stabilization has been used (Arooz & Halwatura, 2017; C. Udawattha et al., 2016b; C. Udawattha et al., 2016a). Chemical soil stabilization depends mainly on chemical reactions between stabilizer (cementitious material) and soil minerals (pozzolanic materials) to achieve the desired effect. The stabilizer is used in weak soils to improve its geotechnical properties such as compressibility, strength, permeability and durability (Afrin, 2017). In MCB technology, cement stabilization is the most common method used due to the availability of more technical information.

Cement stabilized materials fall into two categories of soil cement and cement modified soil. Soil-cement is a mixture of pulverized soil material and aggregate, a measured amount of Portland cement, and water that is compacted into high density.

In the soil cement stabilization, the moisture content of the mixture is a critical factor influence to the dry density and unconfined compressive strength (Shooshpasha & Reza Alijani, 2015). Therefore, the stabilization process should be carried out at the optimum moisture content. Further by increasing the cement content of the mixture, higher compressive strength can be obtained. However, as recorded by Walker, greater than 10% cement content stabilization generally becomes uneconomical (P. J. Walker, 1995b). The reactions in cement stabilization as follows;

Dry Soil + Cement + Water $\longrightarrow$ Calcium Silicate + Calcium Aluminate + Hydrated lime

The strength of cement stabilized soil depends on the chemical composition of the material to be stabilized, the stabilizer content, the degree of compaction achieved, the moisture content, the success of mixing the material with the stabilizer, subsequent external environmental effects. Further, it is directly proportional to the amount of cement admix. Normally the strengthening period is very long for the cement stabilized soil.

2.6. Summary of literature

Production and transportation of many engineering construction materials consume a high amount of energy and as a result, emit a high level of greenhouse gases. This excessive energy consumption and environmental impact can be reduced by using local materials and in-situ cast constructions. For six decades, extensive attempts have been made to make unfired stabilized bricks to be a reliable walling unit against the more expensive fired bricks and concrete blocks (Jagadish, Reddy, & Rao, 2007; Deboucha & Hashim, 2011). Proposing unfired, in-situ cast, quick construction walling techniques can eliminate the labour intensive systems while maintaining the low embodied energy consumption and quality of construction. Thus, existing soil based walling technologies were reviewed to understand the research gap. RE and MCB technologies were mainly focused because the scope of the study is to invent a self-compacting in-situ cast load-bearing walling material through MC technology. Though RE technology is an in-situ cast system, it consumes a high amount of embodied energy due to its compaction process in wall construction. In addition, the RE technology needs thick walling (min.300mm thickness) to build load-bearing structures and it consumes a high amount of raw materials in construction. MCB is a block masonry system and it consumes comparatively high labour in walling construction. In addition, MCB needs a considerable amount of cement mortar to build a wall. Moreover, the usable gravel range is limited in MCB due to the block model and it is causing a huge raw material wastage in construction. In MCB technology it was recommended to use the well-graded gravelly laterite soil in construction.

3. CHAPTER TWO - MIX DESIGN DEVELOPMENT

3.1. General

In this research the first objective is to analyze the best practical mix; soil, sand, gravel, cement with water to obtain the best performing self-compacting in-situ cast Mud-Concrete load bearing walls. Therefore, the following chapter is set out to present how the research was designed to achieve the said objective. Further, the chapter presents the evaluated results attained through laboratory testing in addition including the selection of best moulds to cast the MC specimens, workability and self-compacting consistency of MCW, optimum gravel size which gives the maximum compressive strength of MCW, optimum Gravel: Sand: Fine proportion for best workable mix of MCW, grading curves of MCW and durability of MCW.

3.2. Introduction

The research was designed using the mix of MCB based on the most recent literature related to the Mud-Concrete technology. Although the strength factor governs by gravel content of the mixture of Mud-Concrete, the gravel range which could use in Mud-Concrete block is limited. As far as this is a small block (ex: 300mm x 150mm x 150mm) there is not enough space for coarse gravel (big particle sizes). When particle sizes get bigger, the amount of gravel included in a casted block would not maintain correct proportions. The porosity of the block will increase with this random bigger gravel particles and it would affect to decrease the compressive strength of the block. Therefore, mixture of MCB could only use fine gravel ranges (4.75mm $\leq$ gravel$\leq$ 20mm) in soil. Thus, the first attempt here is to expand the usable gravel size and range in the MCW and reduce the raw material wastage in construction. Then the first research question raised as what is the optimum gravel size which gives the maximum compressive strength to the proposed self-compacting in-situ cast Mud-Concrete load-bearing wall. Unlike a block, wall segment can expand the space in vertical boundaries. Thus, the research was designed, and methodology was adopted to find the answers to the above questions.

Prior to that, it was a necessary to finalize the standard test specimen to use during entire research (cylinder or prism) process as compressive strength of the specimen is most important when analysing the load-bearing capacities of the material. Therefore, following **steps** were adopted to achieve the mix design of self-compacting in-situ cast Mud-Concrete load bearing walls (MCW).

1. Selecting the best mould (cylinder or prism) to cast the Mud-Concrete Specimens.
2. Developing a method of checking workability and self-compacting consistency of Mud-Concrete.
3. Finding optimum gravel size which gives the maximum compressive strength.
4. Finding optimum Gravel: Sand: Fine proportion for the best workable mix.
5. Developing grading curves and standardizing the water percentage from dry mix.

3.3. Selecting the best mould to cast Mud-Concrete specimens.

As stated in literature, the concept of developing Mud-Concrete is similar to the concrete composite material. The compressive strength of concrete is important because the main properties of concrete, such as elastic modulus and tensile strength, are qualitatively and quantitatively related to this property. It is also important because, in structural design, the load-bearing capacity of structures is related to the compressive strength of concrete. The compressive strength of a block has become the basic and universally accepted norm for the measurement for specifying the quality of masonry units as it is an indirect measure of the durability of the blocks. Therefore, the methodology to determine the best mix of a Mud-Concrete wall was based on achieving the standard compressive strength by changing the variables which effect to the mix. Thus, it is important to finalize the best mould to use in testing procedures in the entire research process. It is well known that there are two types of standard test specimens used for the determination of compressive strength; cubes and cylinders.

a) 300mm height, 150mm diameter - Cylinder
b) 150mmx 150mmx150mm - block mould (Prism)

Literature shows, concrete cube has greater compressive strength as compared to cylinder whereas the contact area of a standard cube mould with the upper platen in the testing machine is more which results in more confinement; more confinement resists against specimen expansion resulting in more compressive strength (Neville, 1963). However, in this research, it was a need to check the compressive strength behaviour of these two different specimens made out of Mud-Concrete.

3.4.2. Materials and methods

Gravelly laterite soil sample was randomly selected from Colombo to initiate the research. Gravelly laterite soil samples were obtained from a homogeneous layer; 600mm-900mm below the top of the soil to get the good composition of soil and to avoid the organic particles in the soil samples. The soil was air dried and sieve analysis was done to identify the existing particle size distribution of the selected soil sample. 35% Gravel: 60% Sand: 5% Fine mix ratios of Mud-Concrete block was used to develop the soil samples. Four percent (4%) cement from the total dry mix was added to the Mud-Concrete mixture. Three (03) sets of cylindrical and block specimens were cast from the same Mud-Concrete mixture and cured the samples for 14 days (Figure 8). After 28 days of strength gain, specimens were crushed and the compressive strength values were calculated.

Figure 8: Tests specimens of Cubes and Cylinders

3.4.2. Results and discussions

a) Finding the existing particle size distribution

The results of the sieve analysis (Figure 9 and Table 12) show the soil sample needed to be developed according to the mix proportions of MCB. Table 13 shows how to develop the soil according to the identified mix design of MCB. As per the calculations, to keep 5% fine in the proposed mix, 4.26kg gravel needed to be removed from the total soil sample and 3.57kg sand needed to be added to the total soil sample.

Table 12: Aggregate proportions in existing soil samples

Gravel	Sand	Fine
42.75%	53.51%	3.74%

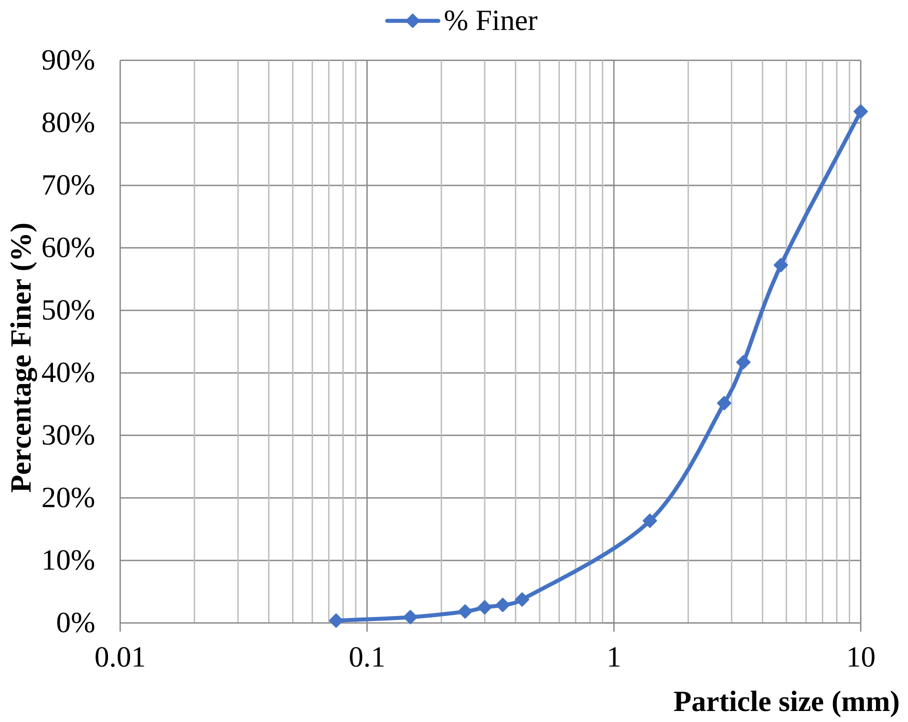


Figure 9: Existing Particle Size Distribution of selected soil

Table 13: Developing the existing soil according to the identified mix design of Mud-Concrete Block

Total mix weight needed to cast 03 block mould& 03 cylindrical moulds (To keep 5% fine in the mix needed total mix weight)					55 kg				
Added Cement (4% of the total weight of the mix)					2.2 kg				
Sample No:	Sample weight of soil (kg)	Existing Proportions & weight			Proposed Proportions & weight			Remove gravel to keep the 5% fine in the mix	Added sand to keep the 5% fine in the mix
		Gravel	Sand	Fine	Gravel	Sand	Fine	Gravel	Sand
01	11kg	42.75%	53.51%	3.74%	35%	60%	5%	4.26kg	3.57kg
		23.51kg	29.43kg		19.25g	33.0kg	2.75kg		

b) Cylinder to cube strength ratio

Table 14: Compressive strength values of cylinders and blocks specimens after 28 days

Blocks		**Dimensions**		**Surface area**	**Weight**	**Crushing Load**	**Compressive Strength**	**Average Compressive Strength**
		L (mm)	W (mm)	(mm^2)	(kg)	(KN)	(N/mm^2)	(N/mm^2)
	B1	149	149	22201	6.4	19	0.86	1.19
	B2	149	149	22201	6.5	26.1	1.18	
	B3	149	149	22201	6.45	26.7	1.20	
Cylinders		**Dia.**	**radius**	**Surface area**	**Weight**	**Crushing Load**	**Compressive Strength**	**Average Compressive Strength**
		(mm)	(mm)	(mm^2)	(kg)	(KN)	(N/mm^2)	(N/mm^2)
	C1	150	75	17662.5	10.2	11	0.62	0.65
	C2	150	75	17662.5	9.95	11.7	0.66	
	C3	151	75.5	17898.785	9.75	12	0.67	

The results shown in Table 14 confirm that, compressive strength of MC blocks is higher than the compressive strength value of the MC cylinders. As a norm the ratio between a concrete cube and a cylinder strength is commonly assumed to be 0.8, however, it is not constant (Neville, 1963). After adding the 0.8 factor the MC block gives 0.95 N/mm^2 and it is still higher than the 0.65 N/mm^2 value of MC cylindrical specimen. Similar to the concrete specimen, MC cubes also have greater compressive strength when compared to cylindrical specimens.

Thus, the results depict that the best mould to check the compressive strength of Mud-Concrete specimens as 150mm x 150mm x 150mm block mould and this size of the block specimen was used during the entire research.

3.4. Developing a method to check workability and self-compacting consistency of Mud-Concrete.

Among the main objectives was to develop a self-compacting mix which would be able to consolidate under its own weight. This self-compacting mix would not require any mechanical vibration or compaction after pouring and would follow the shape and surface texture of the mould/formwork once set. To conceive the mud-concrete mixture as a self-compacting mix, it was essential to manage its fluidity while retaining its strength and durability properties. Thus, water became a key constituent of the mix. The initial task was to determine the proportion of water required to achieve the self-compacting phenomenon in Mud-Concrete. To prepare the self-compacting specimens, the designed amount of water was firstly mixed with the sample, consisting of dry soil, gravel, sand and cement to obtain fluid mixtures. After 10 minutes of mixing in a concrete mixer machine, the composition started to show self-compacting properties such as continuous flow, viscosity and filling ability.

In this research process, the next important question raised was how to test the workability of this soil mix. There is no standard method written to follow the self-compacted mix developed through soil-based material in the literature. Due to the cohesiveness between the clay and the gravel particle in the mix, it is difficult to measure the direct flow of Mud-Concrete like the methods such as slump flow testing to measure the workability of fresh concrete (Figure 11). Therefore, we followed an alternative simple technique to identify and standardize the self-compacting consistency of the Mud-Concrete mix.

The research was designed to check the slump height and the slump diameter of the Mud-Concrete mix with different moisture contents while giving a constant number of blows (25 blows). According to the results in Table 15 and Figure 10, it shows approx. 20% water from the dry mix gives the workable mix of Mud-Concrete. This method is used to check the workability and the self-compacting consistency of all the Mud-Concrete samples used in casting the test blocks.

Here the slump flow is measured after giving 25 blows using the flow table (Figure 12). If the mix achieved the workability it flows up to an approx. 500mm diameter circle on the flow table (Figure 13). Soon afterwards the mixture was prepared it was poured in two layers to cast iron moulds as shown in Figure 14 and remove the existing air in the mixture using a tamping rod. No compaction energy or vibration was needed to maintain the consistency of the Mud-Concrete mix. The intention was to remove labour-intensive construction methods and control the cost, quality and save the time during construction.

Table 15: Added water % to achieve the workability of Mud-Concrete

Number of blows	25		
Added water amount (ml)	Water from the dry mix (%)	Slump diameter (mm)	Slump height (mm)
2000	15%	388	60
2500	16%	423	90
3000	18%	462	130
3500	**20%**	**510**	**173**
4000	23%	569	241
4500	26%	610	292

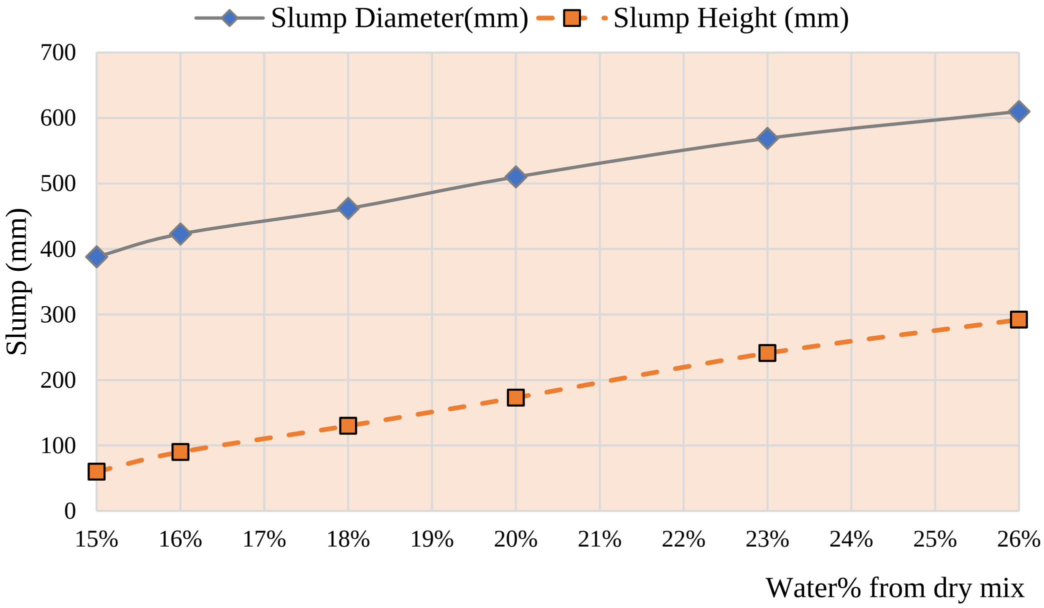


Figure 10: Slump test results with different moisture contents of Mud-Concrete mix

Figure 11: The MC mix has not spread at once due to the cohesiveness of the material.

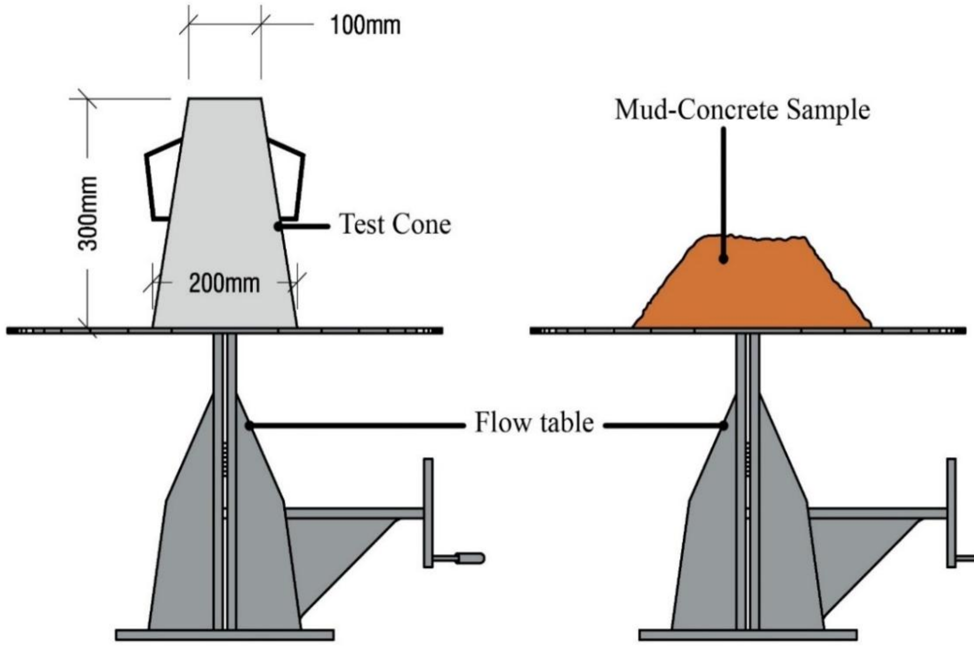


Figure 12: Fill the test cone in one operation without mechanical compaction. Then strike off the excess mix from the top of the test cone. Allow the cone to stand for60s. After that lift the cone in a single movement. Then it will be visible that the mix has not spread at once due to the cohesiveness of the material. Therefore, flow diameter was measured after giving 25 blows using the flow table. As a thumb rule after 25 blows, if the mix spread to about 500mm diameter of a circle then the workability of the mix was

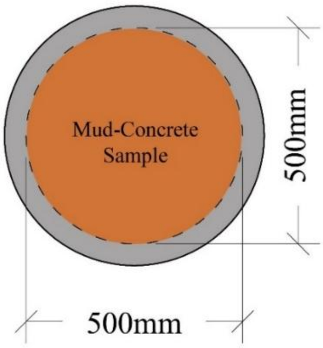


Figure 13: Plan view of the flow table. Spread of the self-compacting Mud-Concrete mix after giving 25 blows using the

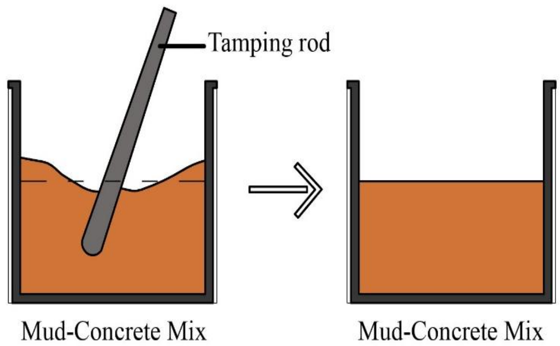


Figure 14: The mixture was poured into 150x150x150 mm cast iron moulds in two layers and a tamping rod used to remove the air existing in the mixture

3.5. Optimum gravel size which gives the maximum compressive strength

MC is a soil-based product. As explained in literature fraction of soil used as the coarse and fine aggregate of MC mixture. According to the unified soil classification system, the soil has been classified as shown in Table 16. In MC technology soil has been classified on considering the practical usage in the construction. Due to the impracticality of proceeding the hydro-meter testing in the field, wet sieving methods are not using in MC technology. This hydrometer analysis is the process by which fine-grained soils, silts and clays, are graded (Soil which passes through No.40 (425μm)). Though few tests were conducted using wet sieving methods it was difficult to identify the exact particle ranges because of the continuous washout condition of granular particles. Thus, only dry sieving methods are using in MC technology. These sandy fine, silt and clay have been considered at the 'fine particle range in M'C technology. Therefore, in MCB technology the soil has been classified as shown in Table 17.

Table 16: Particle size distribution chart according to Unified soil classification system

Particle type	Sieve sizes	Sub-division
Gravel	Particle passes from 75mm (3-in.) and retained in 4.75mm (No.4) sieve	a. Coarse—passes 3-in. (75-mm) sieve and retained on 3/4-in. (19-mm) sieve. b. Fine—passes 3/4-in. (19-mm) sieve and retained on No. 4 (4.75-mm) sieve.
Sand	Particle passes from 4.75mm (No.4) and retained in 75-μm(No.200)	a. Coarse—passes No. 4 (4.75-mm) sieve and retained on No. 10 (2.00-mm) sieve. b. Medium—passes No. 10 (2.00-mm) sieve and retained on No. 40 (425-μm) sieve. c. Fine—passes No. 40 (425-μm) sieve and retained on No. 200 (75-μm) sieve.
Silt	Soil passing a No. 200 (75-μm)	

Table 17: Soil classification in MCB technology

Particle type	Sieve sizes
Gravel	Particle passes from 19mm (3/4") and retained in 4.75mm (No.4) sieve
Sand	Particle passes from 4.75mm (No.4) and retained in 0.425mm (No.40)
Fine (Sandy fine, silt and clay)	Particle passes from 0.425mm (No.40)

Due to the restriction of the size of MCB block, the range of gravel from 4.75mm to 19mm only using in MCB technology. However, MC wall can expand the vertical boundaries in a wall segment and the methodologies were adopted to find the optimum gravel range which can use in in-situ cast Mud-Concrete wall (MCW).

3.3.1. Materials & methods

It is important to find the possible gravel ranges of the existing soil when finding the optimum gravel range which gives the maximum compressive strength of MCW. Otherwise finding the maximum gravel size which gives the maximum strength is an impractical effort on finalizing the mix design. Therefore, gravelly laterite soil was excavated from 600mm to 900mm depth from the ground level has been used for testing. In order to classify the selected soil, sieve analysis and atterberg limit tests were conducted. Particle size distribution of the soil was obtained by conducting sieve analysis. Liquid limit, plastic limit and plastic index were obtained by conducting Atterberg limit tests by using Casagrande's instrument.

a) Identifying the gravel ranges in the soil

Table 18: Identified gravel ranges in the selected soil

	Gravel range	**Used sieve size (available standard sieve sizes)**
Portion 01	4.75 mm – 10 mm	Sieved through 9.50mm (3/8-in) sieve
Portion 02	4.75 mm – 20 mm	Sieved through 19.00mm (3/4-in) sieve
Portion 03	4.75 mm – 30 mm	Sieved through 31.50mm (1 ¼ -in) sieve
Portion 04	4.75 mm – 40 mm	Sieved through 37.50mm (1 ½ -in) sieve
Portion 05	4.75 mm – 50 mm	Sieved through 50mm (2-in) sieve

According to the particle size distribution obtained from sieve analysis, five gravel ranges were arranged from the selected soil type. To prepare gravel ranges, the soil was air-dried and sieved through 4.75 mm sieve size and separated the gravel from the soil. The retained portion on the 4.75mm sieve was taken as the gravel (particle size >4.75mm). Portion passed through 4.75 mm sieve contained fine (particle size < 0.425 mm) and sand (0.425 mm <particle size < 4.75 mm). Then separated gravel was divided into five (05) equal portions and each portion was sieved and prepared as shown inTable 18.

b) *Preparation of soil composition according to different soil types*

In this methodology, the aggregate composition of MCB was (Table 19) used as a thumb rule to develop the soil. In the selected soil, gravel, sand and fine percentages were found in 55.88%, 36.16% and 7.96% respectively. Therefore, it should be changed according to the aggregate percentages achieved in MCB as shown in Table 19. This can be done by separating fine, sand and gravel from the soil and mixing them together according to the MCB percentages. Practically it is a somewhat difficult task to separate fine particles from soil. Therefore, to obtain 5% fine without separating it, an additional amount of sand had to be added to the selected soil. Therefore, to obtain total 45kg of soil sample with the above compositions the amount of gravel, sand and fine had to be added according to Table 20.

Table 19: Aggregate composition of MCB

Aggregate type	Percentage from total dry mix
Gravel (sieve size 4.75mm ≤ gravel≤ 20mm)	≤ max.10% (min. 5%)
Sand (sieve size 0.425mm ≤ sand ≤4.75 mm)	55-60%
Fine (≤ sieve size 0.425mm)	30-35%

Table 20: Added aggregate portions to develop the soil according to the MCB mix proportions

Aggregate type	Added amount (kg)
Gravel	15.75
Sand	16.75
Fine	12.5

Here the attempt was to prepare five (05) soil types of five (05) gravel ranges as identified. Therefore, the prepared gravel ranges (Table 18) were added to the developed soil samples according to the identified best mix of MCB shown in Table 19. That prepared five (05) soil types consist of five (05) gravel ranges shown in

Table 21. For each soil type, sieve analysis was conducted to check the particle size distribution of prepared soil samples.

Table 21: Prepared soil types

Soil Type	Gravel range
01	4.75 mm – 10 mm
02	4.75 mm – 20 mm
03	4.75 mm – 30 mm
04	4.75 mm – 40 mm
05	4.75 mm – 50 mm

c) Cube casting and compressive strength testing

150mmx 150mmx 150mm MC cubes were cast for five different soil types shown in Table 21. Six cubes were cast in each soil type to check wet and dry compressive strength. Four percent (4% of the total dry mix) minimum amount of cement was added. Each soil type prepared in Table 21 was developed according to the achieved optimum mix of MCB. Sufficient amount of water was added to achieve the workable MC mixture which could be poured into 150mm x 150mm x 150mm moulds. MC mixture was poured into 150x150x150 mm cast iron moulds in two layers and a tamping rod used to remove the air existing in the mixture. Once the casting process was completed, cubes were cured 14 days and kept 28 days to gain the strength. The compressive strength of the MC cubes was tested after 28 days. To check the wet compressive strength, the relevant cubes were immersed in water for 24 hours (to obtain saturated condition) prior to the load testing. Three (03) cubes were tested for each type and average values were calculated accordingly.

3.3.2. Results and discussion

a) Soil Classification

Figure 15 shows the overall particle size distribution of selected soil. According to the particle size distribution, gravel, sand and fine percentages are 55.88%, 36.16% and

7.96% respectively. According to the results obtained from the Atterberg limit test (Table 22) and the particle size distribution (Figure 15), this soil can be classified as "GW-GM" (well-graded gravel with silt and sand)" soil according to the Unified Soil Classification System(ASTM, 2016). Also, the coefficient of gradation (C_k) of the soil is 1.35 indicates the soil as a well-graded one.

$C_k = d^2_{30} / (d_{60} \times d_{10}) = (96^2)/(100x68) = 1.36$

(Ck between 0.5 and 2.0 indicates a well-graded soil)

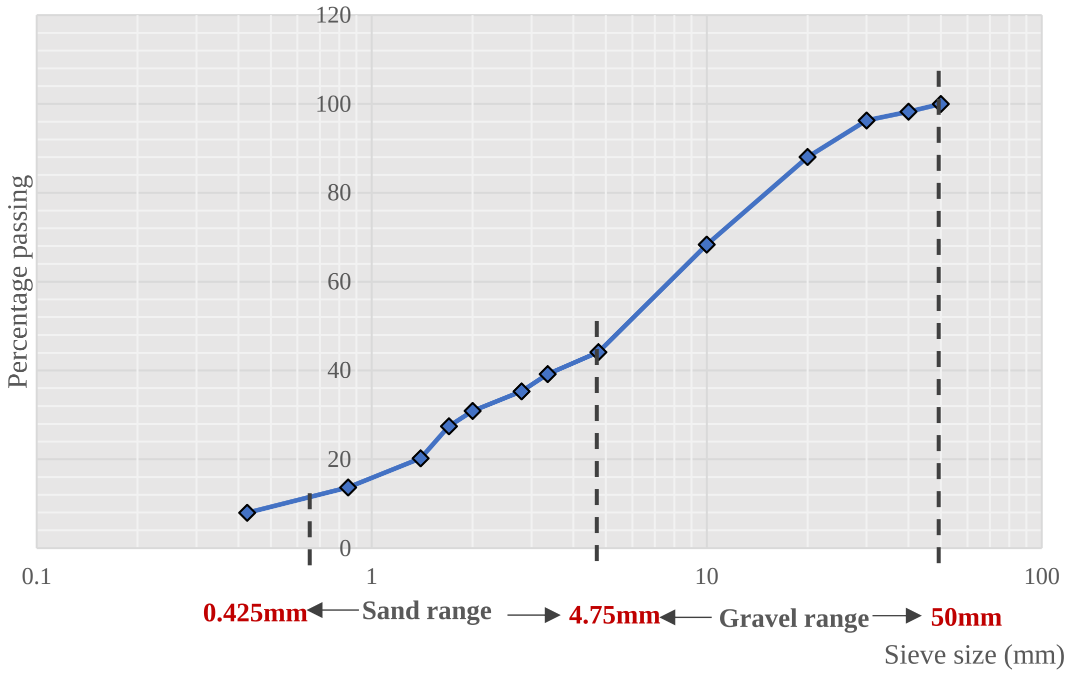


Figure 15: Particle Size Distribution of existing soil samples

Table 22: Liquid and plastic limit

Description	Values
Liquid limit	55.87%
Plastic limit	38.10%
Plastic Index	17.77%

b) Compressive Strength of Mud-Concrete cubes

Average wet compressive strengths and dry compressive strength of MC cubes have shown in Table 23. According to the results of Table 23, Figure 16 graph can be plotted.

Table 23: Results of average wet and dry compressive strength of 150x150x150mm cast blocks with prepared different soil samples

Soil type	**Gravel Size in soil (mm)**	**Avg. wet strength(N/mm^2)**	**Avg. dry strength(N/mm^2)**
01	4.75 – 10	1.18	2.15
02	4.75 – 20	1.45	2.57
03	4.75 – 30	1.94	3.21
04	4.75 – 40	1.70	3.00
05	4.75 – 50	1.49	2.73

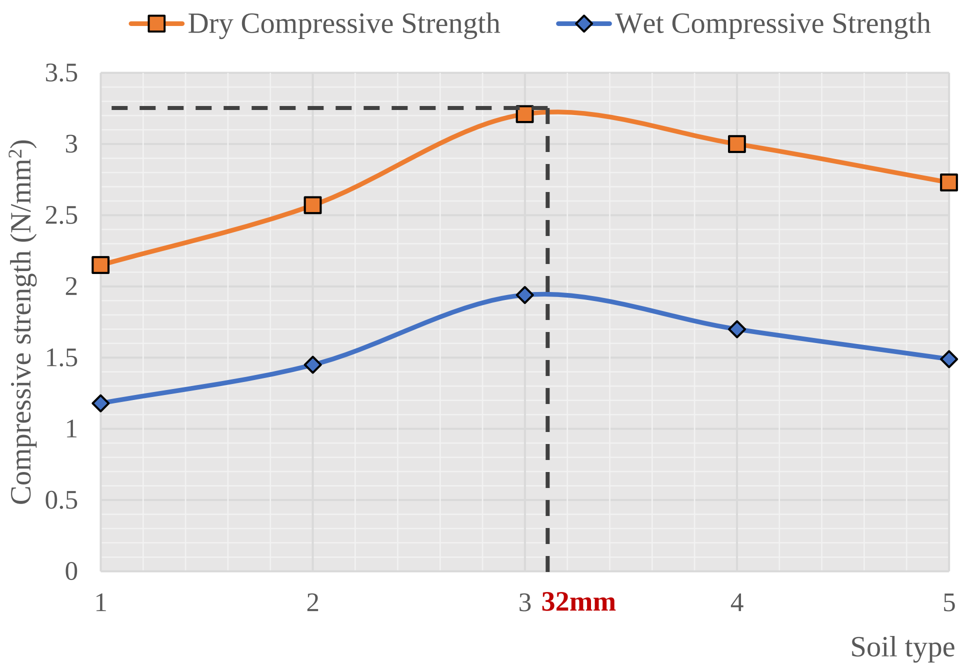


Figure 16: Wet & dry compressive strength curves for different soil types

Figure 16 shows the variation of dry and wet compressive strength of MC cubes against different gravel sizes (gravel ranges or soil types). When the gravel size is increased from 10mm to 50mm, the compressive strength of MC cubes do increase gradually and then decrease. According to Figure 16, 4.75mm to 30mm gravel range (Soil Type 03) has given the highest wet and dry compressive strength for MC cubes.

Soil type: 01 (soil prepared with 4.75mm to 10mm gravel range) has given the lowest wet and dry compressive strength of MC cubes. Therefore, it can clearly see that increasing gravel size does not lead to increase the compressive strength of MC cubes always.

According to the results in Table 23 and Figure 16, there is a considerable effect from gravel size to the strength of Mud-Concrete. When gravel range is changed from 4.75 - 10mm to 4.75 – 30mm, dry strength of cubes has increased 49% and wet strength has increased by 64%. According to Figure 17, when gravel size is increased beyond 32mm, the compressive strength of cubes decreases gradually.

c) Comparison of particle size distribution among prepared soil types

Sieve analysis was conducted to obtain the particle size distribution of each soil samples developed in Table 21. According to the results obtained from sieve analysis (Figure 17) graph was plotted to show the comparison of particle size distribution between the prepared soil types.

Particle size distribution of soil has a great effect on the compressive strength on MC. If the soil is a well-graded one, it helps to form a packed soil structure with low voids. According to Figure 17, the prepared each soil type shows a well-graded particle size distribution except soil type 01. Because soil type 01 got the low quantity of gravel in the mix. In addition, it was observed that when the size of gravel was increased, the amount of water add to obtain a workable mixture has to be increased. Addition of water can cause to increase the porosity of cubes and high porosity leads to a decrease in the compressive strength of MC cubes.

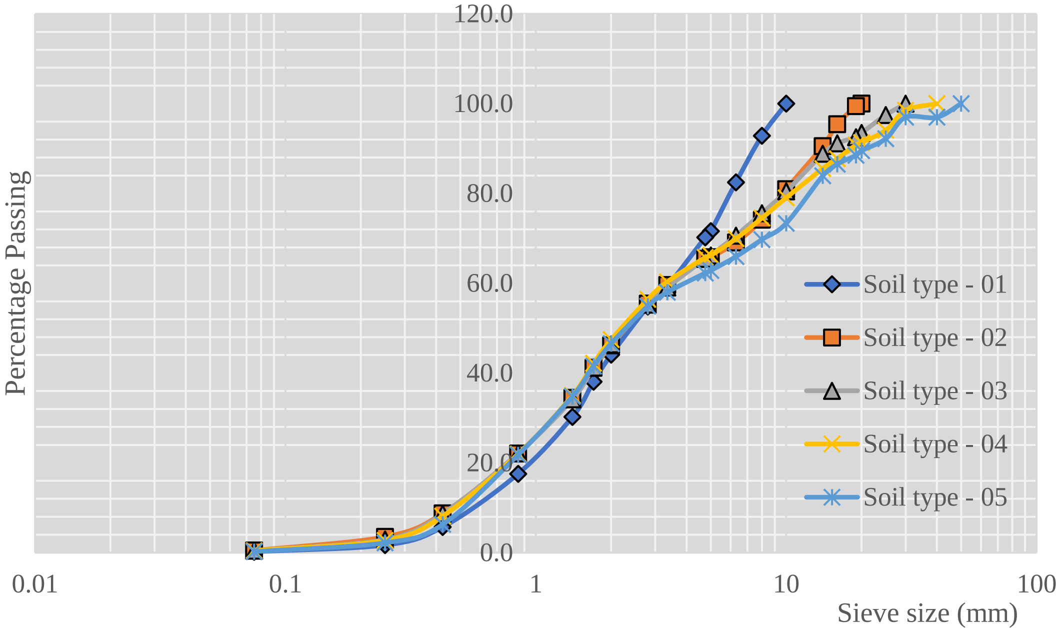


Figure 17: Comparison of particle size distribution for prepared soil types

The results conclude that there is a probability of finding 4.75mm to 50mm gravel ranges in most commonly available native gravely laterite soil. When maximum gravel size in soil increases from 10mm to 50mm, strength increases at the beginning and later it decreases. The maximum strength was given by soil type 03 which consisted of gravel in 4.75mm – 30mm range. Increasing gravel size does not lead to increase the compressive strength of mud concrete always. The compressive strength of mud concrete depends on both gravel size and the particle size distribution of the soil. Therefore, it could be concluded that soil type 03 prepared by adding 4.75mm – 30mm gravel, gives maximum compressive strength. Thus, the effective gravel range of a MCW could consider as 4.75mm-32mm. Therefore, the soil which is using to construct MC walls must sieve through standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix (ASTM, 2001).

3.6. Finding optimum Gravel: Sand: Fine proportion for the best workable mix

After identifying the optimum gravel range, it was urged to find the optimum gravel: sand: fine proportions for the best mix of in-situ cast Mud-Concrete load-bearing walls. Therefore, few steps were used in the methodology to design the research as follows;

1. Finding the particle size distribution of existing soil samples
2. Keep the known fine content and change the sand/gravel percentage to prepare the soil samples for mix and again do the sieve analysis to check the grading curves of developed soil samples
3. Keep the cement and water percentage constant in each cast sample
4. Cure the cast block for 14 days and keep until 28 days to check the crushing strength
5. Finding the effect of different aggregate percentage on compressive strength

3.6.1. Materials and methods

a) Finding the existing particle size distribution of soil & developing the soil mix.

Figure 18: Conducting sieve analysis test to find the existing particle size distribution of soil

Prior to identifying the fine: gravel proportions, it was needed to test the existing particle size distribution of the selected soil for the experiment (Figure 18). This analysis will help to understand the gradation of soil samples which is expected to use in testing. According to testing procedures in section 3.5, optimum gravel range was achieved as 4.75mm-32mm. Therefore, all the gravelly laterite soil samples were sieved through standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix(ASTM, 2001). Total dry soil sample which was used to do the sieve analysis should not less than 2000-3000g (Table 24).

Table 24: Needed minimum mass of portion according to the nominal diameter of largest particle size (mm)

Nominal Diameter of the largest particle (mm)	Approximate Minimum mass of Portion (g)
9.5	500
19.0	1000
25.4	2000
38.1	3000
50.8	4000
75.0	5000

Table 25: Average percentage of existing particle size distribution of soil

	Sieve Analysis: Soil Sample - A	Sieve Analysis: Soil Sample - B	Sieve Analysis: Soil Sample - C	Average
Gravel	47.38%	46.80%	47.29%	47%
Sand	40.28%	43.18%	41.52%	42%
Fine	12.34%	10.01%	11.20%	11%

Randomly selected 03 gravely laterite soil samples extracted from locality (Sample A,

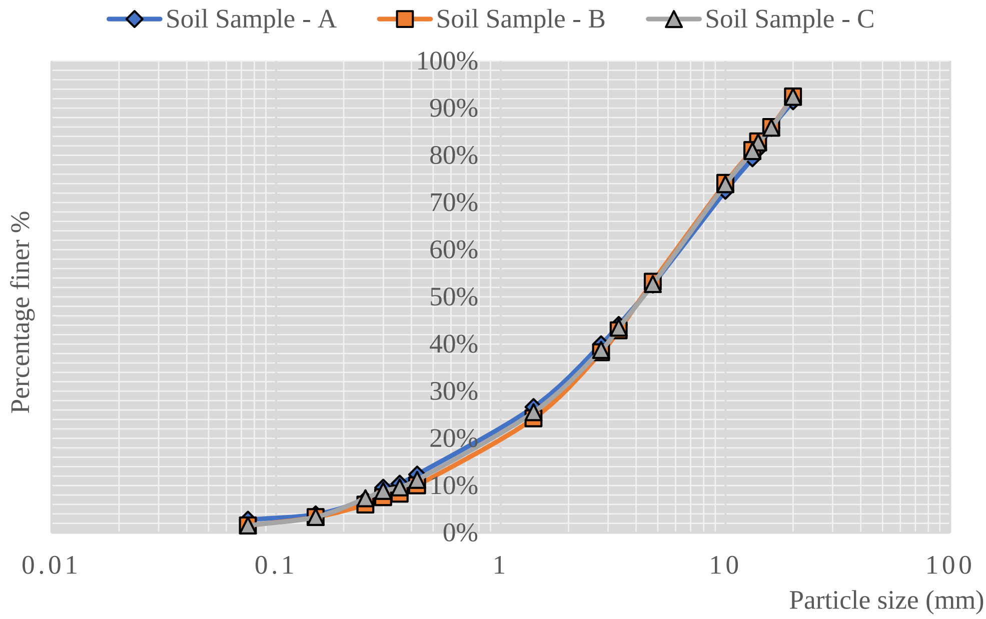


Figure 19: Comparison of particle size distribution of different soil samples use for sieve analysis

B and C) were used to do the sieve analysis. Then the average Particle size distribution values were taken to minimize the errors in testing (Table 25). According to the results it was understood that the used soil was well-graded (Figure 19 and Table 25). The coefficient of gradation (C_k) of the soil is 1.33 and it indicates the soil as a well-graded one.

$C_k = d^2_{30} / (d_{60} \times d_{10}) = (100^2)/(100x75) = 1.33$

(Ck between 0.5 and 2.0 indicates a well-graded soil)

After identifying the exiting particle size distribution of native soil, the next step is to check the optimum sand: gravel ratio for the best mix of MCW. Then the first attempt was to keep the fine percentage constant and changing the gravel and sand percentages to check the optimum sand: gravel ratio of the mix. Therefore, existing mix proportions of the MCB(Gravel-35%, Sand-60%, Fine-5%) (Arooz & Halwatura, 2017) was used as an index to change the gravel: sand proportions of the sample mixtures. Then gravel range was changed from 25% - 65% to check the optimum gravel: sand ratio (Table 26 &Table 27).

Table 26: Cast samples to check the optimum gravel: sand ratio

Sample No:	Gravel %	Sand %	Fine %
B1	25	70	5
A0	35	60	5
A1	45	50	5
A2	55	40	5
A3	65	30	5

Table 27: Detail portions of cast samples to check the optimum gravel: sand ratio

Sample No:	Gravel Range	sample weight (kg)	Existing Propotions			Proposed Propotions			Exisitng fine weight (kg)	To keep fine 5%, needed weight of the soil sample	Added/removed		Used water amount (L)
			Gravel	Sand	Fine	Gravel	Sand	Fine			Gravel	Sand	
B1	25	17	47%	42%	11%	25%	70%	5%	1.87	37.4	1.360	19.04	10
A0	35	17	47%	42%	11%	35%	60%	5%	1.87	37.4	5.100	15.3	10
A1	45	17	47%	42%	11%	45%	50%	5%	1.87	37.4	8.840	11.56	10
A2	55	17	47%	42%	11%	55%	40%	5%	1.87	37.4	12.580	7.82	10
A3	65	17	47%	42%	11%	65%	30%	5%	1.87	37.4	16.320	4.08	10

b) *Preparation of Mud-Concrete mix & determination of workability*

After preparing each soil sample (adding or removing gravel & sand) 3kg of soil was extracted to analyse the particle size distribution of developed soil again. Because it is necessary to check whether the prepared soil samples were well graded or not. According to the results (Figure 20) obtained through the sieve analysis, it was understood that developed soil samples were well-graded.

Once the sieving procedure was completed each weighted ingredient (soil, gravel, sand, cement and water) were mixed in a concrete mixer machine. Constant cement (4 % from total weight of developed soil sample) and water percentage was used in each cast sample (Table 28). Ordinary Portland cement (Sri Lankan Standard Institute, 2007) was used as the stabiliser when casting the MC cubes. 150mm x 150mm x150mm size concrete cube moulds were used for the testing procedures. Six (06) cubes were cast from each sample to check the wet and dry compressive strength. Then total 30 cubes were cast for 05 nos. of samples. As a thumb rule cube casting was started from A0 sample - 35% gravel, 60% sand and 5% fine which is the best mix design achieved for Mud-Concrete block. Then B1 sample (25% gravel, 70% sand and 5% fine) and A1 sample (45% gravel, 50% sand and 5% fine) were cast to check the pattern of compressive strength. As per the results obtained it was understood the increasing gravel percentage from 35% to 45% has increased the compressive strength of the block. Then decisions were taken to increase the gravel percentage and check the pattern of changing the compressive strength of cubes. Ultimately, each cast sample were oven dried to measure the total water percentage in the dry mix (Table 28). Total water percentage was given a slight increment (the difference was ~1%) while increasing the gravel range. Cast blocks were kept to self-compaction and moulds were dismantled after 48 hours. Then cast blocks were covered from wet gunny bags for 14 days for curing. Then wet & dry compressive strength of each cast block were tested after 28 days.

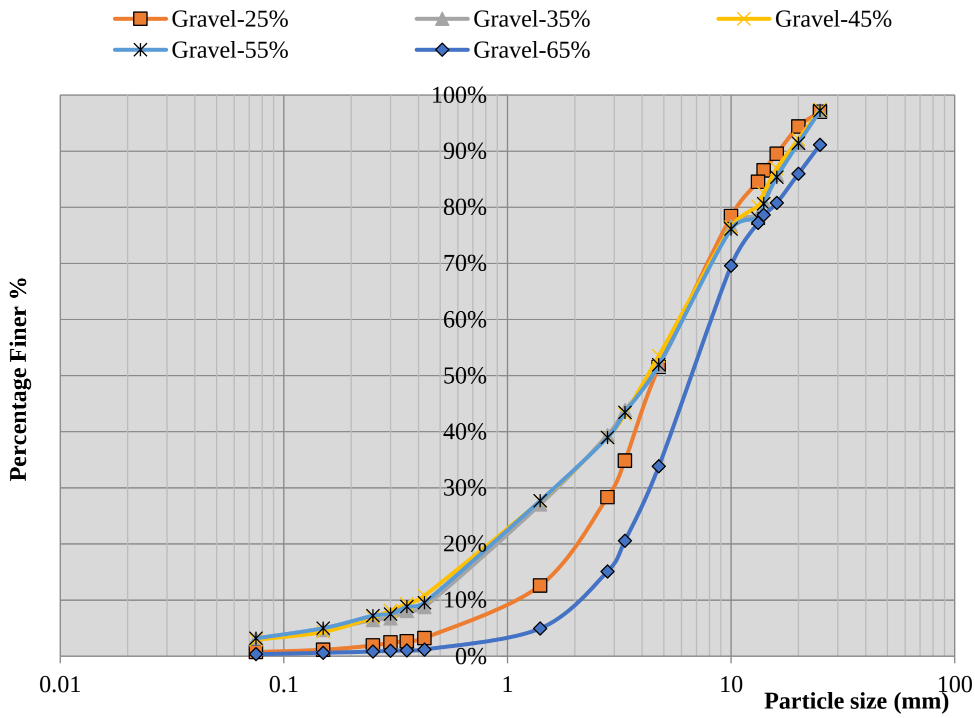


Figure 20: Particle size distribution of developed soil samples

Table 28: Detail proportions of used cement stabilizer% and water % for Mix design

Sample Number	Cement 4% from total mix (kg)	Added water (L) for the workable mix	Total water % in the dry mix
B1-25	1.5	10	26.09%
A0-35	1.5	10	26.91%
A1-45	1.5	10	27.13%
A2-55	1.5	10	27.55%
A3-65	1.5	10	27.83%

3.6.2. Results & discussion

The results of dry and wet compressive strength for different gravel: sand ratios are shown in Table 29. According to the results, A1 sample – 45% Gravel: 50% Sand ratio gives the maximum wet & dry compressive strength for the mix design of in-situ cast Mud-Concrete load bearing wall (Table 29).

Table 29: Dry & Wet compressive strength results for different gravel: sand ratios

Sample No:	Gravel %	Sand%	Dry Strength (N/mm^2)	Wet Strength (N/mm2)
B1	25	70	2.01	1.13
A0	35	60	2.42	1.56
A1	45	50	2.78	1.73
A2	55	40	2.48	1.64
A3	65	30	2.04	1.33

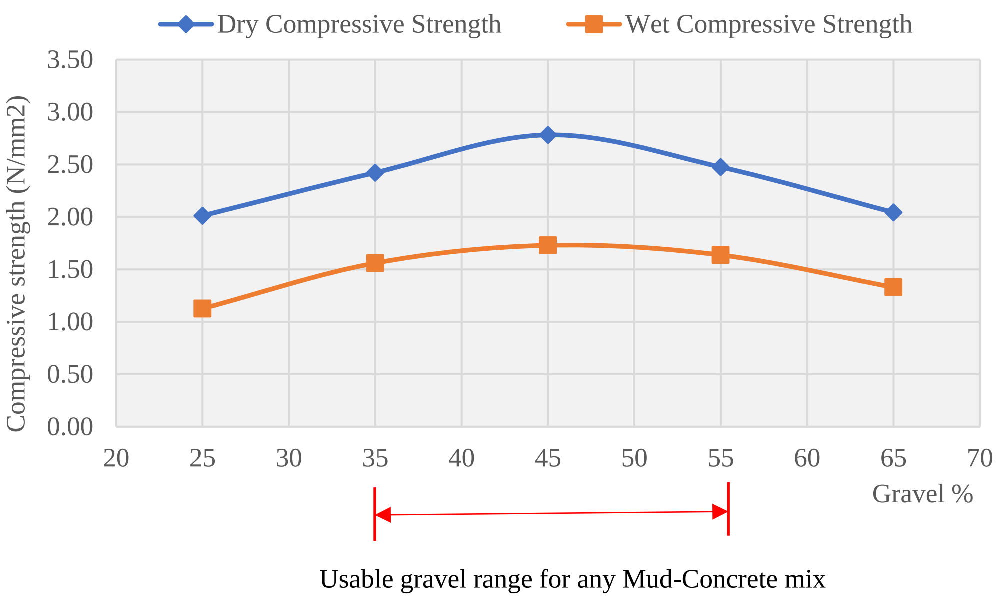


Figure 21: Comparison of dry & wet compressive strength achieved for different gravel: sand ratios

Further the results show that usable gravel range in soil for Mud-Concrete construction is limited for 35%-55% with 4% cement. As recorded in literature (Arooz & Halwatura, 2017), MCB followed the minimum strength requirement given in Sri Lankan standards (SLS standards) for compressed stabilised earth blocks (CSEB) manufactured with cement stabilizer as the minimum requirement of 28 days wet compressive strength for a block should be 1.2 N/mm^2, and dry compressive strength of a block should be 2.8 N/mm^2 with minimum of 4% cement stabilizers (Sri Lankan Standard Institute, 2009). Therefore, it is recommended to use 35%-55% gravel ranges with 4% cement in any Mud-Concrete construction.

However, according to the Walker et al, 1.0 N/mm^2 wet compressive strength and 2.0 N/mm^2 dry compressive strength (with minimum 4% cement)were recommended for stabilized load-bearing earth walls in 28 days age of the wall (Peter Walker et al., 2010a). According to the results, 25%-65% gravel range still achieve the required strength of MCW.

The results depict that optimum gravel range was achieved as 4.75mm-32mm. Therefore, all soil samples used for casting should be sieved from standard 31.5 mm (1.25 inch) sieve size. With a minimum 4% of cement, 45% Gravel: 50% Sand ratio gives the maximum wet & dry compressive strength for the mix design of in-situ cast MC load bearing wall. 5% fine was maintained as fine percentage always needed to be kept in low quantities in MC construction.

- Fine - 5% (≤ sieve size 0.425mm)
- Sand - 50 % (sieve size 0.425mm ≤ sand ≤4.75 mm)
- Gravel - 45% (sieve size 4.75mm ≤ gravel≤ 32mm)

Usable gravel range in soil for any MC construction is limited for 35%-55% with 4% cement, as sand is limited to 60%-40%. Also, increasing gravel percentage does not lead to increase the compressive strength of MC always. Its compressive strength will depend on the particle size distribution of developed soil, optimum gravel size and the optimum gravel: sand ratio of the mix. Continuous particle size distribution provides soil particles to form a packed soil structure with minimum voids and this quality helps to enhance the compressive strength of self-compacting in-situ cast MC load-bearing wall.

There is a slight increment in used total water percentage of the dry mix when increasing the gravel range. However, it is difficult to conclude the effect of water percentage in the dry mix on compressive strength of the MC wall. Therefore the values of water-cement ratio should be standardised in MCW construction.

3.7. Developing grading curves and standardising the water percentage from dry mix

This section of research designed due to the difficulty of keeping the exact water amount of the dry mix even though the same water amount was added to the mix.

Then the question raised whether this ambiguous behaviour of water in the dry mix will affect to the strength of the MC wall? Even though there is an optimum mix for cast MC wall, it is essential to use the closest best mix of gravel, sand and fine. This will ensure the best use of available soil at the close vicinity to minimize the embodied energy and the construction cost. MC as a self-compacting material, it uses considerably high-water content in the mix. Evidently, increasing the water content reduces the compressive strength of the mix. Therefore, understanding the strength behaviour with respect to different water contents is important, as even a small change in the water content can drastically change the assumed grade strength of the final product.

Then, the initial methodology was adopted to check the behaviour of water and its effect on the strength of MC wall. Thus, to obtain a proper data matrix, the initial framework was designed in few steps as follows;

a) Checking the strength behaviour in **different gravel ranges and different water percentages** in dry mix
b) Checking the strength behaviour with **different cement quantities while adding same water content** to the mix
c) Checking the strength behaviour with **different cement quantities while adding different water content** to the mix
d) Developing the grading curves for dry and wet compressive strength of Mud-Concrete load-bearing walls

3.6.1. Materials and methods

a) Finding particle size distribution and developing the soil according to the achieved the best mix.

According to the previous testing procedures, optimum gravel range was achieved as 4.75mm-32mm. Therefore, all the soil samples were sieved through standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix (Bandara, Arooz, & Halwatura, 2016).

The selected total dry soil sample (which was used to do the sieve analysis) should not be less than 2000-3000g to minimize the errors in testing (ASTM D7928 -17, 2017). Randomly extracted three gravelly laterite soil samples (Sample A, B and C) were used to do the sieve analysis (Table 30). Then the average Particle size distribution values were taken to minimize the errors in testing (Figure 22).

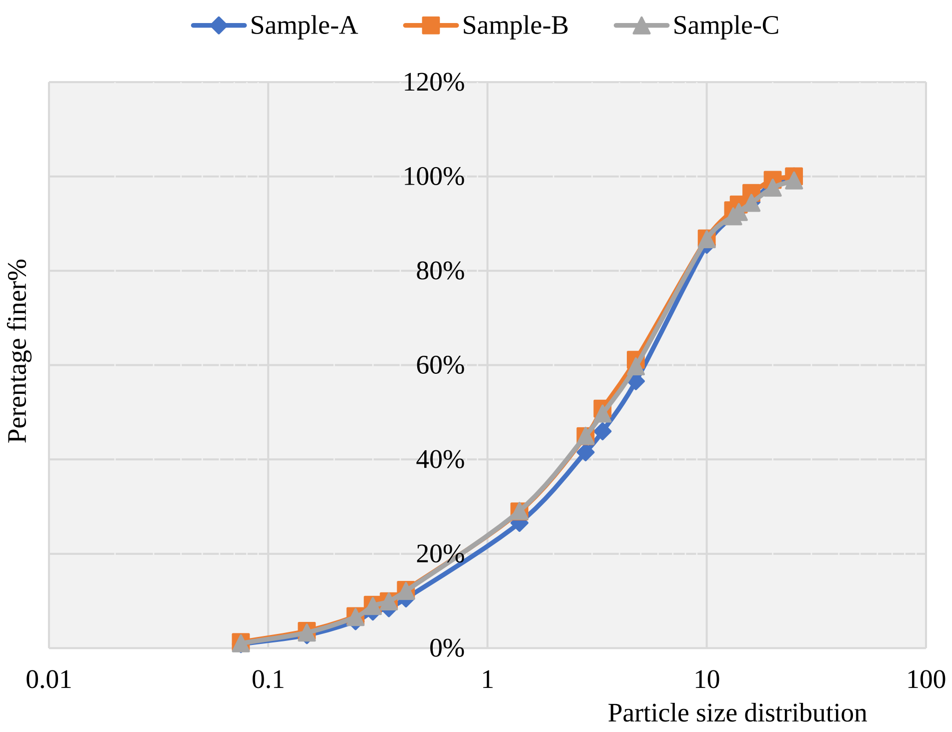


Figure 22: Particle size distribution of selected soil

The coefficient of gradation (C_k) of the soil is 1.18 indicates the soil as well graded one.

$C_k = d^2_{30}/(d_{60} \times d_{10}) = (100^2)/(100x85) = 1.18$

(Ck between 0.5 and 2.0 indicates a well-graded soil)

Table 30: Average particle size distribution of selected soil

Type	Sample-A	Sample-B	Sample-C	Average value	Values of best mix design
Gravel	43.42%	38.89%	40.25%	40.85%	45%
Sand	46.05%	48.79%	47.62%	47.49%	50%
Fine	10.53%	12.32%	12.13%	11.66%	5%

Table 31: Physical properties of selected gravelly laterite soil for testing purposes

Properties	Values
Liquid limit	35.99%
Plastic limit	21.78%
Plasticity index	14.95%
Dry density (soil gravel)	1600 -1800 kg/m^3
Wet density (soil gravel)	1800 - 2100 kg/m^3

Industrially available Portland cement was used as the stabiliser for this entire research (Type I, strength class 42.5N) [21]. For the experiment purpose, one-line production of cement was used and stored in the required lab condition before using it for the mix development.

b) Step 01: (S1) - Checking strength behaviour in different gravel ranges and different water percentages in the dry mix.

Initially, the research was designed to understand the behaviour of strength with the different MC mix (changing the gravel range) with different water (moisture) percentage in different time periods.

The identified usable gravel range is 35%-55% in Mud-Concrete wall construction and keeping 45% of gravel is giving a high strength in the mix design. Therefore, the first attempt was to understand the effect of gravel percentage with different moisture content and build a data matrix to see the co-relationship between the gravel percentage and water percentage in the dry mix. Then according to the results received next experimental steps of research was designed.

The virgin soil was developed up to the proportions of each expected mix design according to the results of sieve analysis (Table 32). The gravel range was managed in 35%, 45% and 55% in the mix. Water content was increased from 250ml gradually and five set of block samples were prepared for each specimen type. Four percent cement was used in each specimen as 4% is the minimum cement percentage which can obtain the standard compressive strength of MCB (Arooz & Halwatura, 2017). Three cubes will be cast for each set to take the average dry compressive strength and 18 blocks were cast in each set (Table 32). Total 90 blocks were cast to get the data matrix. Each prepared sample was oven dried to check the water percentage from dry mix. After 14 days of curing, cubes were crushed in 14 days and 28 days to check the dry compressive strength.

Table 32: Added aggregate proportions to develop the existing soil according to the identified mix designs

Total mix weight needed to cast 18 nos. of 150x150x150mm blocks in one set of specimens (To keep 5% fine in the mix needed total mix weight)								128.26 kg	
Added Cement (4% of the total weight of the mix)								5.13 kg	
Sample No:	Sample weight of soil (kg)	Existing Proportions & weight			Proposed Proportions & weight			Added gravel to keep the 5% fine in the mix	Added sand to keep the 5% fine in the mix
		Gravel	Sand	Fine	Gravel	Sand	Fine	Gravel	Sand
35% gravel	55	40.85%	47.49%	11.66%	35%	60%	5%	16.01kg	50.83kg
		22.47 kg	26.1 kg		38.48kg	76.96kg	6.413kg		
45% gravel	55	40.85%	47.49%	11.66%	45%	50%	5%	35.25kg	38.01kg
		22.47 kg	26.1 kg		57.72kg	64.13kg	6.413kg		
55% gravel	55	40.85%	47.49%	11.66%	55%	40%	5%	48.08kg	25.18kg
		22.47 kg	26.1 kg		70.54kg	51.30kg	6.413kg		

c) ***Step 02: (S2) – Checking the strength behaviour with different cement quantities while adding same water content to the mix.***

According to the results of sieve analysis, the soil was developed for the best mix design (45% gravel, 50% sand and 5% fine) of MC load-bearing wall. The cubes were cast using 4%, 6%, 8%, 10% cement from the total weight of the dry mix. Same water amount (4.5liters) was added to all the samples in preparing the MC mix (Table 33). Simultaneously, part of each sample was oven dried (105 ºC constant temperature) to check the water percentage from the dry mix. After 14 days of curing dry and wet compressive strength were measured in 07, 14, 21, 28 days. Three cubes for dry compressive strength and three cubes for wet compressive strength were cast in each set of testing within 07, 14, 21, 28 days and altogether 120 cubes were cast to get the total set of data. Four days cube strength also considered and tested in this procedure to minimize the errors in obtained data.

Table 33: Developed mix design for each sample varying the cement %

Total mix weight needed to cast 03 nos. of 150x150x150mm blocks in one set of specimens (To keep 5% fine in the mix needed total mix weight)								23.32 kg	
Sample weight of soil to cast 03 nos. of blocks								10kg	
Added water amount to the mix				4.5liters (19% of the total mix)					
Sample No:	Existing Proportions & weight			Proposed Proportions & weight			Added gravel	Added sand	Added cement
	Gravel	Sand	Fine	Gravel	Sand	Fine	Gravel	Sand	Cement
4% Cement	40.85%	47.49%	11.66%	45%	50%	5%	6.41kg	6.91kg	0.9kg
	4.09 kg	4.75 kg		10.49kg	11.66kg	1.166kg			
6% Cement	40.85%	47.49%	11.66%	45%	50%	5%	6.41kg	6.91kg	1.4kg
	4.09 kg	4.75 kg		10.49kg	11.66kg	1.166kg			
8% Cement	40.85%	47.49%	11.66%	45%	50%	5%	6.41kg	6.91kg	1.87kg
	4.09 kg	4.75 kg		10.49kg	11.66kg	1.166kg			
10% Cement	40.85%	47.49%	11.66%	45%	50%	5%			2.33kg
	4.09 kg	4.75 kg		10.49kg	11.66kg	1.166kg			

d) Step 03: (S3) - Checking the strength behaviour with different cement quantities while adding different water content to the mix.

Table 34: W1 dry strength (for 18 blocks) - Example of developing soil for best mix design

Total mix weight needed to cast 18 nos. of 150x150x150mm blocks in one set of specimens (To keep 5% fine in the mix needed total mix weight)					128.26kg		
Sample No:	Sample weight of soil (kg)	Existing Proportions & weight			Proposed Proportions & weight		
		Gravel	Sand	Fine	Gravel	Sand	Fine
W1 – Dry strength	55	40.85%	47.49%	11.66%	45%	50%	5%
		2.47 kg	26.1 kg		57.72kg	64.13kg	6.413kg
Added gravel to keep the 5% fine in the mix					35.25kg		
Added sand to keep the 5% fine in the mix					38.01kg		

According to the results of sieve analysis, soil samples were developed to achieve the best mix of Mud-Concrete load-bearing wall. The cubes were cast using 4%, 6%, 8%, 10% cement and adding different water amounts (W1, W2, W3, W4 and W5). Water content was increased from 250ml gradually and 18 blocks were cast to check the dry compressive strength and another 18 blocks were cast to check the wet compressive strength in one set of samples (Table 34). Part of each sample was oven dried (105 °C constant Temperature) and measured the water percentage from the dry mix. Total

600 blocks were cast to get the data matrix. After 14 days of curing blocks were tested in 7, 14, 21 and 28 days to check the wet and dry compressive strength. Four days cube strength also considered and tested in this procedure to minimize the errors in obtained data.

Step 04: (S4) – Developing the grading curves for dry and wet compressive strength of Mud-Concrete load-bearing wall and standardizing the water percentage from the dry mix.

After conducting all these tests, the relationship between strength vs. water/cement ratio was identified through grading curves. An equation was derived from the obtained data matrix and it helped to determine the actual strength of Mud-Concrete load-bearing wall in a standard water percentage from the dry mix.

3.6.2. Results & Discussion

a) S1 –Strength behaviour of Mud-Concrete load-bearing wall in different gravel ranges and different water percentages in the dry mix.

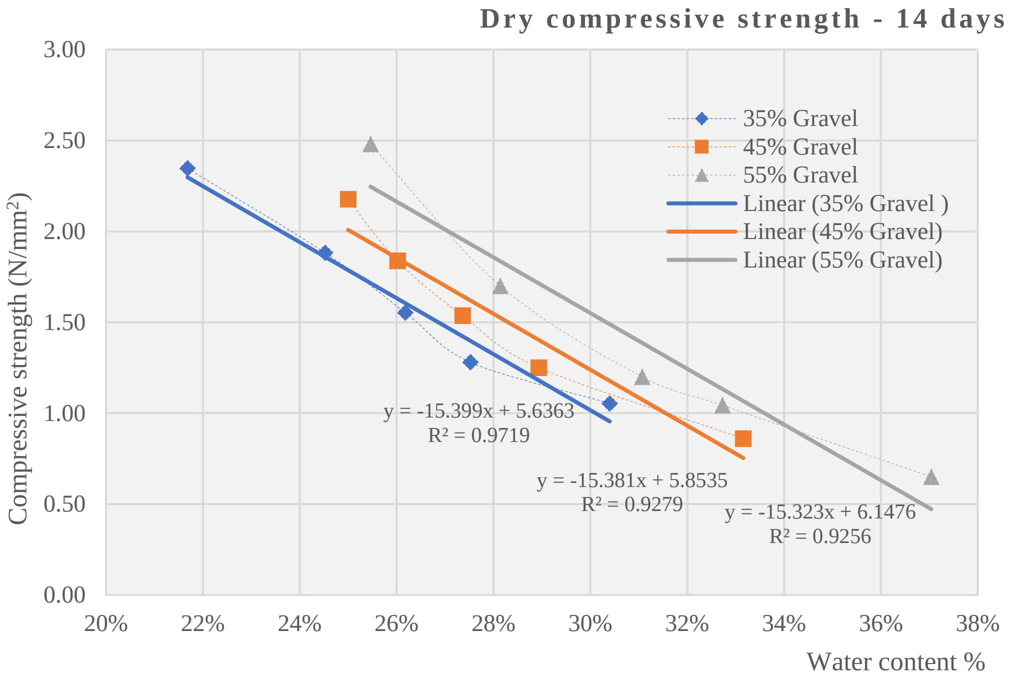


Figure 23: The dry compressive strength of Mud-Concrete in 14 days of the age of Mud-Concrete in different gravel ranges and different water percentages in the dry mix.

Table 35: The Dry compressive strength of Mud-Concrete in 14 & 28 days of the age of Mud-Concrete in different gravel ranges and different water percentages in the dry mix

Sample No:	Added water amount (ml)	Water % dry mix			Compressive strength in 14 days (N/mm²) with 4% cement			Compressive strength in 28 days (N/mm²) with 4% cement		
		35% gravel	45% gravel	55% gravel	35% gravel	45% gravel	55% gravel	35% gravel	45% gravel	55% gravel
W1	3250	21.7%	25.0%	25.5%	2.35	2.18	2.48	2.51	2.40	2.50
W2	3500	24.5%	26.0%	28.1%	1.88	1.84	1.70	2.14	2.08	1.78
W3	3750	26.2%	27.4%	31.1%	1.55	1.54	1.20	1.80	1.78	1.33
W4	4000	27.5%	28.9%	32.7%	1.28	1.25	1.04	1.47	1.58	1.10
W5	4250	30.4%	33.2%	37.0%	1.05	0.86	0.65	1.19	1.05	0.72

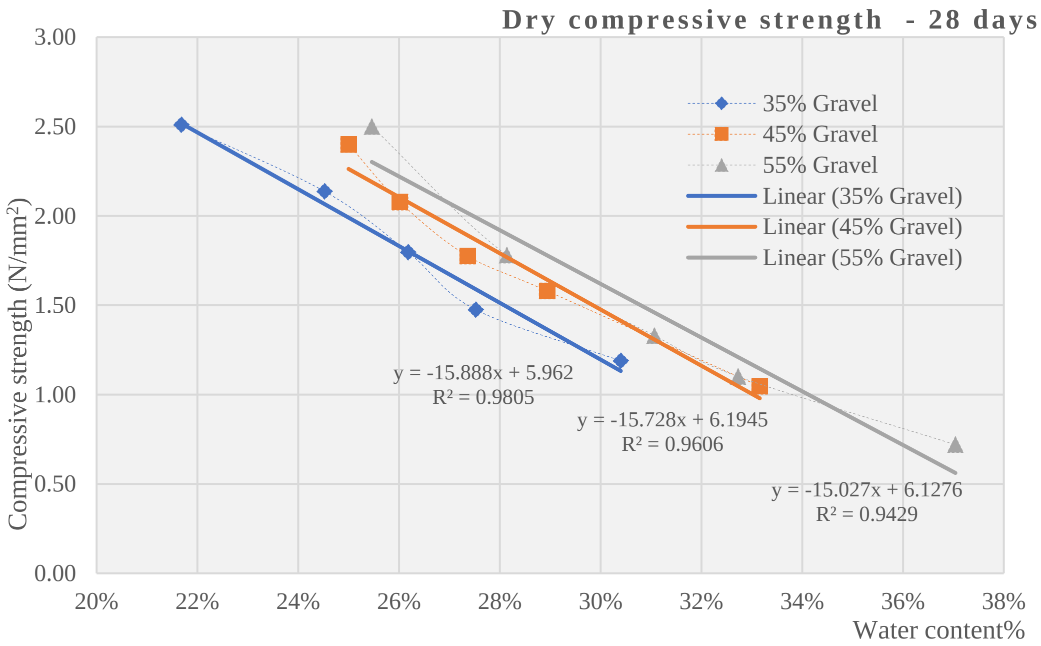


Figure 24: The dry compressive strength of Mud-Concrete in 28 days of the age of Mud-Concrete in different gravel ranges and different water percentages in the dry mix.

b) S2 – Strength behaviour of Mud-Concrete load-bearing wall with different cement quantities while adding same water content to the mix.

Table 36 and Table 37, show that final water percentage from the dry mix is different though the same water amount was added to the all samples.

Table 36: Water percentage in dry mix - Blocks cast to check the wet compressive strength

	To check wet strength of Mud-Concrete	*4 days*	*7 days*	*14 days*	*21 days*	*28 days*
4% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	18.59	20.15	22.17	22.11	23.42
6% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	19.59	20.15	25.51	23.57	24.12
8% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	20.31	22.59	23.32	27	23.57
10%Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	20.52	22.91	25.72	26.48	24.6

Table 37: Water percentage in dry mix - Blocks cast to check the dry compressive strength

	To check dry strength of Mud-Concrete	*4 days*	*7 days*	*14 days*	*21 days*	*28 days*
4% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	20.15	22.72	26.17	23.1	23.42
6% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	19.59	19.15	23.51	27.5	23.21
8% Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	20.31	25.59	24.6	24.98	20.67
10%Cement	Added water amount (Liter)	4.5	4.5	4.5	4.5	4.5
	Water% from dry mix	19.52	24.91	24.72	22.48	19.6

Table 38: Wet compressive strength with different cement percentages

Added cement % to the mix	Wet strength (N/mm^2)				
	4 days	7 days	14 days	21days	28 days
4%	0.77	0.78	0.83	0.97	0.84
6%	1.06	1.39	0.98	1.51	1.54
8%	1.49	1.84	2.55	2.32	2.96
10%	1.93	2.61	2.93	3.16	3.62

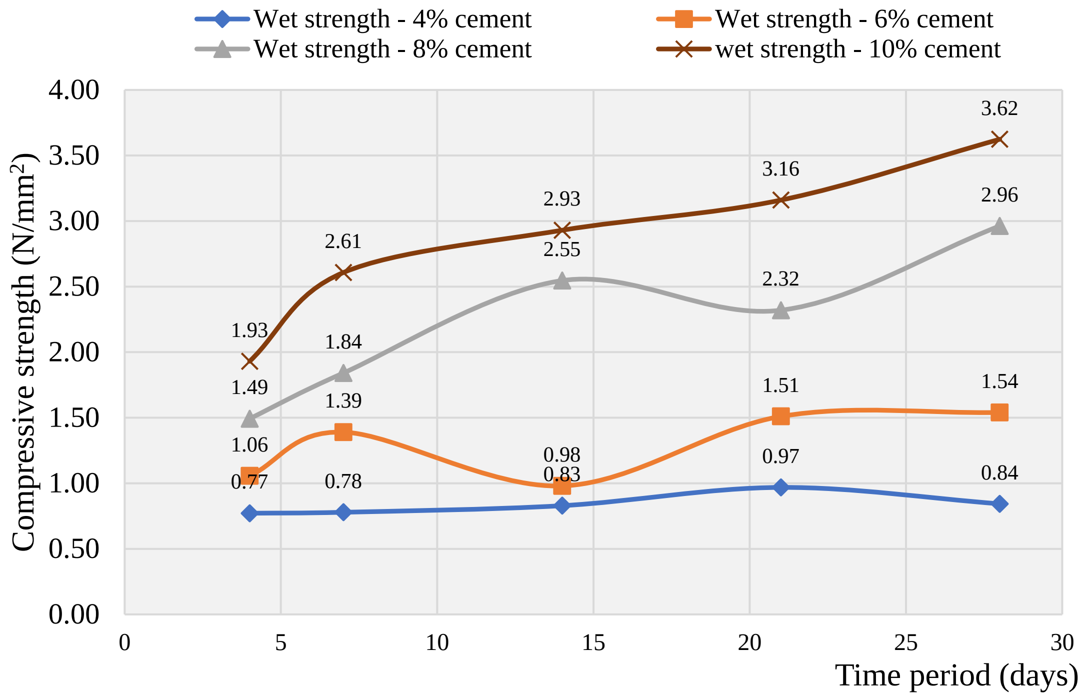


Figure 25: The wet compressive strength of Mud-Concrete with different cement percentages in 7, 14, 21 and 28 days

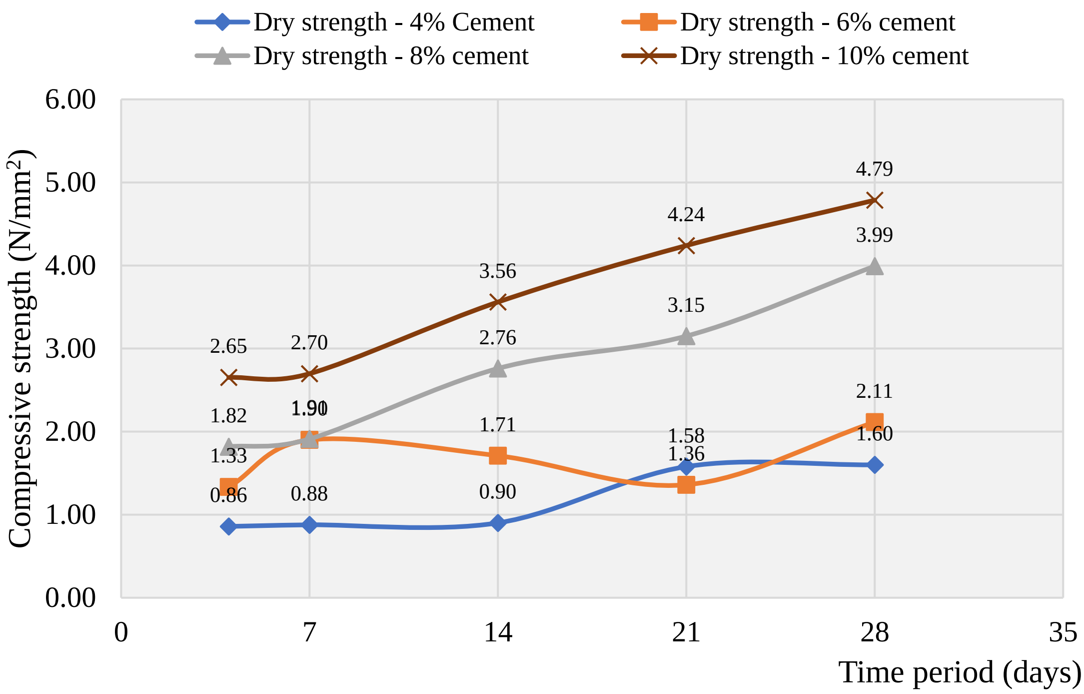


Figure 26: The dry compressive strength of Mud-Concrete with different cement percentages in 7, 14, 21 and 28 days

Table 39: Dry compressive strength with different cement percentages

Added cement % to the mix	Dry strength (N/mm^2)				
	4days	7days	14days	21days	28days
4%	0.86	0.88	0.90	1.58	1.60
6%	1.33	1.90	1.71	1.36	2.11
8%	1.82	1.91	2.76	3.15	3.99
10%	2.65	2.70	3.56	4.24	4.79

The results plotted in Figure 25 and Figure 26 show that the behaviour of compressive strength of MC with different cement percentages in 4, 7, 14, 21 and 28 days. As a norm, it was considered as both wet and dry compressive strength should increase while increasing the cement percentage in the mix, while keeping other factors constant in testing. However, here the compressive strength values have dropped at some points and the water percentage from the dry mix is high in those samples.

This leads to the question as to what is the actual strength behaviour of using different water percentage with different cement ratios in the mix in a different age of Mud-Concrete. To find out the answers the new methodology was adopted to check the strength behaviour of MC with different water amounts and with the different cement ranges. The obtained results were shown in Table 40 to Table 47.

c) S3 – Strength behaviour with different cement quantities while adding different water content to the mix

Figure 27 to Figure 34 show the compressive strength behaviour of the Mud-Concrete with different moisture content with 4%, 6%, 8% and 10% cement ranges. According to the gradient (m) of each graph gives a similar pattern and range. This confirms that the increase in water percentage causes a constant drop in the compressive strength of MC. The main reason for irregular grading curves shown in Figure 25 and Figure 26, can be the result of variation of this final water percentage from the dry mix and it also results in the variation in compressive strength of Mud-Concrete. Then a question raised as what is the actual compressive strength if the water percentage is constant in the dry mix? Thus, equations received in each wet and dry compressive strength testing for 4%,6%,8% and 10% (From Figure 27 to Figure 34) can be used to define the phenomenological equation to generate the actual compressive strength values for constant water percentage of dry mix and standardizing the strength behavior of Mud-Concrete with respect to its water content. Thus, the research was designed to keep the water in 20% and plot the compressive strength for different cement percentages.

For that below equation is used:

$y = mx + c$

Where,

y = Compressive strength, x = water % from dry mix, c= Cement %

If,

$y\,1 = m.x\,1 + c$ ⟶ (1)

$y\,2 = m.x\,2 + c$ ⟶ (2)

To find the compressive strength in 20% water in dry mix with added 4% cement:

1-2,

$y\,1 - y2 = m.(x\,1 - x\,2)$ ⟶ (3)

(As an example)

Where,

y 1= Dry compressive strength in 20% water in dry mix with added 4% cement

y 2 = Dry compressive strength received for the actual water in the dry mix with added 4% cement

m= gradient plotted from the Figure 27 graph

x1 = 20% water from dry mix

x2= Actual water % from dry mix

Table 40: 4% Cement- Dry compressive strength

	For 4% Cement					
	Water % of dry mix	Dry compressive strength (N/mm^2)				
		4 days	7 days	14 days	21 days	28 days
W1	19.6%	1.51	1.76	1.90	1.96	2.00
W2	22.3%	1.05	1.17	1.24	1.50	1.70
W3	22.4%	0.95	1.05	1.19	1.45	1.64
W4	23.9%	0.78	0.89	1.01	1.20	1.32
W5	26.9%	0.38	0.60	0.72	0.86	0.90

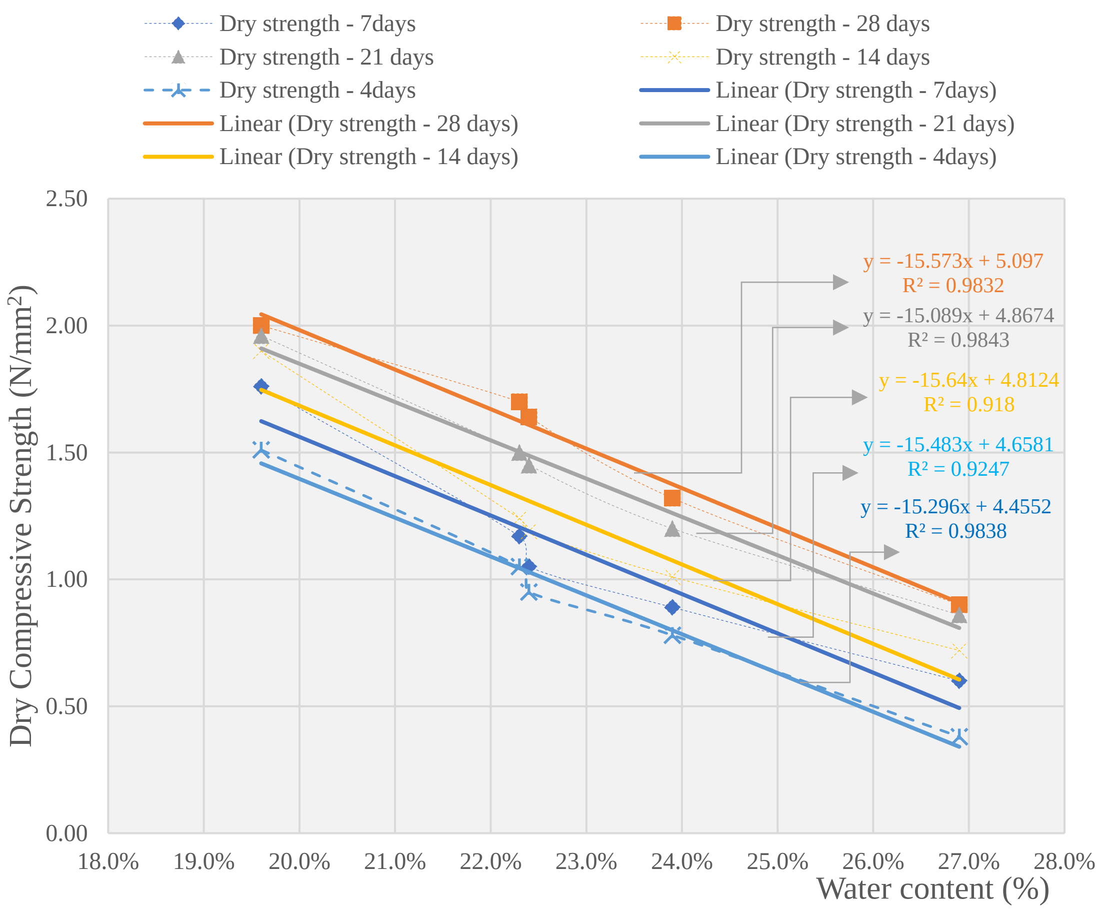


Figure 27: The dry compressive strength of 4% cement with a different water % dry mix

Table 41:4% Cement- Wet compressive strength

	For 4% Cement					
	Water % of dry mix	Wet compressive strength (N/mm^2)				
		4 days	7 days	14 days	21 days	28 days
W1	19.6%	1.4	1.68	1.86	1.94	1.97
W2	22.3%	1.02	1.15	1.20	1.45	1.68
W3	22.4%	0.8	1.05	1.14	1.43	1.62
W4	23.9%	0.64	0.85	0.96	1.17	1.30
W5	26.9%	0.34	0.54	0.70	0.83	0.84

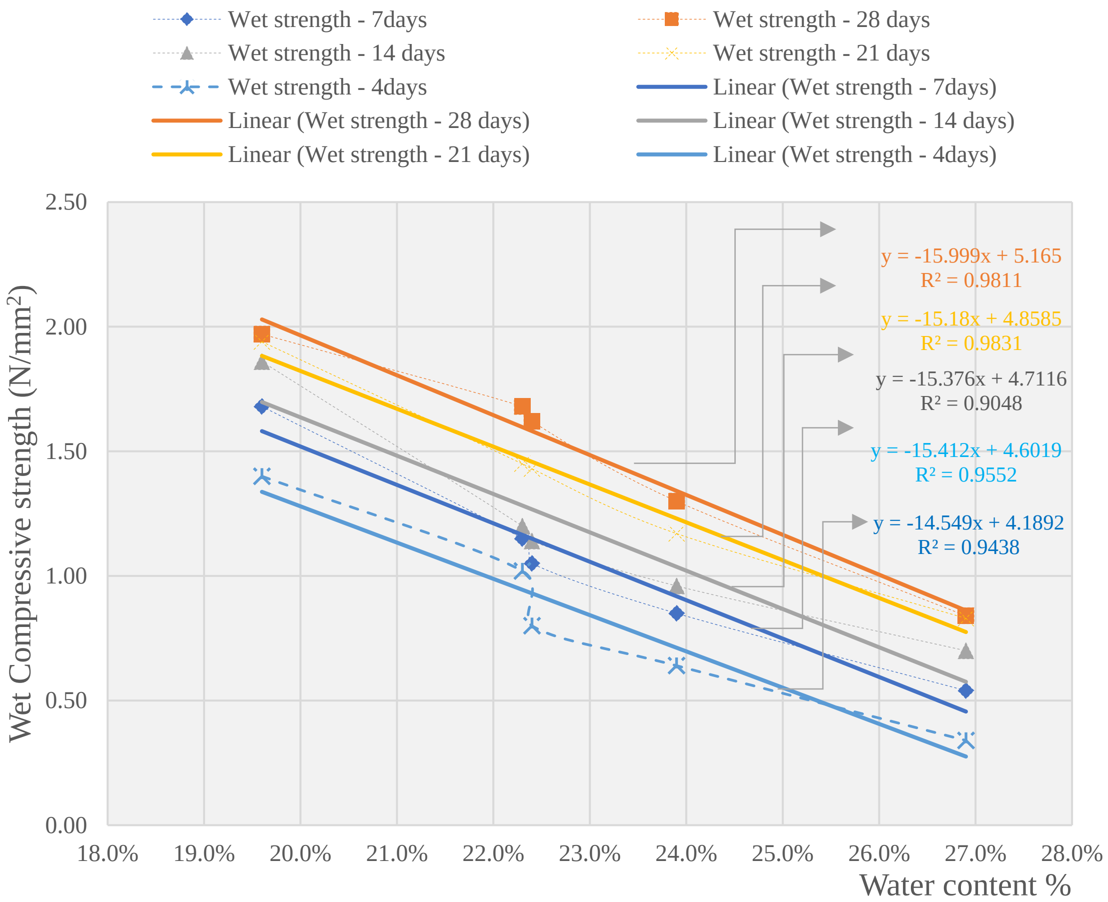


Figure 28: The wet compressive strength of 4% cement with a different water% dry mix

Table 42: 6% Cement- Dry compressive strength

	For 6% Cement					
	Water % of dry mix	Dry Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	24.3%	1.74	1.82	1.96	2.02	2.18
W2	26.0%	1.32	1.48	1.62	1.74	1.96
W3	27.5%	1.15	1.32	1.41	1.53	1.65
W4	28.6%	1.01	1.05	1.10	1.20	1.38
W5	32.2%	0.44	0.56	0.72	0.85	0.99

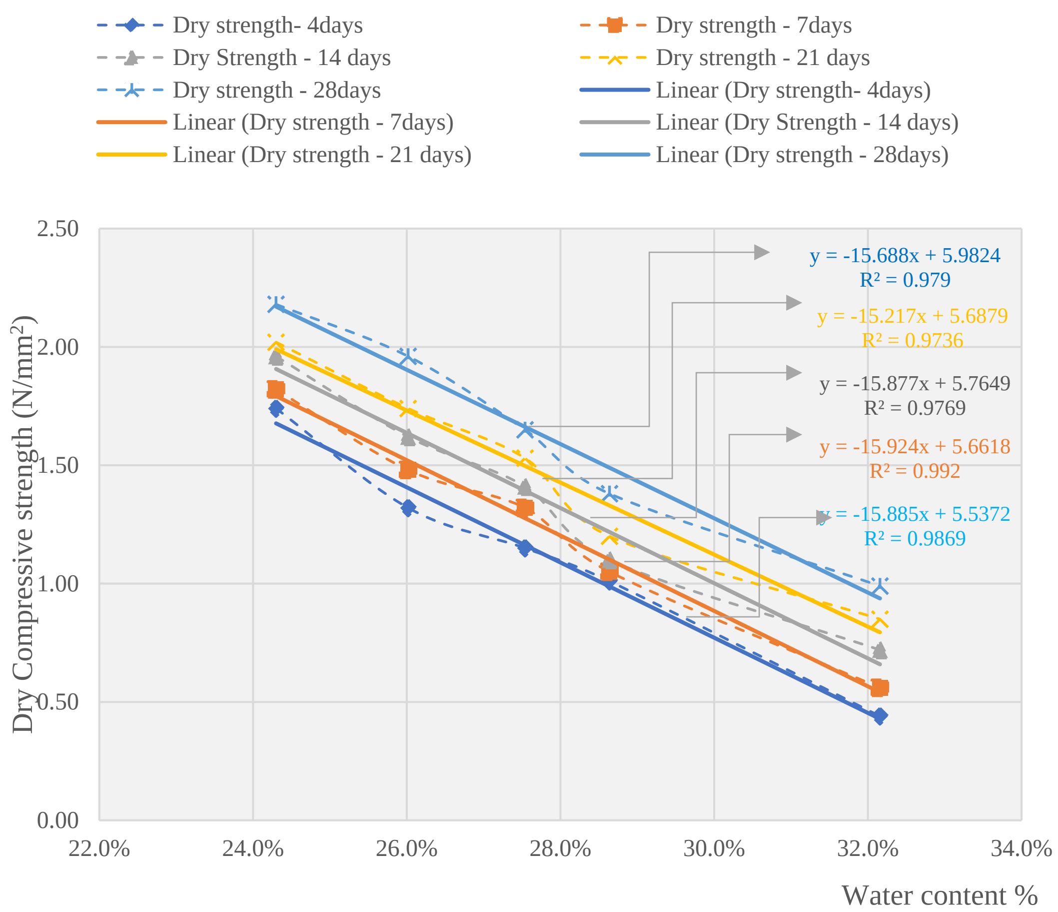


Figure 29: The dry compressive strength of 6% cement with a different water % dry mix

Table 43: 6% Cement- Wet compressive strength

	For 6% Cement					
	Water % of dry mix	Wet Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	24.3%	1.61	1.80	1.92	1.96	2.09
W2	26.0%	1.25	1.43	1.54	1.66	1.72
W3	27.5%	1.02	1.19	1.35	1.48	1.53
W4	28.6%	0.97	1.02	1.04	1.18	1.22
W5	32.2%	0.31	0.54	0.69	0.78	0.86

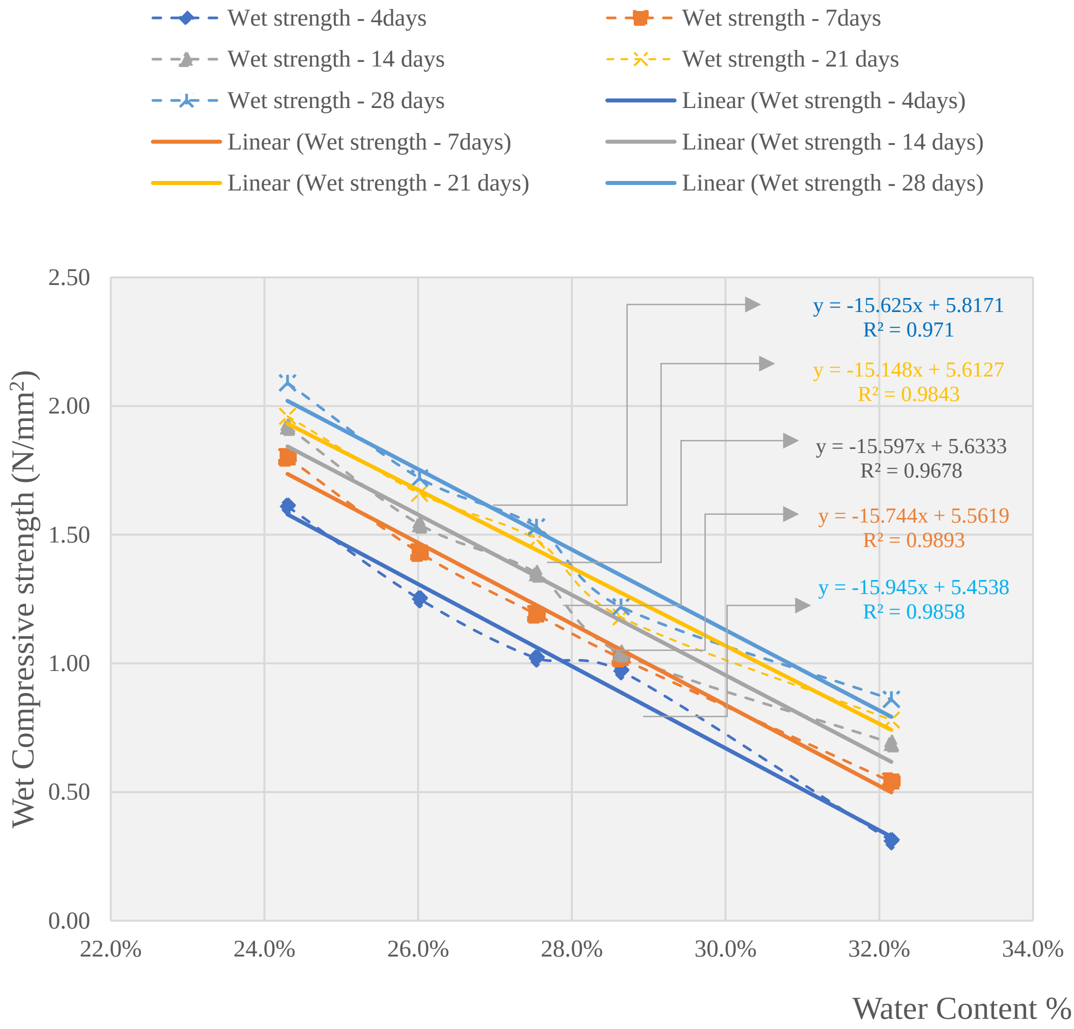


Figure 30: The wet compressive strength of 6% cement with a different water% dry mix

Table 44: 8% Cement - Dry compressive strength

	For 8% Cement					
	Water % of dry mix	Dry Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	26%	1.81	2.00	2.18	2.25	2.30
W2	26%	1.54	1.60	1.84	1.96	2.08
W3	27%	1.39	1.46	1.54	1.66	1.78
W4	29%	0.98	1.02	1.15	1.23	1.41
W5	33%	0.64	0.76	0.86	0.97	1.05

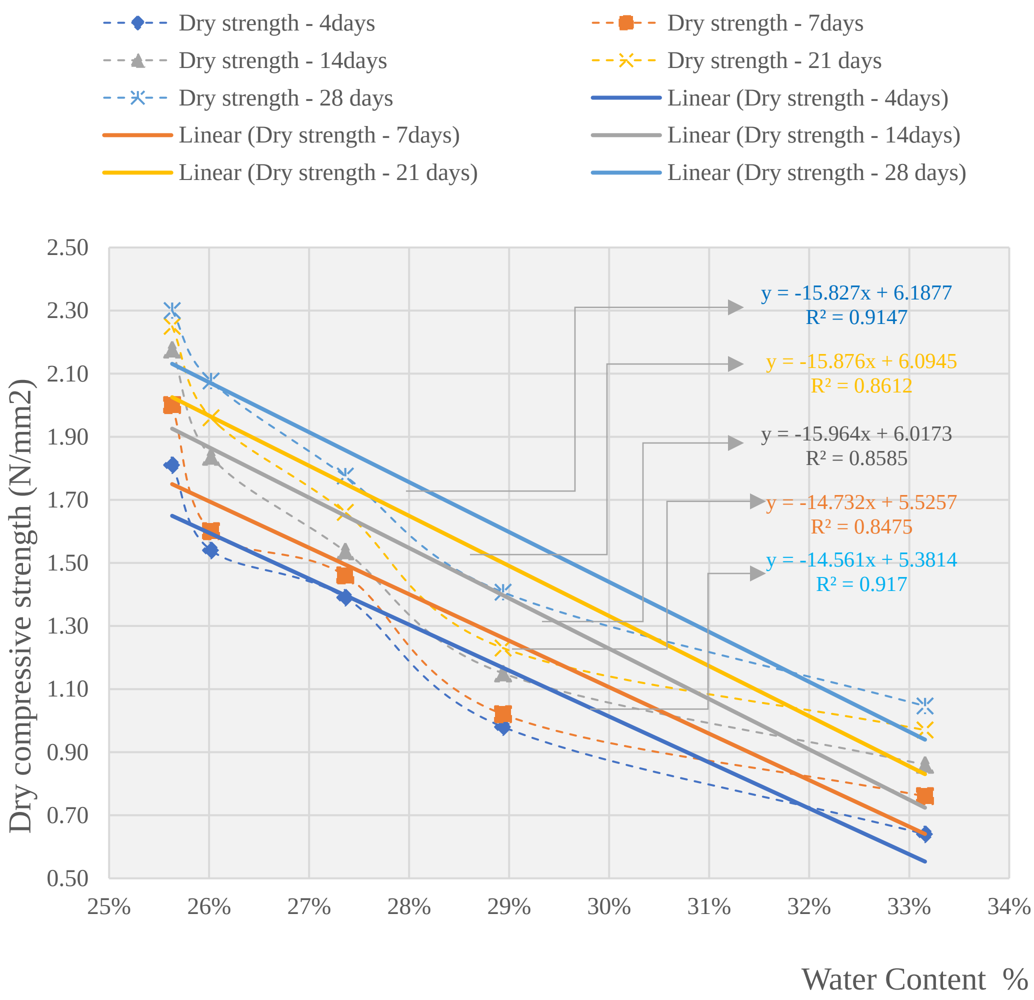


Figure 31: The dry compressive strength of 8% cement with a different water % dry mix

Table 45: 8% Cement - Wet compressive strength

	For 8% Cement					
	Water % of dry mix	Wet Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	20%	1.62	1.78	1.90	2.00	2.15
W2	22%	1.35	1.42	1.58	1.74	1.85
W3	24%	0.92	1.01	1.17	1.25	1.37
W4	24%	0.84	0.96	1.09	1.21	1.28
W5	27%	0.64	0.75	0.83	0.96	1.11

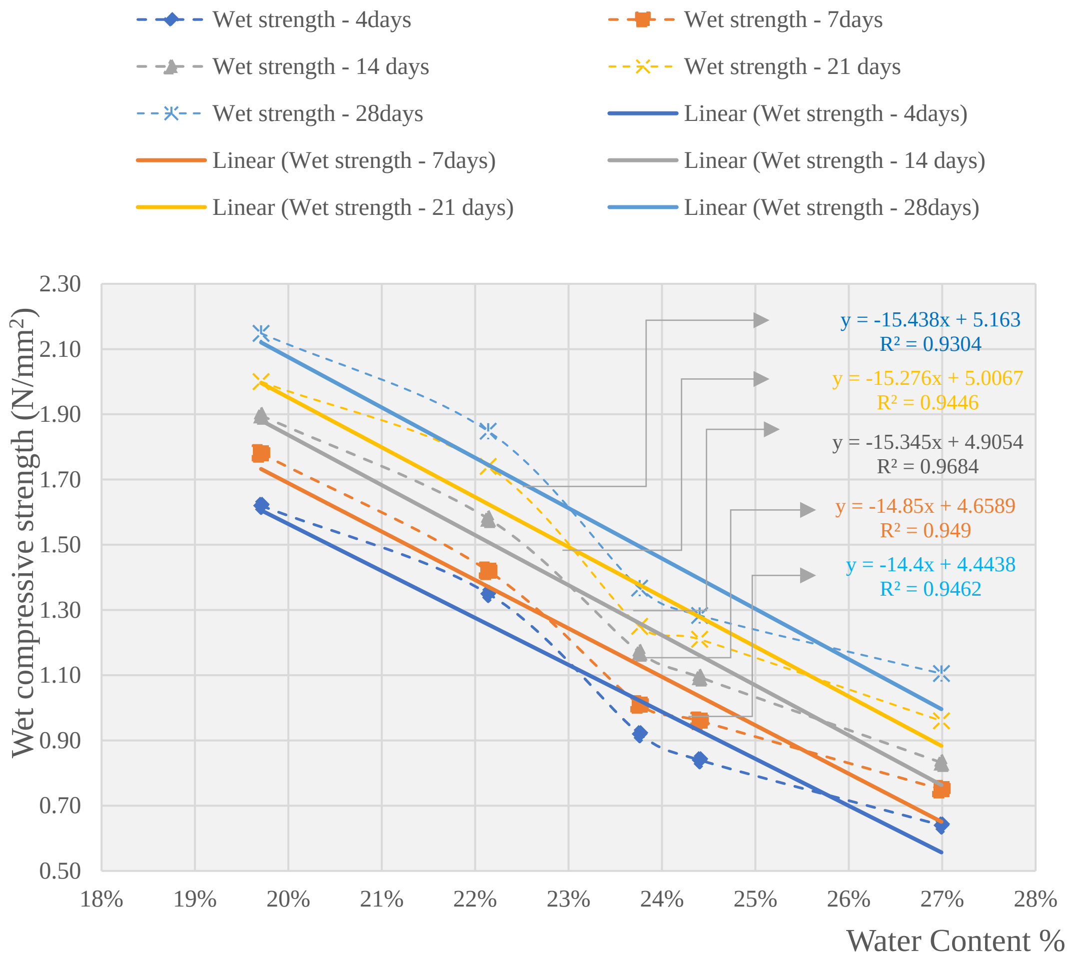


Figure 32: The wet compressive strength of 8% cement with a different water % dry mix

Table 46: 10% Cement - Dry compressive strength

	For 10% Cement					
	Water % of dry mix	Dry Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	27.4%	1.99	2.51	2.83	3.10	3.32
W2	28.6%	1.86	2.35	2.66	2.86	3.02
W3	29.9%	1.55	2.16	2.38	2.59	2.78
W4	31.7%	1.37	1.85	2.19	2.37	2.56
W5	33.5%	1.02	1.60	1.89	2.18	2.32

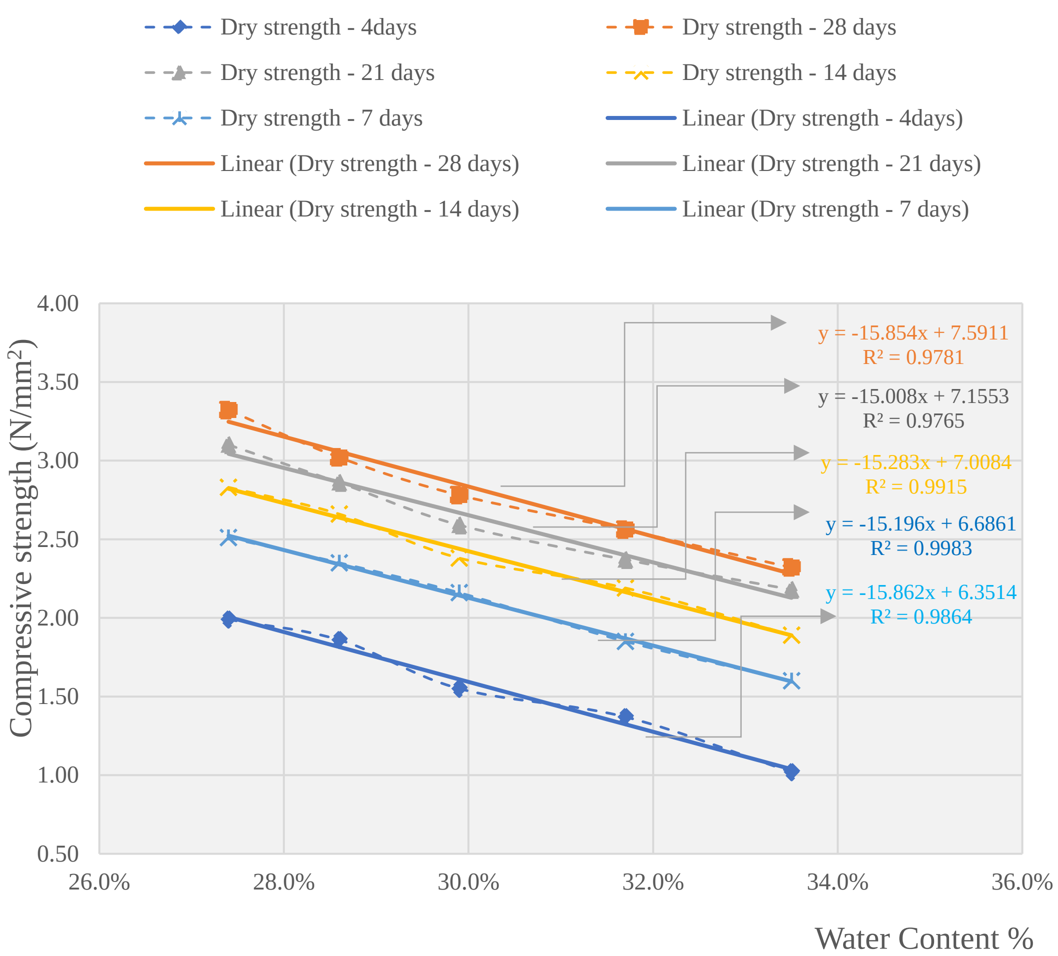


Figure 33: The dry compressive strength of 10% cement with a different water% dry mix

Table 47:10% Cement - Wet compressive strength

	For 10% Cement					
	Water % of dry mix	Wet Compressive Strength (N/mm^2)				
		4days	7days	14 days	21 days	28 days
W1	27.4%	1.99	2.42	2.70	2.86	3.21
W2	28.6%	1.86	2.27	2.49	2.63	2.75
W3	29.9%	1.55	2.12	2.23	2.45	2.54
W4	31.7%	1.37	1.68	2.02	2.21	2.36
W5	33.5%	1.02	1.53	1.74	1.89	2.19

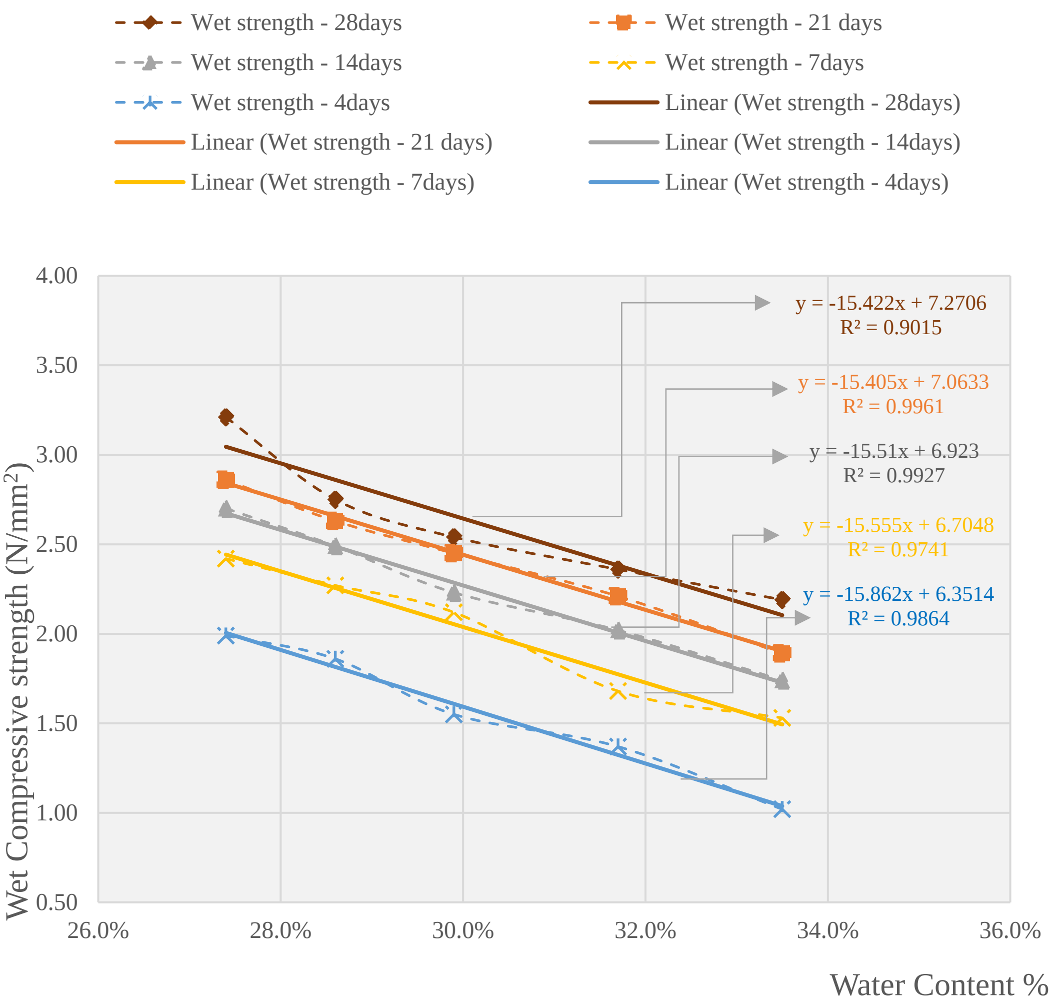


Figure 34: The wet compressive strength of 10% cement with a different water% dry mix

d) ***S4 –Developing the grading curves for dry and wet compressive strength of Mud-Concrete load-bearing wall and standardizing the water percentage from the dry mix.***

In this section, the derived equation was used to find the actual compressive strength of MC load-bearing wall in 04, 07,14,21,28 days with 4%, 6%, 8% and 10% cement from the total mix. As an example, the compressive strength with 20% water of the dry mix was calculated; because 20% water from dry mix offers the optimum values in the strength of Mud-Concrete in previous testing procedures (Arooz & Halwatura, 2017). As a result, the decisions were made to use 20% water as a thumb rule in calculations and showcase the actual strength values. Table 48 and Table 49 contains the tested data and Table 50 and Table 51 show the derived actual strength values using the defined equation (1, 2 and 3). Figure 35 and Figure 36 show the actual compressive strength values of the Mud-Concrete wall in 20% water of the dry mix.

Table 48: Tested data of wet compressive strength

			For wet compressive strength				
			4 days	7 days	14 days	21 days	28 days
1	4% cement – Strength (N/mm^2)	y2	0.77	0.78	0.83	0.97	0.84
	Water% in dry mix	x2	18.59	20.15	22.17	22.11	23.42
	Gradient of the graph	m	14.55	15.41	15.38	15.18	15.303
2	6% cement– Strength (N/mm^2)	y2	1.06	1.39	0.98	1.51	1.54
	Water% in dry mix	x2	19.59	20.15	25.51	23.57	24.12
	Gradient of the graph	m	15.945	15.744	15.597	15.148	15.625
3	8% cement– Strength (N/mm^2)	y2	1.49	1.84	2.55	2.32	2.96
	Water% in dry mix	x2	20.31	22.59	23.32	27	23.57
	Gradient of the graph	m	14.4	14.85	15.345	15.276	15.438
4	10% Cement– Strength (N/mm^2)	y2	1.93	2.61	2.93	3.16	3.62
	Water% in dry mix	x2	20.52	22.91	25.72	26.48	24.6
	Gradient of the graph	m	15.86	15.56	15.51	15.41	15.42

Table 49: Tested data of dry compressive strength

			For dry compressive strength				
			4 days	7 days	14 days	21 days	28 days
1	4% cement– Strength (N/mm^2)	y2	0.86	0.88	0.90	1.58	1.60
	Water% in dry mix	x2	20.15	22.72	26.17	23.1	23.42
	Gradient of the graph	m	15.29	15.483	15.64	15.089	15.573
2	6% cement– Strength (N/mm^2)	y2	1.33	1.90	1.71	1.36	2.11
	Water% in dry mix	x2	19.59	19.15	23.51	27.5	23.21
	Gradient of the graph	m	15.885	15.924	15.877	15.217	15.688
3	8% cement– Strength (N/mm^2)	y2	1.82	1.91	2.76	3.15	3.99
	Water% in dry mix	x2	20.31	25.59	24.6	24.98	20.67
	Gradient of the graph	m	14.561	14.732	15.964	15.876	15.827
4	10% Cement– Strength (N/mm^2)	y2	2.65	2.70	3.56	4.24	4.79
	Water% in dry mix	x2	19.52	24.91	24.72	22.48	19.6
	Gradient of the graph	m	15.86	15.2	15.28	15.01	15.85

Table 50: Wet compressive strength for 20% water from dry mix – y1

Added cement %	*Wet strength (N/mm^2) – for 20% water from dry mix*					
	0 days	4 days	7 days	14 days	21 days	28 days
4%	0	0.57	0.80	1.16	1.29	1.37
6%	0	0.99	1.41	1.84	2.05	2.18
8%	0	1.54	2.23	3.06	3.39	3.51
10%	0	2.01	3.06	3.82	4.16	4.33

Table 51: Dry compressive strength for 20% water from dry mix – y1

Added cement %	*Dry strength (N/mm^2) – for 20% water from dry mix*					
	0 days	4 days	7 days	14 days	21 days	28 days
4%	0	0.88	1.30	1.87	2.05	2.13
6%	0	1.27	1.76	2.27	2.50	2.62
8%	0	1.86	2.74	3.49	3.94	4.10
10%	0	2.58	3.44	4.28	4.61	4.72

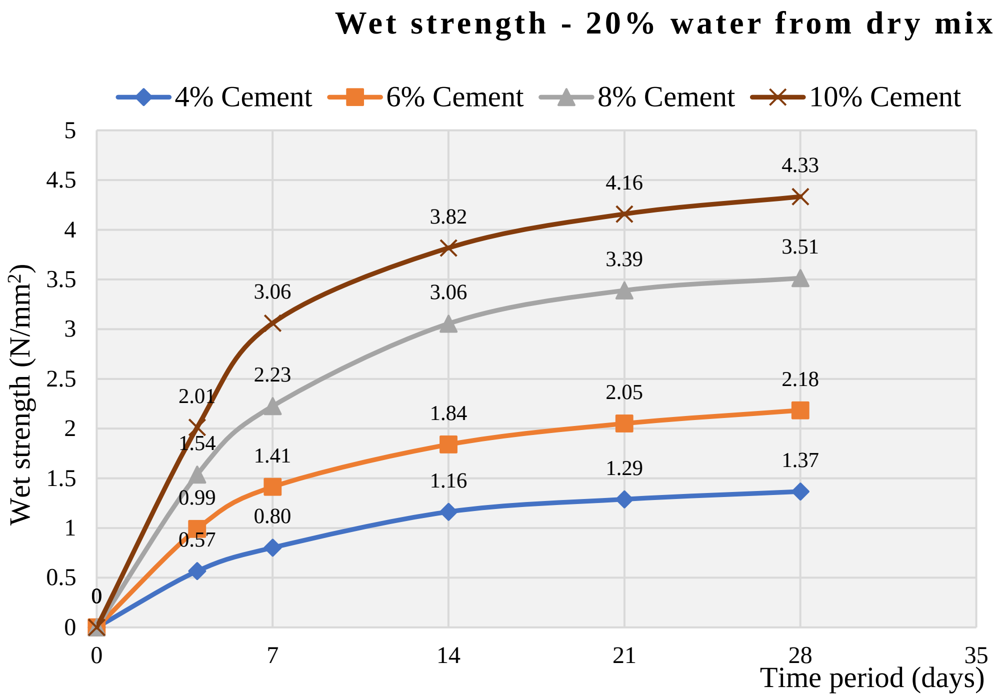


Figure 35: Grading Curve for wet strength - 20% water of the dry mix

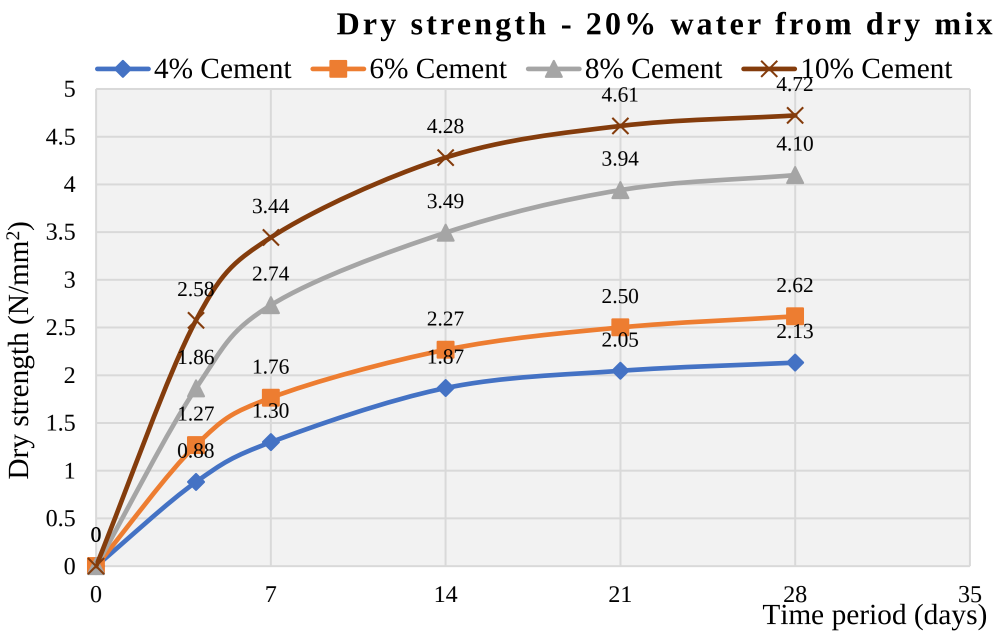


Figure 36: Grading Curve for dry strength - 20% water of the dry mix

According to results received, the trends are uniform irrespective to the soil type as well as the age of the block. The data matrix obtained through the testing procedures help to define a phenomenological equation which can derive the accurate compressive strength for constant water percentage of the dry mix. According to the results obtained in wet & dry compressive strength values for minimum 4% cement were exceeding the recommended minimum values of 1.0 N/mm^2 wet compressive strength and 2.0 N/mm^2 dry compressive strength for stabilized load-bearing earth walls (Peter Walker et al., 2010a) in 28 days age of the wall. A simplified method of measuring the sensitivity of water/cement ratio towards the compressive strength of MC wall has been identified and validated. Further, the obtained results can be used to standardize the strength behaviour of MC with different water-cement ratios in the field.

The following ideas will show the importance of developing the grading curves for the use in practical field:

- Developing grading curves of MCW helps to predict the grade strength of MCW with different cement ranges in prior construction. Also, this method helps to identify the optimum way of developing the available soil in a construction. This will save the time that allocates to get the strength reports.
- In addition, the gained data matrix helps to calculate the compressive strength with different moisture contents of MCW while achieving its self-compacting quality. It is evident that the considerable high water content is used in MCW technology to keep the self-compacting quality while achieving its required compressive strength that maintains load-bearing characteristics.
- It is easy to identify the methods of developing the available soil in construction. As an example, it is easy to build a rational justification of how much cement percentage need to be added to increase the expected strength of available soil mix. (Ex: To increase the 2.27 N/mm^2 dry compressive strength (6% cement, 14 days) to 3.5N/mm^2; then need to increase the cement percentage from 6% to 8% and can gain the expected dry compressive strength in 14 days age of the wall.) (Figure 36)

These findings will be useful to predict and maintain the quality of MC construction in the field and minimize the repercussions in construction.

3.8. Durability of MCW in laboratory conditions

The same stockpile was used and soil was developed according to the achieved the best mix by adding needed gravel and sand that keeps the 5% of a maximum fine of the total dry mix. Here the test was done to the 4% minimum cement content of the total dry mix of MCW (Table 52).

Considering the arrangement of the apparatus, it was decided to keep the 150mm (diameter) surface area to be exposed on the sprayed water. Therefore, three (03) rectangular MCW specimens were cast in 300mm -height, 150mm- width and 150mm- thickness for the purpose of conducting the accelerated erosion test.

Table 52: Needed soil quantities for three MCW rectangular specimens and developing the soil according to the best mix of MCW

Total mix weight needed to cast three (03) no. of MC beam specimens. (To keep 5% fine from the total weight of the mix)				42 kg		
Added cement (4% of the total weight of the mix)				1.679 kg		
Added water amount to the mix to keep the self-compacting quality				8.5 litres (20% of the total mix)		
Sample weight of the soil (kg)	Existing proportions and weight			Proposed proportions and weight		
	Gravel	Sand	Fine	Gravel	Sand	Fine
18	40.85%	47.49%	11.66%	45%	50%	5%
	8.88kg	20.98kg		11.54kg	12.44kg	2.09kg
Added gravel to keep the 5% fine in the mix (kg)				7.35 kg		
Added sand to keep the 5% fine in the mix (kg)				8.55 kg		

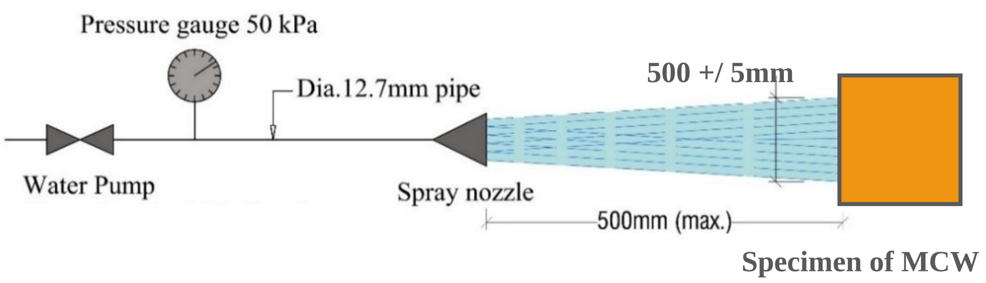


Figure 37: Arrangement of apparatus for accelerated erosion test

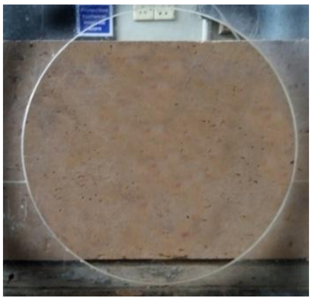
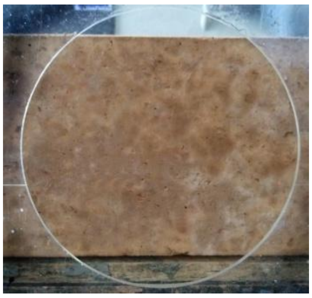
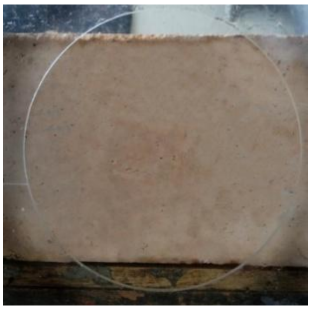
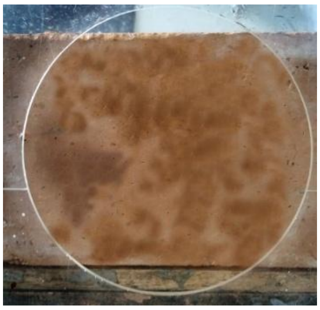
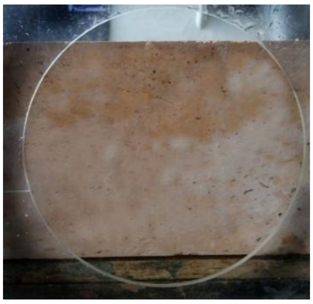
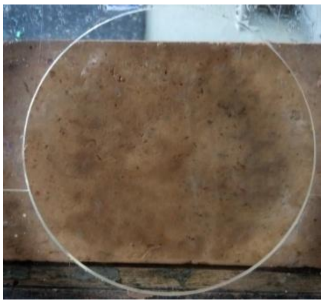
Formwork was removed after 24 hours and the curing procedure was started soon after formwork dismantling. MCW rectangular specimens were cured for 14 days (reduce the drying shrinkage) using wet gunny bags at room temperature (± 25 ºC Temperature, ± 75% Relative humidity). Casted three (03) rectangular specimens of MCW were tested after oven dried at 105 ± 5 °C for 24 hours and then left the blocks for another 24 hours under saturated surface dry condition (after 24-hour immersion of water).

The testing method involved placing the sample at 500mm from a spray nozzle and spraying water horizontally at a pressure of 50 kPa (Sri Lankan Standard Institute, 2009). A surface area of 150mm diameter was exposed to water. Each sample was exposed to the water spray for 1 hour (60 minutes) and the pit depths were observed every 15 minutes (excluding time lost for pit depth measurement) (Figure 37 and Figure 38). Pit depths were measured using a 10mm diameter flat ended rod. After the test average moisture content of each sample was determined

Figure 38: Accelerated erosion test conducted in laboratory

Table 53 shows the photographic records of the MCW specimens before and after the accelerated erosion test. There was no erosion were recorded within the tested hour (60 minutes). Thus the MCW material is deemed to satisfy the standards (Sri Lankan Standard Institute, 2009) with the 4% minimum cement content in the total dry mix.

Table 53: Erosion values per minutes and photographic records of specimens before and after the test

Sample No:	Before the test	After the test
01		
	Erosion = 0.00 (mm/min)	
02		
	Erosion = 0.00 (mm/min)	
03		
	Erosion = 0.00 (mm/min)	

3.9. Investigation on moisture buffering capacities

Moisture buffering occurs when porous building materials modify the relative humidity of indoor air, through absorption, storage and desorption of water vapour (Allinson & Hall, 2012). It is known that humidity has an impact on both working efficiency and health of occupants. However due to microclimatic variations, the indoor humidity exhibits significant variations daily or seasonally in tropical conditions. The hygroscopicity of raw earth drives the material to achieve equilibrium with the vapour pressure in its environment (McGregor et al., 2016).

Many earth building materials such as rammed earth (RE), compressed stabilized earth blocks (CSEB), adobe, cob are acknowledged with the moisture buffering capacity (Matthew Hall & Allinson, 2009; McGregor, Heath, Fodde, et al., 2014; Allinson & Hall, 2012;Cagnon, Aubert, Coutand, & Magniont, 2014; Liuzzi, Hall, Stefanizzi, & Casey, 2013). Thus earth materials have the ability to provide superior levels of indoor thermal comfort by regulating indoor humidity than industrial building materials (Matthew Hall & Allinson, 2009). Also, the moisture content of the raw earth also influences its thermal properties (McGregor et al., 2016). However, the MBV of un-stabilized RE was highly influenced by particle size distribution and mineralogy (Arrigoni, Grillet, et al., 2017). Also, stabilization considerably reduced the moisture buffer ability of stabilized RE.

The moisture buffering value (MBV) is a single parameter that can be used to describe and compared the humidity buffering potential of building materials (Rode et al., 2007). Mud-Concrete (MC) as an unfired walling system, necessitates to check the hygrothermal properties of the material. The previous results proved that in-situ cast Mud-Concrete wall is acting as a good thermal mass (air temperature buffering). Thus, these abilities can perhaps be attributed to the combined effects of the air temperature buffering and moisture buffering potential.

The aim of this section of the research is to quantify the speculated moisture buffering capacity of self-compacting in-situ cast Mud-Concrete load bearing walls (MCW). In order to achieve this objective, number of literature were referred to understand the testing methods of moisture buffering capacity of earth-based walling materials. Table 54 shows the summary of tested methods of stabilised rammed earth, earth blocks and compressed stabilised earth blocks.

Table 54: Literature Summary of MBV testing in earth-based walling materials.

Soil based material type	**Sample size**	**Pre-condition**	**Testing techniques**	**Ref.**
Stabilized rammed earth	Disc type with dia. 105mm, approx. 40mm thickness	50% RH at 23ºC, kept 5days to reach equilibrium in a climate chamber	NORDTEST techniques	(Allinson & Hall, 2012)
Earth blocks	100mm x100mm blocks	35% RH, kept 8 weeks to reach equilibrium in climate chamber	NORDTEST techniques	(McGregor, Heath, Shea, et al., 2014; Minke,2006; McGregor et al., 2016)
CEB (compressed earth blocks)	Discs 100mm in dia. & 30mm in thickness with approx. 1800 kg/m^3 density	50% RH at 23ºC in TAS environmental chamber	NORDTEST techniques	(McGregor, Heath, Shea, et al., 2014)

NORDTEST test methods and protocol were declared in 2003 on Moisture Buffer capacity (Rode et al., 2007) because there was a need of a robust definition of the term which is technically appropriate yet logical and certain for the industry and users (Rode et al., 2005; Peuhkuri & Rode, 2005; Rode, 2004). There is also a need for further explanation of the possible benefits and relevance of setting up moisture buffer capacity of materials as a passive way of conditioning air, in relation to using other means to ensure healthy indoor environments of buildings by active conditioning systems (Carsten et al., 2003). Thus, Rode at el, (2007) explains the moisture buffer phenomena at different levels as shown in Figure 39.

In NORDTEST there is a good agreement between the results, however it is clear that particular attention needs to be given to the experimental set-up. The NORDTEST proposes a unique value; the moisture buffering value (MBV), which offers a simple method of rating the moisture buffering properties of materials. Even though there are different protocols and standards developed such as Fraunhofer IBP, Lund University, DIN (German Industry Norm) standard, Japanese Industrial Standards (JIS), ISO

(International Standards Organization) standards (“Hygrothermal performance of building materials and products — Determination of moisture adsorption/desorption properties in response to humidity variation,” n.d.),(Kim, Kim, Lee, & Song, 2010), the NORDTEST method is currently the most commonly used, especially for earth building materials (McGregor et al., 2016; Allinson & Hall, 2010b; Collet, Bart, Serres, & Miriel, 2008; Dubois, McGregor, Evrard, Heath, & Lebeau, 2014; Liuzzi et al., 2013; McGregor, Heath, Shea, et al., 2014; McGregor, Heath, Fodde, et al., 2014; Latif, Lawrence, Shea, & Walker, 2015). Other protocols and standards are used in very limited as references in scientific publication.

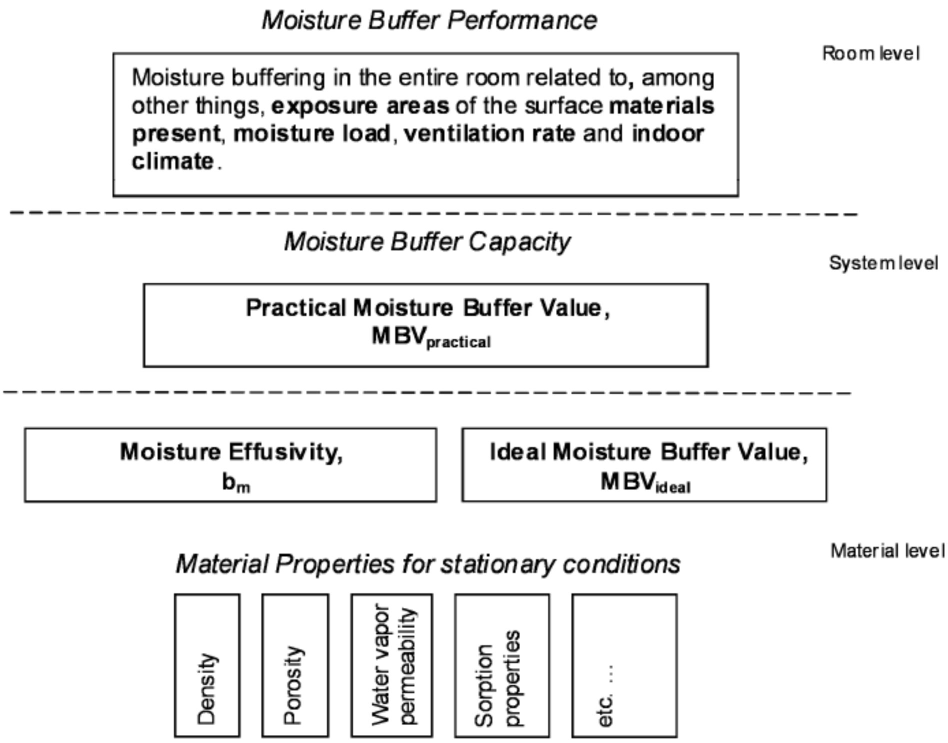


Figure 39: Moisture buffering performance at different levels (source: (Rode et al., 2007*))*

Hence, this research also follows the NORDTEST protocol in sample preparation and MBV testing. Here the initial objective is to investigate the moisture buffering capacity of the newly developed self-compacting in-situ cast Mud-Concrete load-bearing wall. The first attempt was to find the moisture buffering capacity for best mix design with 4% (low) cement and 8% (high) cement content of the dry mix. Further research design was expanded to check the moisture buffering of MCW with varying the water percentage of the mix. As recorded in previous test procedures the required optimum water quantity to keep the self-compacting quality and the maximum compressive strength was found as 20% from the dry mix in Mud-Concrete mix. Thus the research was designed to check the MBV of MCW in 15% (low), 20% (optimum) and 25% (high) with 4% and 8% cement of the total dry mix. In addition, the objectives were extended to compare the MBV of MCW with the brick and cement blocks which are highly used in nowadays wall constructions.

3.9.1. Materials and methods

a) Existing particle size distribution of used sub-soil for testing

Gravelly laterite soil was used in the entire testing procedure. Soil samples were obtained from a homogeneous layer; 600mm-900mm below the top of the soil to get the good composition of soil and to avoid the organic particles in the soil samples. Three (03) random air-dried soil samples were used to conduct the sieve analysis (Figure 40) tests to understand the existing particle size distribution of the soil while minimizing the errors. Liquid limit, plastic limit and plastic index were obtained by conducting atterberg limit tests (Table 55). The average values of gravel 40.85%, sand 47.49% and fine 1.66% were available in existing soil samples. Then the soil was developed up to the achieved best mix design of MCW.

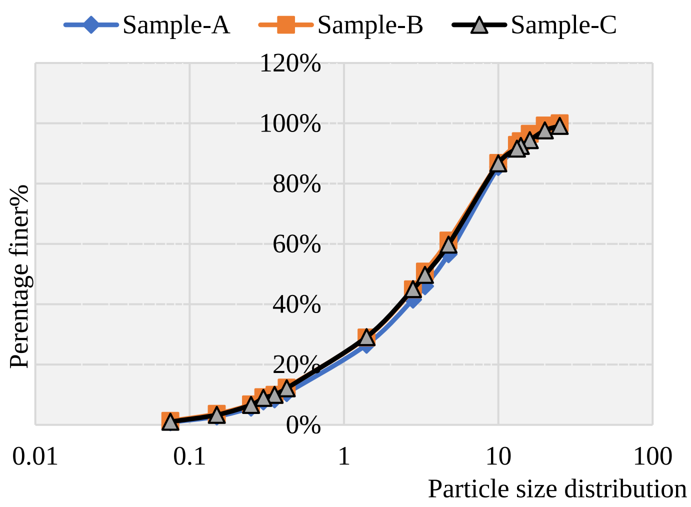


Figure 40: Particle size distribution of existing soil

Table 55: Properties of existing soil

Properties	Values
Liquid limit	35.99%
Plastic limit	21.78%
Plasticity index	14.95%
Dry density (soil gravel)	1600 - 1800 kg/m^3
Wet density (soil gravel)	1800 - 2100 kg/m^3

b) **Developing the existing soil according to the mix properties and sample preparation**

In MCW technology, the soil was always developed by keeping the maximum 5% fine (fine < 0.425mm sieve size) content of the total dry mix (Arooz, Babilegedara, et al., 2017). Hence, needed gravel and sand was added to the initial soil samples to prepare the needed total soil quantity to cast the entire set of MC specimens (Table 56). For the experimental campaign, 18 samples of MC were produced only to check the MBV values. In addition, the same mix was used to produce the samples to check the water vapour permeability and thermal conductivity of the MCW material.

Table 56: Developing existing soil according to the needed MC specimen mix with 4% and 8% cement

	4% cement			**8% cement**		
Sample no:	**4S-1**	**4S-2**	**4S-3**	**8S-1**	**8S-2**	**8S-3**
Initial soil weight (kg)	1.50	1.50	1.50	1.50	1.50	1.50
Added gravel weight to keep 5% fine (kg)	0.96	0.96	0.96	0.96	0.96	0.96
Added sand weight to keep 5% fine (kg)	1.04	1.04	1.04	1.04	1.04	1.04
Added cement (kg)	0.14	0.14	0.14	0.28	0.28	0.28
Added water (kg)	0.55	0.73	0.91	0.57	0.76	0.94
Added water %	16.00%	20.00%	26.00%	15.08%	20.96%	24.27%
Water % of total dry mix	15%	20.0%	25%	15%	20.0%	25%

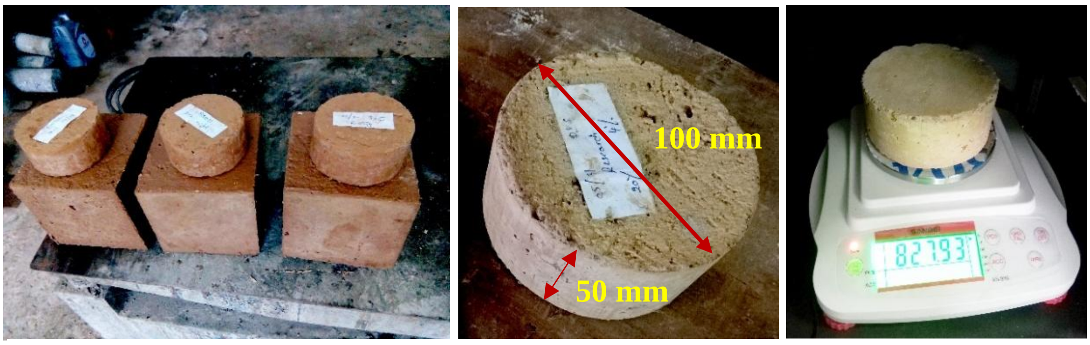


Figure 41: Prepared Mud-Concrete samples

100mm diameter, 50mm thickness cylindrical (disk type) MC samples were used to measure the moisture buffer values in entire testing (Figure 41). The samples were cured for minimum 14 days within a ± 75% Humidity, ± 30 ºC Temperature. Three (03) samples were tested for each set of specimens and average values were calculated. 100mm x200mm x400mm sized 1:5 cement: sand ratio solid cement blocks were used in testing. Similarly, 215mm x102.5mm x65mm sized burnt clay bricks were used in testing. Needed disk type samples sizes were cut and prepared prior to testing.

c) Experimental measurement of MBV

i. Pre-conditioning

Before conducting moisture adsorption and desorption tests, the specimen was preconditioned inside the chamber with the ambient temperature of 23 ± 0.5°C and the relative humidity of 50% until the specimen reached a constant mass. The specimen was considered to have reached a constant mass when the rate of mass increase was less than 0.01 g in 24 hours.

ii. Climatic chamber

290mm (width), 320mm (depth) and 605mm (height) electronic dry cabinet (with 7th generation micro-processor) was used as the moisture proof climatic chamber. It consists of an electronic balance, temperature and humidity sensor and humidity gauge. Humidity can be controlled within the range of 30%-90%. Mobile phone with camera application was used to record the results continuously (Figure 42).

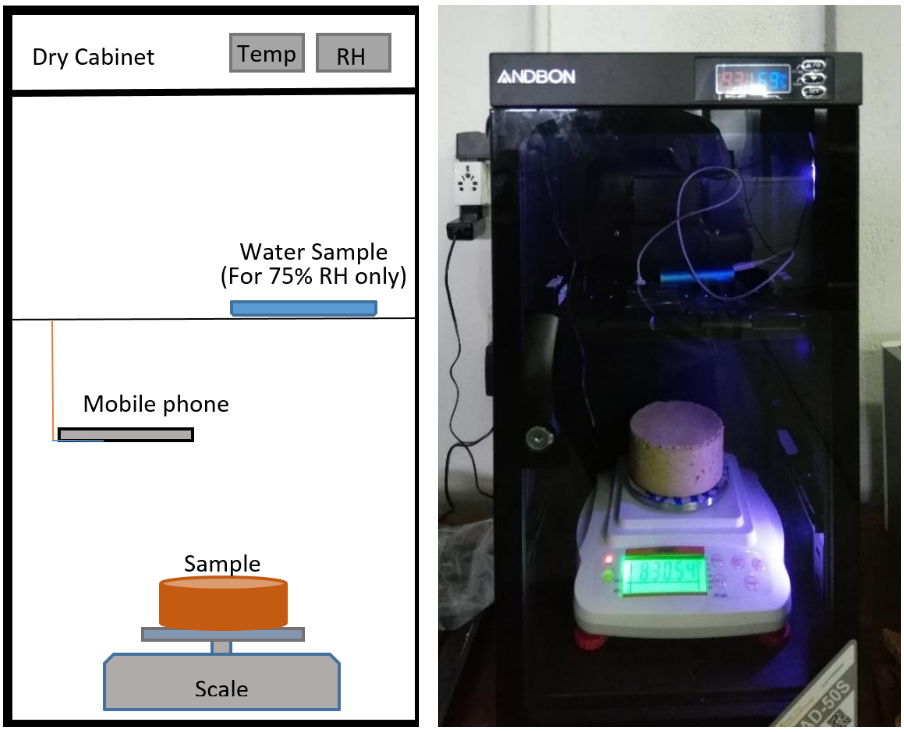


Figure 42: Test set-up in climatic chamber

iii. Method of testing the moisture buffering capacity – Step response method

Step-response method was used in identifying the moisture buffering values. This method records the mass variation during relative humidity (RH) cycles of a specimen with a known exposed surface area over daily cycle. Two different RH levels were used to investigate the behaviour of the material. Moisture adsorption/desorption tests were then performed by maintaining the relative humidity levels inside the chamber. First, a moisture adsorption test was carried out at 75% RH for 8 hours. A desorption test was then performed at 33% RH for an additional 16 hours. During the 24-hour moisture adsorption/desorption tests, the mass change of the test specimen was measured at a 10-minute interval to the nearest 0.01g. The mass was then recorded at the end of the first 8 hour period as the result of the moisture adsorption process, and at the end of the second 16 hour period as the result of the desorption process.

d) Water vapour permeability testing

Water vapour permeability is one of the fundamental performance lists of package materials. In this testing, the 'cup method' was used to measure the water vapour permeability according to ASTM 96 (C16 Committee, 2016).

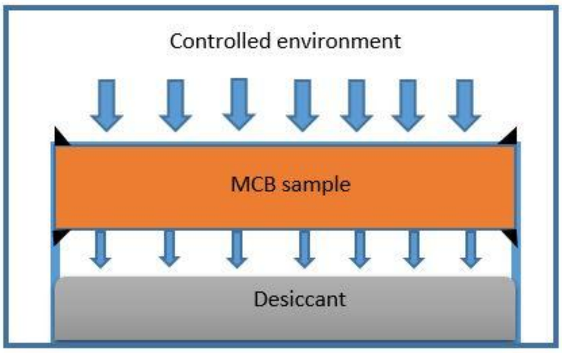


Figure 44: Testing set-up in climatic chamber

Figure 43: MC sample was fixed and sealed to a PVC cup using epoxy resin

Cup method can be worked into two different ways depending on similar testing rules: Desiccant method in which water vapour transmits into the test dish and water technique in which water vapour transmits out of the test dish. Desiccant method was used in testing and the samples were fixed and sealed with an epoxy resin applying to the mouth of the cup or test dish having a desiccant (Figure 43). Then the prepared sample / set-up were kept in an electronically controlled climate. 25mm of MC samples were used in testing (C16 Committee, 2016). Random weighing decided the rate of water vapor development through the sample into the desiccant. Figure 44 shows the testing principle of the desiccant method.

Water vapour permeability was calculated using the following equations 6, 7 and 8.

$$\boldsymbol{WVT = (G/t)/A} \quad \textbf{(6)}$$

WVT = rate of water vapour transmission, g/h·m^2.
G = weight change (from the straight line), g and *t* = time, h,
G/t = slope of the straight line, g/h,
A = test area (cup mouth area), m^2

$$\boldsymbol{Permeance = WVT/\Delta P = WVT/S(R_1 - R_2)} \quad \textbf{(7)}$$

Δp = vapor pressure difference, mm Hg (1.3333x 10^2 Pa),
S = Saturation vapor pressure at test temperature, mm Hg (1.3333 x10^2 Pa),
*R*1 = Relative humidity at the source expressed as a fraction (the test chamber for desiccant method; in the dish for water method), and
*R*2 = Relative humidity at the vapour sink expressed as a fraction.

$$\boldsymbol{Permeability = Permeance * Thickness} \quad \textbf{(8)}$$

e) MBV practical

The MBV$_{practical}$ value was calculated using the average of the mass gained by the sample at high relative humidity (absorption at 75% RH climate) and the mass reduction at the low relative environment (desorption at 33% RH climate). This change in mass was divided by the exposed area of the sample and the difference in relative humidity between the two environments, as shown in equation 9. The mentioned values of MBV$_{practical}$ were the average of three consecutive results.

$$\boldsymbol{MBV_{practical} = \frac{\Delta m}{A_S \Delta RH}} \quad \textbf{(9)}$$

Δm = Change in mass (g)
A_s = Area of surface (m^2)
RH = Relative humidity (%)

f) MBV ideal

An analytical method for figuring the MBV from standard material properties was characterized by the NORDTEST project (Rode et al., 2005) as shown in equation 10.

$$MBV_{ideal} = 0.00568\, P_s b_m \sqrt{t_p} \qquad \textbf{(10)}$$

P_s = Saturation vapour pressure (Pa)
b_m = Moisture effusivity (kg/ (m^2 Pa S$^{1/2}$))
t_p = time period (S)
Value moisture effusivity of material is calculated by equation 11.

$$b_m = \sqrt{\frac{\delta_p \rho_0 (\partial w_m / \partial \varphi)}{P_{sat}}} \qquad \textbf{(11)}$$

δ_p = water vapour permeability (kg/m s Pa)
ρ_0 = dry density (kg/m^3)
w_m = moisture content (kg/kg)
φ = Relative humidity (decimal)
For the SRE materials, a single value of was $\partial w_m / \partial \varphi$ calculated from the gradient of the straight line portion of the measured moisture storage function for each material.

g) Experimental measurement of thermal conductivity

Figure 45: Measuring the thermal conductivity of Mud-Concrete walling material

After casting each MC specimen, the thermal conductivity (ƛ), specific heat capacity (c) and density (ρ) was measured by using DRM-II coefficient of thermal conductivity tester (hot plate method) (Figure 45). This instrument is based on stable thermal conductive principle (one-way). When the two sides of the samples are in different stable temperatures the heat transfer area through effective heat flow and the surface temperature difference between the two surfaces and thickness calculation will measure the coefficient of thermal conductivity. The data collection process was started by using simple hot plate techniques and one-third of sample specimens were placed in between two similar walling sample specimens. The apparatus reading was given as a coefficient of thermal conductivity/resistance (R) in $m^{2.}$ K/W. Through this, resistance value thermal conductivity (ƛ), W/m.K was calculated.

3.9.2. Results and discussion

Physical structural properties of the MC samples, cement blocks and bricks were calculated to understand the range of hydrothermal functional properties; moisture dependent thermal conductivity, moisture capacity and the values of water vapour permeability (Table 57 and Table 58). The calculated water vapour permeability values were used to find the MBV $_{ideal}$ values using equation 11. Hence, the MBV $_{practical}$ values were calculated using the step-response method and the data were recorded in Table 59. Figure 46 shows the MBV $_{practical}$ MC with 4% cement. According to Figure 46, it can be seen the samples produced using 4% cement with 15% water (4S-1) and 4% cement with 25% water (4S-3) have given a higher mass change than the sample produced using 4% cement with 20% optimum water (4S-3). It is justifiable for the 4S-1 sample because low water quantities can make more porous structures in Mud-Concrete. This porosity of material can increase the vapour permeability within the structure and absorb more moisture from the outer environment while changing the surrounding micro-climate. However it is problematic for 4S-3 samples as for how the results have shown a considerably higher value of mass change than 4S-2 samples. It was clear as hairline cracks appeared in 4S-3 samples after 28 days due to the high water consumption in sample preparation (Figure 48).

Table 57: Properties of tested Mud-Concrete Samples, cement blocks and bricks

Sample	Weight of the sample (kg)	Density (kgm^{-3})	Compressive Strength (N/mm^{-2})	Thermal conductivity (W/m.K)	Moisture capacity (kg/kg)
4S-1 MC	7.1	2104	2.91	0.98	0.02008
4S-2 MC	7.4	2193	2.13	0.98	0.01842
4S-3 MC	7.5	2210	1.35	1.00	0.01822
8S-1 MC	7.5	2227	4.89	1.02	0.03019
8S-2 MC	7.6	2256	4.10	1.02	0.01943
8S-3 MC	7.7	2267	3.31	1.03	0.02141
Cement block	6	1650	2.2	1.40	0.00973
Brick	3.5	2000	3.5	0.69	0.01442

Table 58: Water Vapour Permeability values of tested samples

Sample	G/t (g/h)	A (m^2)	WVT	S (Pa)	R1-R2	Permeance (Kg/m^2.S.Pa)	Thickness of the sample (m)	Permeability δp (Kg/m.S.Pa)
4S-1 MC	0.10	0.0087	11.02	4666	0.5	1.31×10^{-9}	0.025	3.28×10^{-11}
4S-2 MC	0.09	0.0087	10.06	4666	0.5	1.20×10^{-9}	0.025	2.99×10^{-11}
4S-3 MC	0.09	0.0087	10.54	4666	0.5	1.25×10^{-9}	0.025	3.14×10^{-11}
8S-1 MC	0.09	0.0087	10.30	4666	0.5	1.23×10^{-9}	0.025	3.07×10^{-11}
8S-2 MC	0.09	0.0087	10.54	4666	0.5	1.25×10^{-9}	0.025	3.14×10^{-11}
8S-3 MC	0.09	0.0087	10.57	4666	0.5	1.26×10^{-9}	0.025	3.15×10^{-11}
Cement block	0.05	0.0087	5.75	4666	0.5	6.84×10^{-10}	0.025	1.71×10^{-11}
Brick	0.08	0.0087	9.58	4666	0.5	1.14×10^{-9}	0.025	2.85×10^{-11}

Table 59: MBV practical values of tested samples

Sample	∆m (g)	As (m^2)	∆RH (%)	MBV practical (g/m^2.%RH)
4S-1 MC	0.90	0.0087	42	2.46
4S-2 MC	0.87	0.0087	42	2.38
4S-3 MC	0.95	0.0087	42	2.60
8S-1 MC	1.09	0.0087	42	2.98
8S-2 MC	0.92	0.0087	42	2.52
8S-3 MC	1.08	0.0087	42	2.96
Cement block	0.59	0.0087	42	1.61
Brick	0.75	0.0087	42	2.05

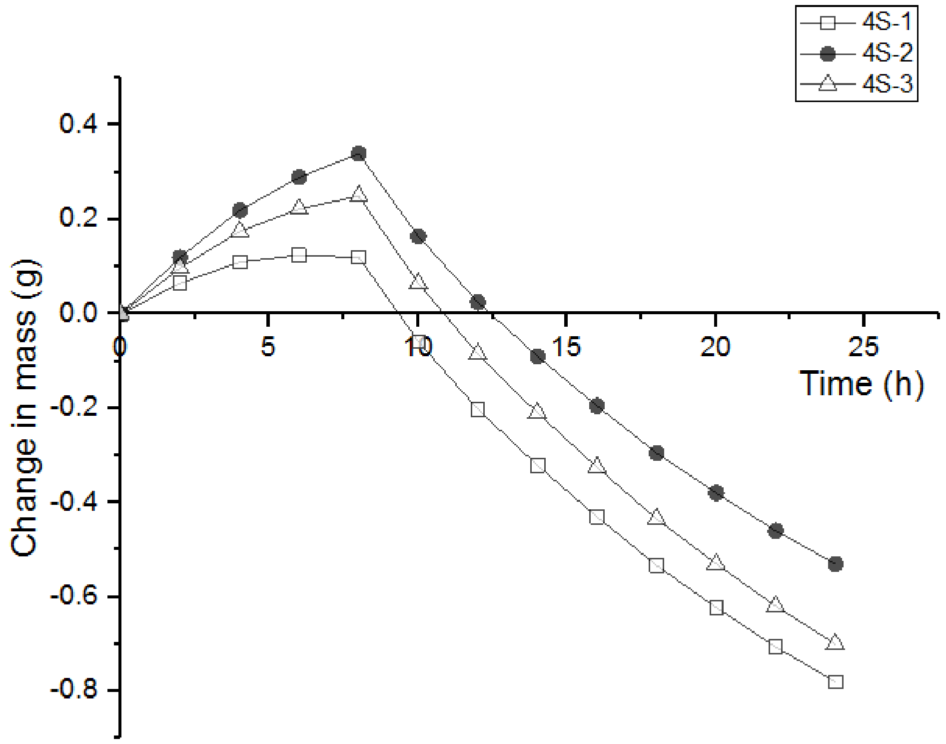


Figure 46: Recorded mass-time profile for MBV practical measurement - MC with 4% cement

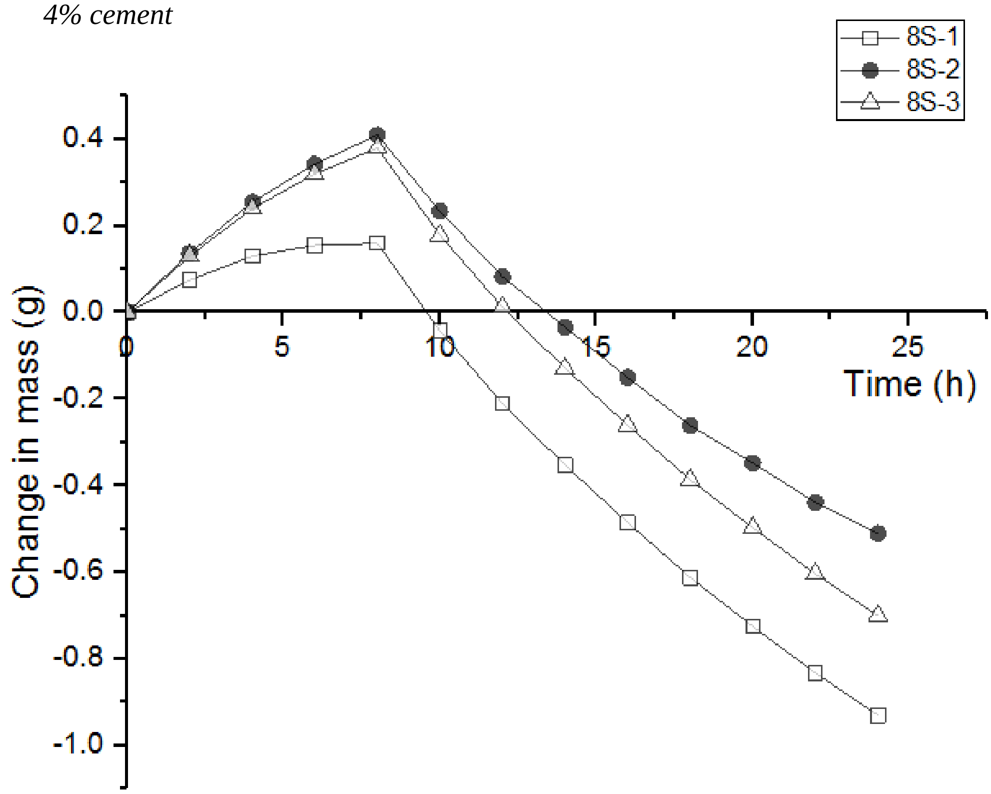


Figure 47: Recorded mass-time profile for MBV practical measurement - MC with 8% cement

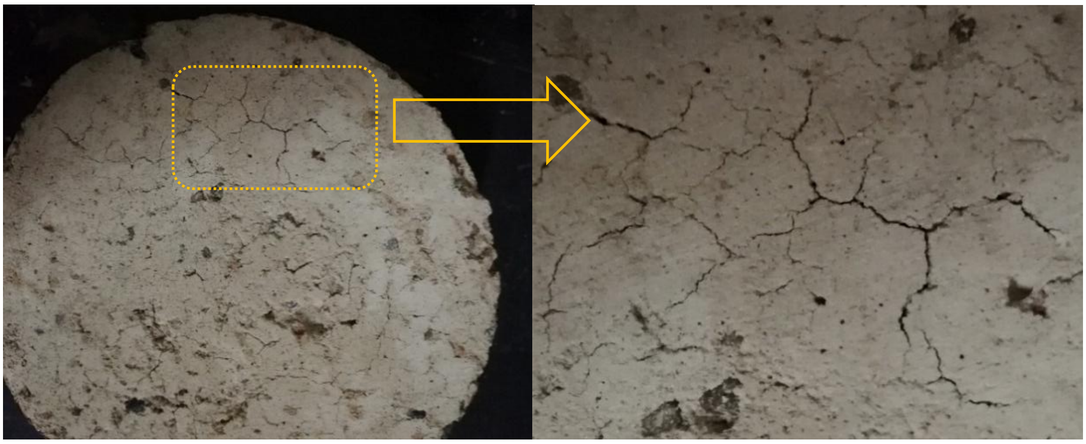


Figure 48: Hairline cracks on 4S-3 Mud-Concrete sample (4% Cement with 25% water)

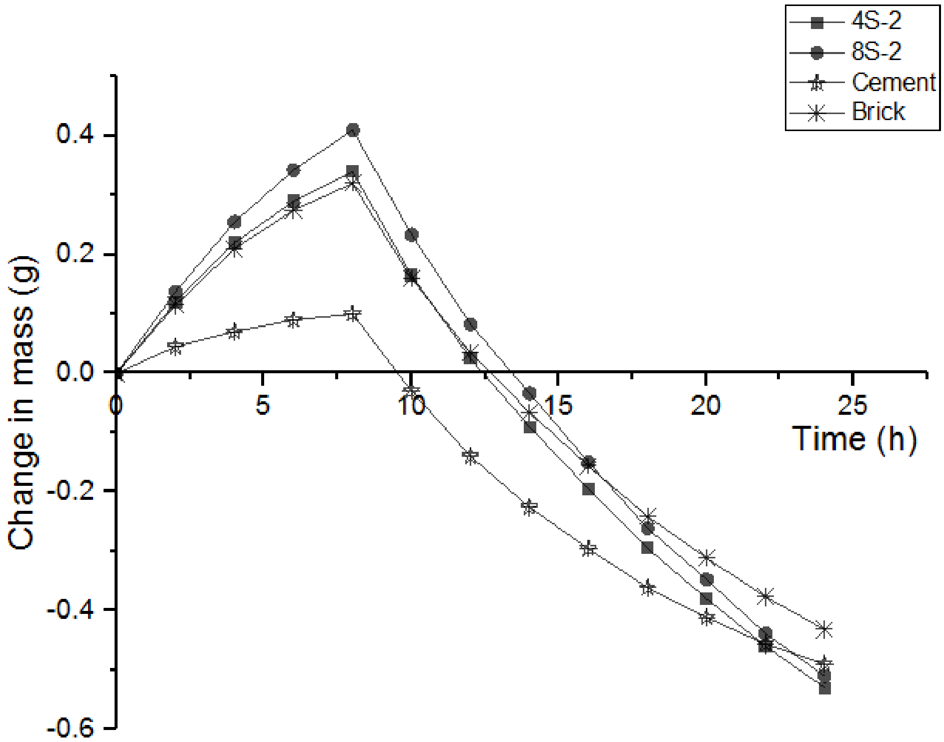


Figure 49: Recorded mass-time profile for MBV practical measurement – Comparison between 4% cement, 20% water of MC, 8% cement, 20% water of MC, brick and cement block.

Figure 47 shows the MBV practical of MC with 8% cement (8S) and the patterns were almost similar to the results of MC with 4% cement (4S) samples. Thus the results depict that increasing the water content in mix of MC is not effective because it is difficult to avoid the cracks on the material surface. Reducing the water in mix always increases the mass change (water that is transported in or out of a material per open surface area) of MC material. However it is difficult to keep the self-compacting quality with less water consumption. Therefore, it is recommended to go for optimum 20% water with 4% or 8% cement in MC material.

However the overall results demonstrate that MC can have excellent range of $MBV_{practical}$ values with 4% and 8% cement with different moisture capacities (moderate: 0.5–1.0 g/m^2%RH; good: 1.0–2.0 g/m^2%RH; excellent: < 2.0 g/m^2%RH) (Rode et al., 2007). Figure 49 shows that 8S-2 MC sample (8% cement with 20% water) has a higher capacity of changing mass than 4S-2 sample (4% cement with 20% water). This results show that increasing cement content did cause the increase in the mass change of MC material. Similarly the thermal conductivity and moisture capacity of 8% cement with MC (8S-2 MC) has a higher value than 4% cement with MC (4S-2) (Table 57). To analyze this reaction few micro-structural images were taken of 4% cement with MC and 8% cement with MC (Figure 50 and Figure 51). By the process of hydration (reaction with water) Portland cement mixed with soil (a mixture of gravel, sand and fine) and water produces the synthetic rock that we call “Mud-Concrete”. This hardened soil, cement (Mud-Concrete) paste contains micro-pores (< 2nm) mesopores (2-50nm) and macropores (>75µm) structures. When increasing the cement content in the MC mix, the fine content increase and it effect to increase the water storage by providing an abundance of micro-pores (Figure 51).

Figure 53 shows the recorded temperature and relative humidity that achieved acceptable values in relation to the target set points. The maximum and minimum achieved values of relative humidity were used in the calculation of $MBV_{practical}$. The mass changing value of bricks and cement blocks were always lower than the $MBV_{practical}$ values of MC (Figure 52). MBV_{ideal} values were calculated using equation 05 and 06 (Table 60). Furthermore, it can be seen from Table 61 that MBV practical > MBV ideal in all cases. In addition, MC can be kept as non-plastered walls and leave the surface exposed to the indoor air, unlike bricks and cement blocks which are traditionally covered or painted; reducing water vapour permeability and their effectiveness. Thus, MC material has the respiration quality and it can be optimized with the exposed surface areas and thickness of the walls. This optimizes thermal and moisture buffering quality of the MC material which can control the microclimatic (thermal profile in the room) environment in and around the building while thermally comforting the occupants of the building.

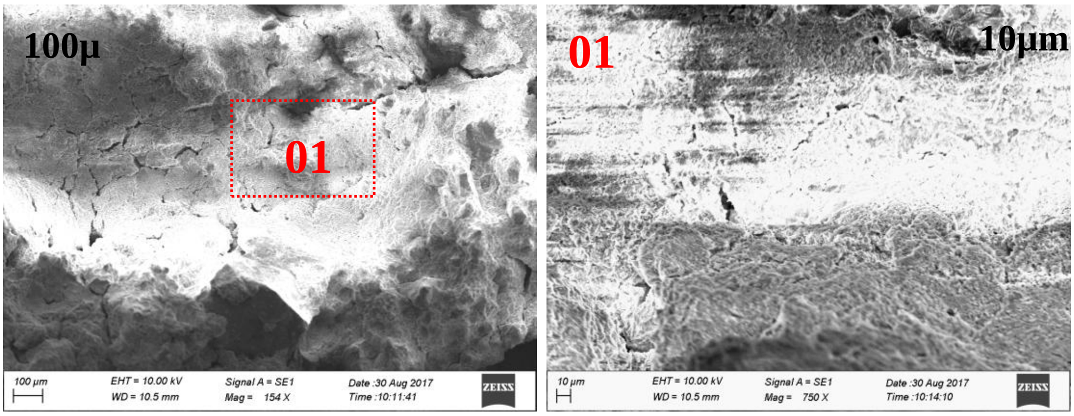


Figure 50: SEM images of MC samples made with 4% Cement and 20% optimum water in 28 days

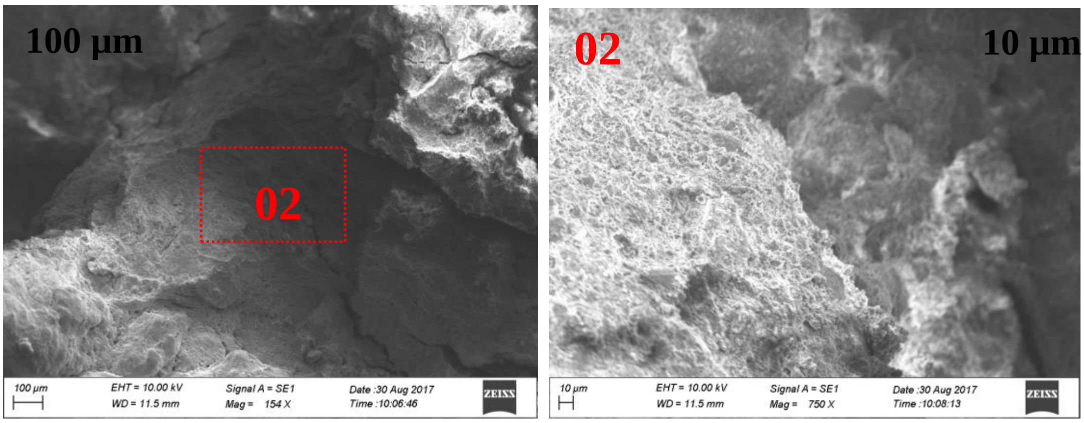


Figure 51: SEM images of MC samples made with 8% Cement and 20% optimum water in 28 days

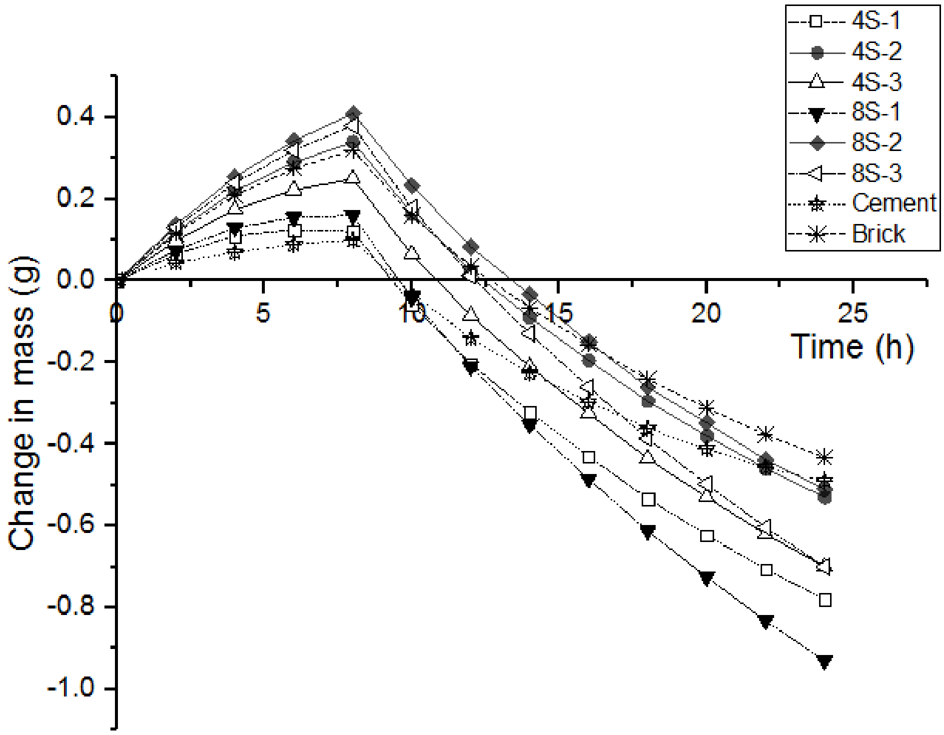


Figure 52: Recorded mass-time profile for MBV practical measurement – Comparison between all tested samples

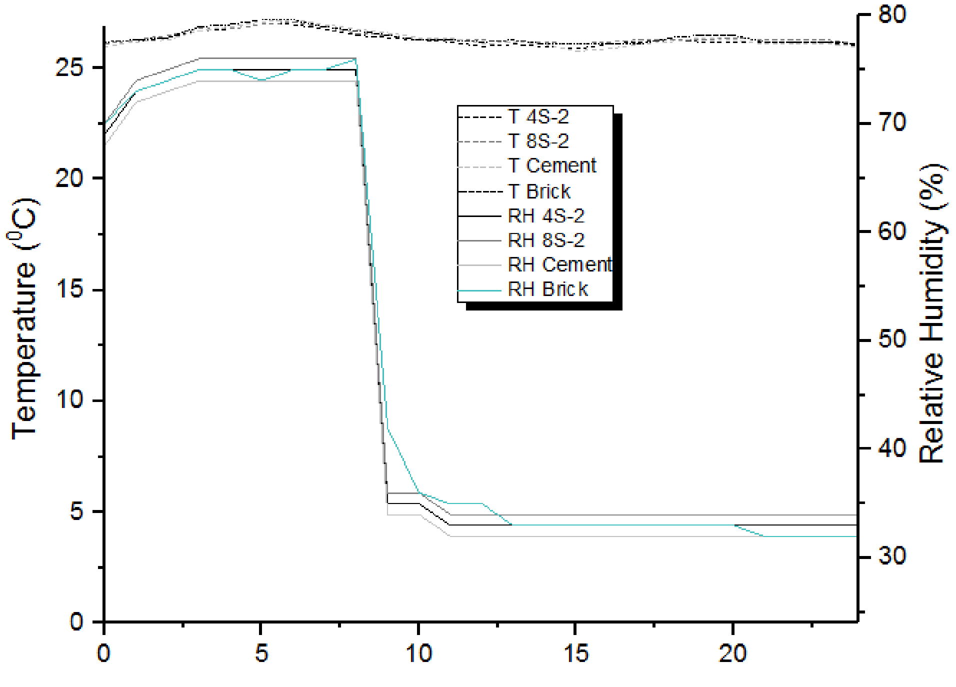


Figure 53: Recorded relative humidity and temperature profiles for the MBV measurement

Table 60: MBV ideal values of tested samples

Sample	δp (kg/m.S.Pa)	ρ0 (Kg/m^3)	Chage in mass(g)	∆RH (%)	∂wm/∂ϕ	Ps (Pa)	bm	tp	MBV ideal (g/m^2.%RH)
4S-1 MC	3.28×10^{-11}	1977	0.9	0.42	0.002142857	4212	1.816×10^{-7}	86400	1.28
4S-2 MC	2.99×10^{-11}	1836	0.87	0.42	0.002071429	4212	1.64412×10^{-7}	86400	1.16
4S-3 MC	3.14×10^{-11}	1794	0.95	0.42	0.002261905	4212	1.73825×10^{-7}	86400	1.22
8S-1 MC	3.07×10^{-11}	1976	1.09	0.42	0.002595238	4212	1.93176×10^{-7}	86400	1.36
8S-2 MC	3.14×10^{-11}	1850	0.92	0.42	0.002190476	4212	1.73707×10^{-7}	86400	1.22
8S-3 MC	3.15×10^{-11}	1820	1.08	0.42	0.002571429	4212	1.87014×10^{-7}	86400	1.32
Cement block	1.71×10^{-11}	2100	0.59	0.42	0.001404762	4212	1.0946×10^{-7}	86400	0.77
Brick	2.85×10^{-11}	1580	0.75	0.42	0.001785714	4212	1.38198×10^{-7}	86400	0.97

Table 61: Summary of MBV practical vs. MBV ideal

Material	Description	$MBV_{practical}$ (g/m^2.%RH)	MBV_{ideal} (g/m^2.%RH)
4S-1 MC	Mud-Concrete with 4% cement and 15% water of dry mix	2.46	1.28
4S-2 MC	Mud-Concrete with 4% cement and 20% water of dry mix	2.38	1.16
4S-3 MC	Mud-Concrete with 4% cement and 25% water of dry mix	2.60	1.22
8S-1 MC	Mud-Concrete with 8% cement and 15% water of dry mix	2.98	1.36
8S-2 MC	Mud-Concrete with 8% cement and 20% water of dry mix	2.52	1.22
8S-3 MC	Mud-Concrete with 8% cement and 25% water of dry mix	2.96	1.32
Cement blocks	Cement block with 1:5 cement sand ratio	1.61	0.77
Bricks	Fired clay bricks	2.05	0.97

The results of measuring the MBV of six (06) representative MC material types indicate that Mud-Concrete can be an excellent moisture buffering material. This buffering potential of the MC material can be developed with optimizing the surface exposure and walling thickness in a given space while passively balancing the micro-climatic conditions. Increasing water content in the mix did not effectively increased the buffering potentials of the MC material. Because MC wall may crack if a higher water content is found in the mix. Although the low water content has given a better moisture buffering value of MC, practically it is difficult to keep the self-compacting quality of the material in construction. Thus, 20% optimum water content is recommended to be used in MC construction and it always deemed to satisfy the self-compacting quality, required strength and excellent moisture buffering capacities.

Even though we have assumed that increasing cement content will drastically reduce the moisture buffering capacity of the MC material, the results have shown the opposite condition as increasing the cement content increased the moisture buffering capacity of MC material by increasing the thermal conductivity as well as the moisture capacity of the microstructural arrangements.

Overall experimental results depict that $MBV_{practical}$ values are higher than MBV_{ideal} values in all cases. In addition Mud-Concrete (MC) proved to be working as an excellent moisture buffering material than bricks and cement blocks according to the obtained results. However, further work is needed to improve the reliability of MBV measurements by carefully controlling the experimental conditions and material hygrothermal properties. In addition, future work can be extended to investigate the porosity of the structure and hygrothermal simulations.

However, MC can be used as non-plastered walls while optimizing the thickness of the walls (thermal mass) to improve the moisture buffering capacity according to the microclimatic conditions. This will help to save the life cycle cost and the embodied energy of the construction. Ultimately, it is clear that MC walls can passively create a thermally comfortable environment and improve the quality of indoor air while catering to the sustainable demands.

3.10. Concluding remarks

As recorded in literature any soil type can be used in MC construction(Arooz et al., 2015); however gravelly laterite soil is effective because of its ease in making a well-graded soil sample in the mix(Arooz, Babilegedara, & Halwatura, 2017), (Bandara et al., 2016). Thus, gravelly laterite soil was chosen in entire testing procedures. The selected soil was air dried and sieve analysis was conducted prior to use in tests. In this study Ordinary Portland Cement (OPC)/ (Type I) (ASTM C150 -07, 2007)was used as the stabilizer in the mix and for the entire test. 150mmx150mmx150mm cast iron block moulds were used to cast the MC testing blocks. Blocks were cured for 14 days using wet gunny bags at room temperature (± 25 ºC Temperature, ± 75% Relative humidity).

To check the workability and the self-compacting consistency of the MC mix, custom methods were developed. MC mix can achieve the workability if it flows up to an approx. 500mm diameter circle on the flow table after giving 25 blows using flow table. Results show approx. 20% water from the dry mix gives the workable mix of Mud-Concrete.

There is a probability of finding 4.75mm to 50mm gravel ranges in most commonly available native gravely laterite soil. The effective gravel range of self-compacting in-situ cast load bearing wall is 4.75mm-32mm. Therefore, the soil use for construct the MC walls must sieve through standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix. With a minimum 4% of cement, 45% Gravel: 50% Sand ratio gives the maximum wet & dry compressive strength for the mix design of in-situ cast MC load bearing wall.

- Fine - 5% (≤ sieve size 0.425mm)
- Sand (fine aggregate) - 50 % (sieve size 0.425mm ≤ sand ≤4.75 mm)
- Gravel (coarse aggregate) - 45% (sieve size 4.75mm ≤ gravel≤ 32mm)

Low quantities of fine (5% fine) were kept in the mix to maintain the high compressive strength values of in-situ cast MC wall. Usable gravel range in soil for any Mud-Concrete construction is limited for 35%-55% with 4% cement, as sand is limited to 60%-40%. Increasing gravel percentage does not lead to increase the compressive strength of MC always. The compressive strength of MC wall depends on the particle size distribution of developed soil, optimum gravel size and the optimum gravel: sand ratio of the mix.

Increasing the water content reduces the compressive strength of the MC mix. However, the behaviour of water in MC was ambiguous as it is difficult to keep the exact water percentage of the dry mix even though the same water was added in every sample while mixing. Therefore, data matrix was obtained through series of testing procedures and a phenomenological equation was developed to plot the exact grading curves in identified water percentage of dry mix in MC walls.

In addition, the MCW material is deemed to satisfy the durability standards of an earth-based material (Sri Lankan Standard Institute, 2009) with the 4% minimum cement content in the total dry mix in laboratory testing conditions.

MCW is an excellent moisture buffering material. Increasing water content in the mix did not effectively increased the buffering potentials of the MC material. Because MC wall can crack with the high water content in the mix. Although the low water content has given a better moisture buffering value of MC, practically it is difficult to keep the self-compacting quality of the material in construction. Thus, 20% optimum water content is recommended to be used in MC construction and it always deemed to satisfy the self-compacting quality, required strength and excellent moisture buffering capacities. Overall experimental results depict that MBV practical values are higher than MBV ideal values in all cases.

Increasing the cement content increased the moisture buffering capacity of MC material by increasing the thermal conductivity as well as the moisture capacity of the microstructural arrangements. This buffering potential of the MC material can be developed with optimizing the surface exposure and walling thickness in a given space while passively balancing the micro-climatic conditions.

4. CHAPTER THREE - SYSTEM DEVELOPMENT

4.1. General

After identifying the best mix design for the MCW, the next step is to develop an optimum construction technique for the walling system. Hence, this section discusses one of the main objectives of analyzing the structural performance of the MCW.

Prior to find the optimum lifting height of a MC wall segment, it was essential to introduce a most practical, user friendly, cost effective and durable formwork system for MC wall construction. Thus a rationale was built up to identify the most optimum formwork system for MC wall construction. In this research process, it was understood that both structural capacity and the social acceptance among users would affect on decision making on designing a modular Formwork system for in-situ cast walls made of self-compacting soil-based material. After identifying the formwork the research was designed to investigate the optimum lifting height of MCW segment. Accordingly, linear drying shrinkage of a MCW segment will be investigated. The research objectives were extended to check strength behaviour between construction joints of MCW, in order to achieve the objectives- the methodologies were adopted.

Hence chapter mainly focuses on the areas of developing the formwork system, finding the optimum lifting height of a MC wall segment, investigating drying shrinkage of a MC wall segment and understanding on possible construction joints between wall segments.

4.2. Developing the formwork

Prior to designing a formwork, there are a few factors to be considered in terms of social acceptance and structural capacity (Figure 54). End user perception is important to invent user-friendly systems while enhancing the efficiency of construction technology. Thus the decisions were made to find out the public perception toward available formwork system through literature review and the questionnaire survey was conducted among concrete workers.

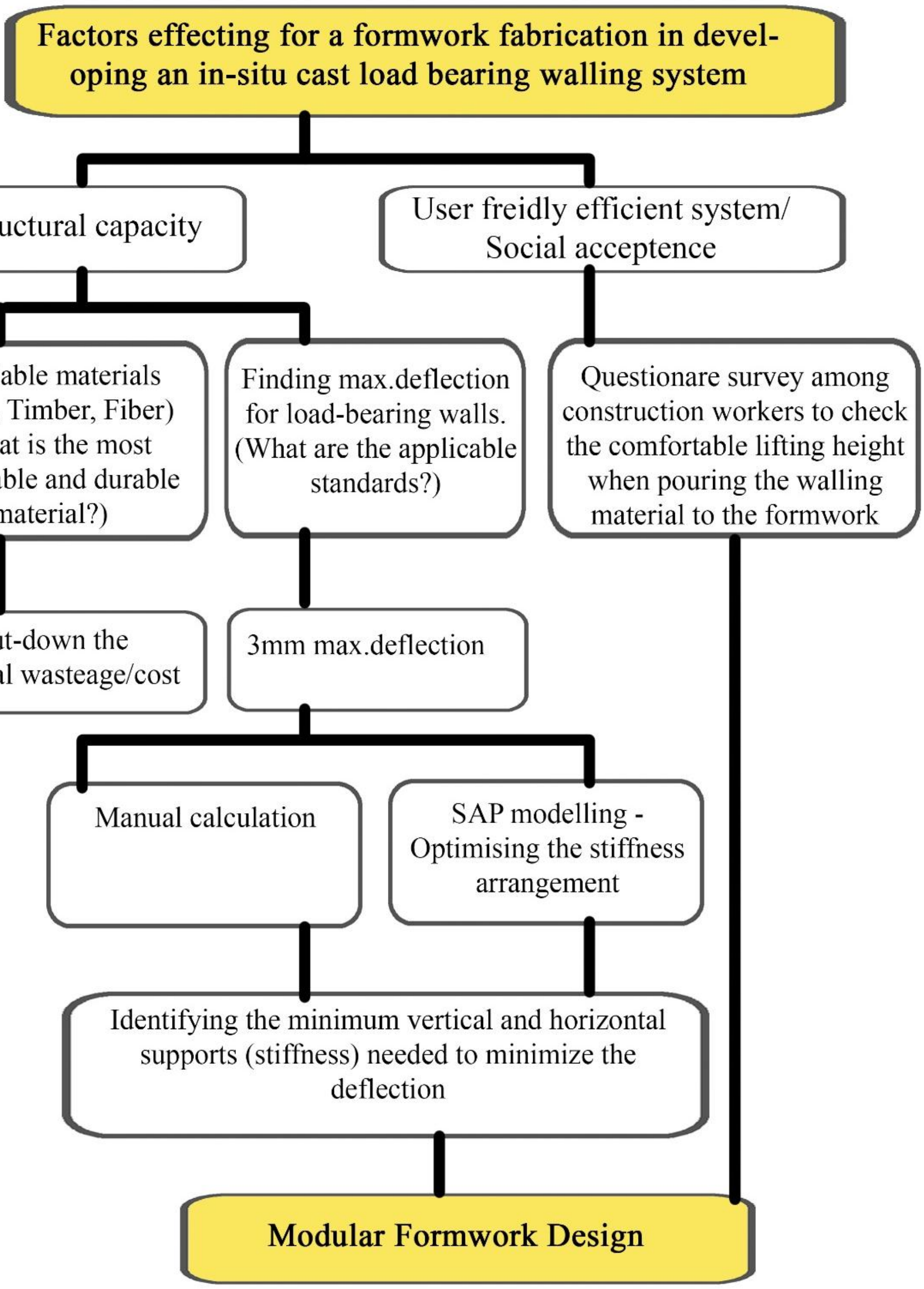


Figure 54: Factors effecting for a formwork fabrication in developing an in-situ cast load-bearing walling system

4.2.1. End-user perception towards available formwork system

A questionnaire survey was conducted among 400 sampling of construction workers (especially concrete workers in different sites) to identify mainly the comfortable lifting height of pouring concrete to a wall or a column. Simultaneously, the questionnaire was focused to identify the issues in placing the concrete to a wall or a column and the practical issues occurred in assembling and dissembling the formwork systems.

a) Results obtained by the questionnaire survey

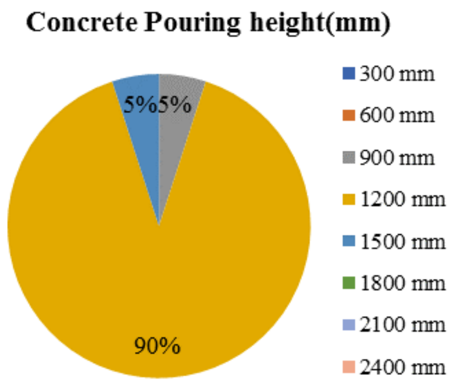


Figure 55: Worker's preferences on concrete pouring height

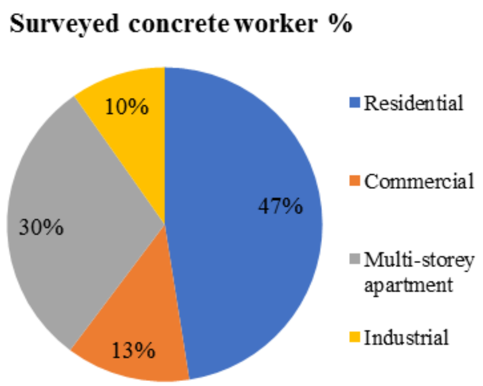


Figure 56: Survey carried on different construction sites and surveyed percentage of workers

According to the results analysed of survey conducted among construction workers at different construction sites (Figure 55), it was found that 90% of workers are comfortable with 1200mm (4'-0") of concrete pouring height to a wall or a column (Figure 56). Further, 5% of the workers are comfortable with 1500mm (5'-0") pouring height and the rest of 5% of the workers are comfortable with 900mm (3'-0") pouring height. Thus, it was understood the correct physical ergonomics are more important to optimize the construction methodologies and introduce labour free methodologies effectively.

b) Conclusion of the questionnaire survey

The strength of the wall may vary with different parameters, mainly the height due to segregation of MC. Though the comfortable height was found as 1200mm (4’-0”), it was doubtable whether the needed strength could achieve within this 1200mm height in MCW segment. Therefore, it was urging to fill this gap between the end-user acceptance and the structural capability in practical aspects. Maximum construction height of a wall segment should not reduce the strength of the wall in total construction process. Hence the research was designed to conduct core testing to check the behaviour of compressive strength of core samples extracted along MC wall to identify the most optimum lifting height of a MCW segment. Prior to that 1200mm of comfortable height was used to design a segment of modular formwork system.

4.2.2. Formwork design - Structural optimization through computer simulations

The invention relates to a modular formwork made of steel, which was designed and manufactured off-site. The formwork was designed according to the set-out load calculations. None of the techniques exists yet in the world relating to formwork for in-situ cast walls made of soil-based materials except rammed earth walling system. However, rammed earth systems are not based on self-compactions and they are designed totally for heavy compactions through manual or pneumatic ramming process (Hall & Djerbib, 2004), (Minke, 2012) and (Walker, Keable, Marton, & Maniatidis, 2010b). Thus, the novel invention was particularly designed for in-situ cast walls made of self-compacting soil-based materials.

Considering the durability and the long term cost factors, ‘steel’ sheets were selected as most appropriate material to use for formwork fabrication rather than wood and fiber boards. Prior to design the formwork load calculations were done through both manual and finite element modelling to optimize the system and reduce the material usage. Manual calculations were done to verify the computer modelling.

According to the tolerance in masonry construction, maximum horizontal or vertical deviation of a surface from a plane surface (bow) in any 2m length is 3mm.

Therefore, maximum allowable deflection is 3mm each mould plate of the formwork (Victorian Building Commission, 2007).

After identifying the maximum allowable deflection, SAP 2000 finite element modeling was used to model the formwork system. Different types of structural arrangements were experimented through this computer modelling and then selected the most optimum arrangement for formwork fabrication. Soil density - 20 kN/m^3, steel sheet thickness – 3mm and elastic modulus of steel – 200 kN/mm^2 were given as input data to simulate the numerical model. To reduce the material wastage 2400mm (8'-0") x 1200mm (4'-0") steel sheet has been used on formwork fabrication. Seven (07) types of arrangements were tested to find the optimum bracing and lateral support arrangements as follows (Figure 57 and Figure 58);

a) Results obtained by numerical modelling

<u>2400mm x 1200mm steel sheet,</u>

a) Outer frame + one horizontal support from center
b) Outer frame + one vertical support from center
c) Outer frame + 1/3 vertical support
d) Outer frame + ¼ vertical support
e) Outer frame + ¼ vertical support + one horizontal support from center
f) Outer frame + ¼ vertical support + 1/3 horizontal support
g) Outer frame + 300mm C/C vertical support

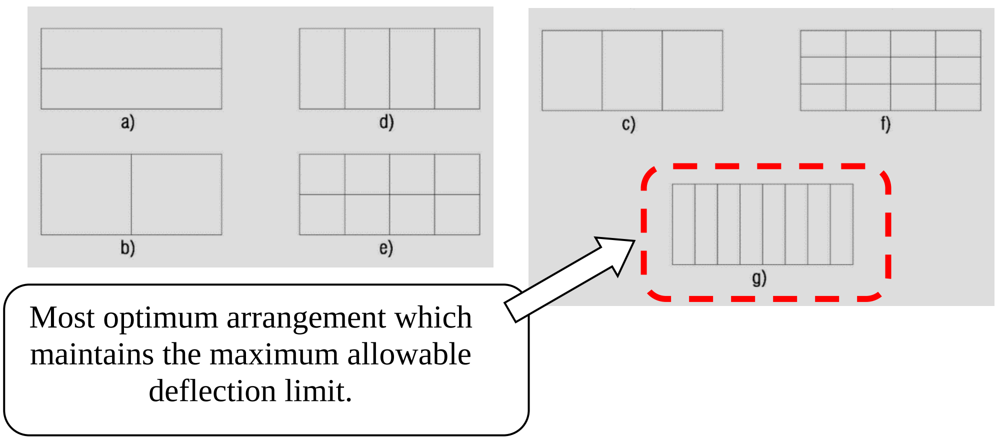


Figure 57: Different types of support arrangements to achieve the optimum structure with keeping the limit of maximum allowable deflection limit

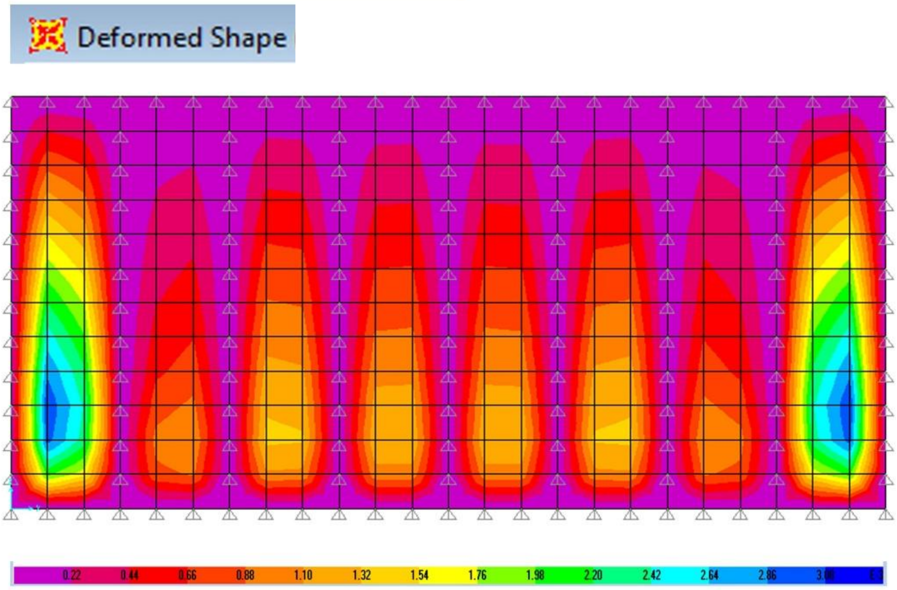


Figure 58: SAP model analysis of most optimum arrangement of formwork

b) Conclusion of formwork arrangement

The experiment was mainly based on the calculated design loads (water and soil pressure, wind loads). Through finite element modelling, it was decided the minimum spacing of studs and wales, which needed to avoid the maximum bending, deflections, rolling shear occur due to water and soil pressure of the poured self-compacting material. Then it was calculated the minimum number of lateral bracings need to avoid the bending of a wall segment. While the strength was finalized, it was designed with minimum materials and simple technologies which could use for fabrication. Further, the joints were ensured in watertight and surfaces were kept in smooth. Then the quick & safe methods were introduced to erect and dismantle the formwork system. The needed minimum number of labour has been optimized to assemble the system in site. Through this conscious design and techniques, manufacturing cost of the formwork has been optimized.

<u>Allowable deflection is 3mm</u>

<u>Minimum Supports</u>:

- Only outer frame with Vertical plane 300mm in C/C
- Angle propping should less than 3m distance

Materials used:

- 3mm thickness, 1200mm(height) x2400mm(length) size steel sheets as mould plates
- 50mmx50mm 'L' iron frame, welded with 'L' iron bars in each 300mm c/c gaps
- 3mm thick, steel strip welded to two 'L' (50mmx50mm) angles as End plates of the formwork (Needed depth of the End panel will change according to the needed thickness of wall segment)
- 50mm x 50mm box bars with chamfered one side edge
- Thread bars to tie the mould plates
- 50mmx50mm 'L' bars to stop the bending of mould plates from the bottom
- Lateral Bracing (Angle propping/ vertical adjustable devices) to stop the bending of mould plates from the top

4.2.3. Formwork design – Construction components

Five (05) main construction components are identified in the design process. Those are as follows;

Construction Components-

A. Formwork for typical wall segment
    a. Side mould plates
    b. End plates
    c. Construction joint between wall segments
B. Formwork at a wall corner
C. Formwork at window opening
D. Formwork at door opening

A. Formwork for typical wall segment

a. Side mould plates

As per the results received from the finite element modelling, the maximum height of a wall segment has been decided. Then 1200mm (height) x 2400mm (width) steel sheet has welded to 50mmx50mm, 'L' iron frame to make the mould plate. According to the load calculation, 'L' iron bars were welded in each 300mm (C/C) of the 'L' iron frame in the vertical side to avoid the buckling. Mould plates were fixed through threaded bars from the top and the side of the 'L' iron frame. According to load calculation, four nos. adjustable angle propping was used to stop the bending of the mould plates from top. 50mmx50mm 'L' bars were horizontally supported to stop the bending of mould plates from the bottom (Figure 59, Figure 60, Figure 61, Figure 62 and Figure 63).

b. End plates

End plates were prepared with 3mm thick steel sheets welded to two nos. of ‘L’ iron bars. End plates were designed up to two levels of height to ease the construction process. This will minimize the time and cost of erecting & dismantling process of the Formwork system. The end panels are separable, stackable, interchangeable and such that one set of formworks may be used to create several different wall configurations (Figure 64).

c. Construction joints between wall segment

50x50mm box bars were welded to the end plates from the inner side to make a groove in the constructed wall edge (STEP – 01). In the next step of the construction of wall segment, (STEP – 02) that groove embedded in the previous wall segment will fill with the poured walling material to make the vertical construction joint between the two wall segments (Figure 65).

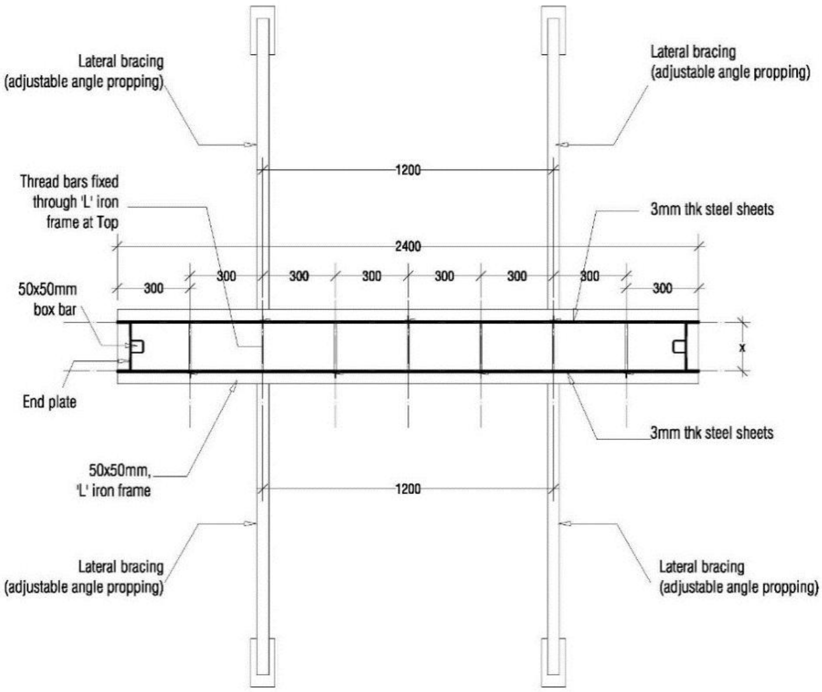


Figure 59: Formwork arrangement to typical wall segment – PLAN VIEW

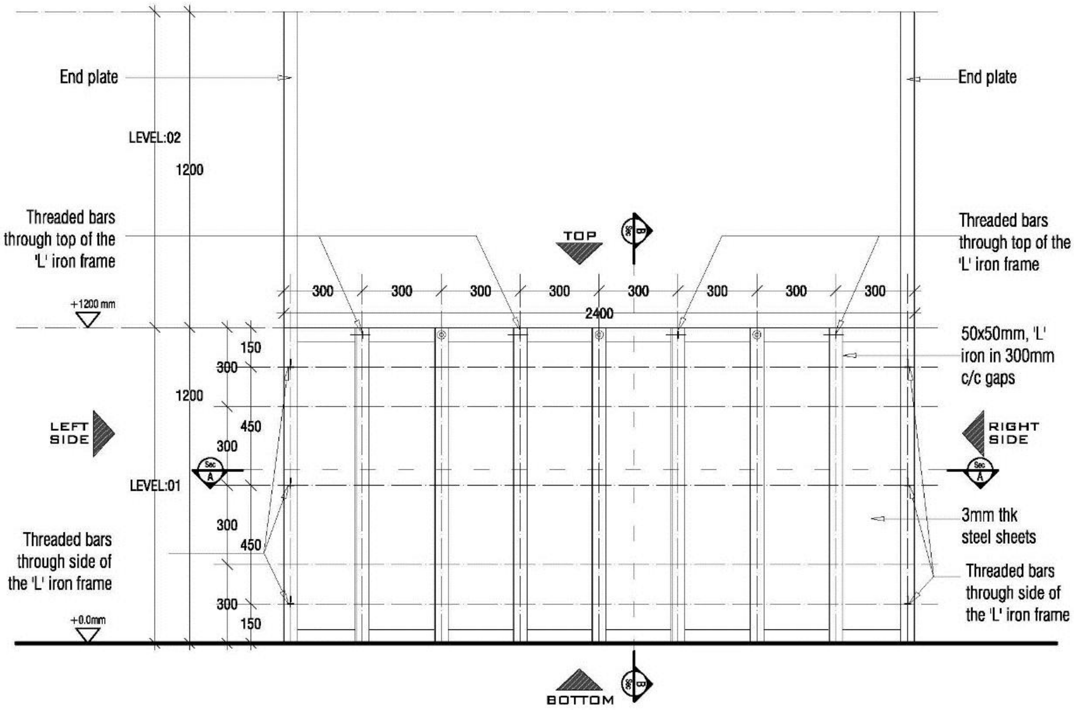


Figure 60: Formwork arrangement to typical wall segment – FRONT ELEVATION

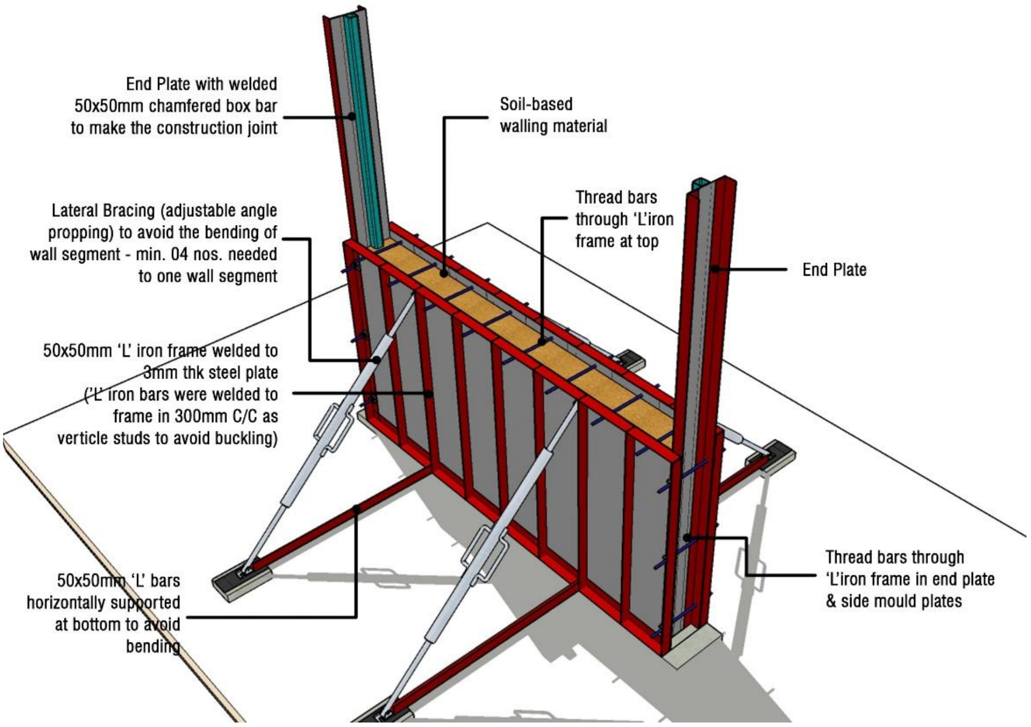


Figure 61: Formwork arrangement to typical wall segment - Step: 01

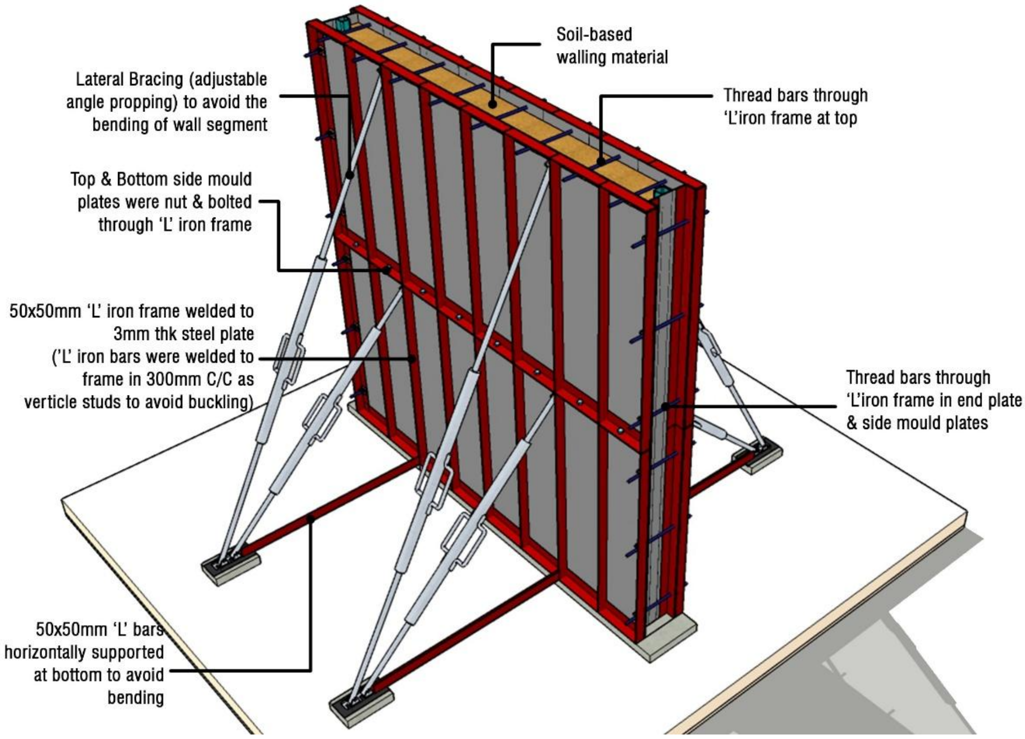


Figure 62: Formwork arrangement to typical wall segment - Step: 02

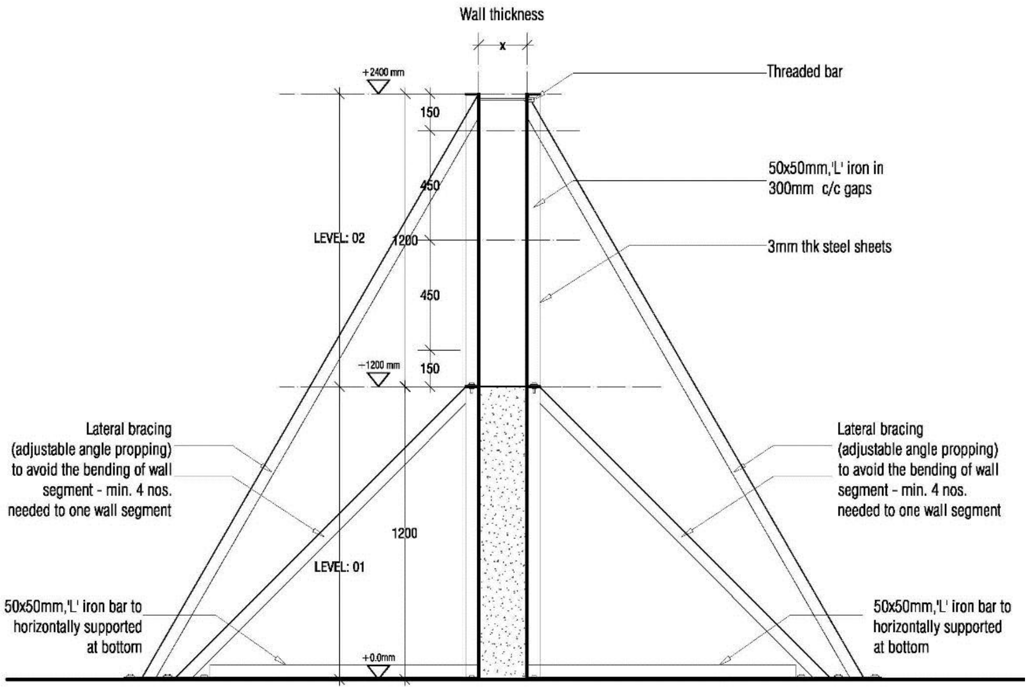


Figure 63: Formwork arrangement to typical wall segment – SIDE ELEVATION

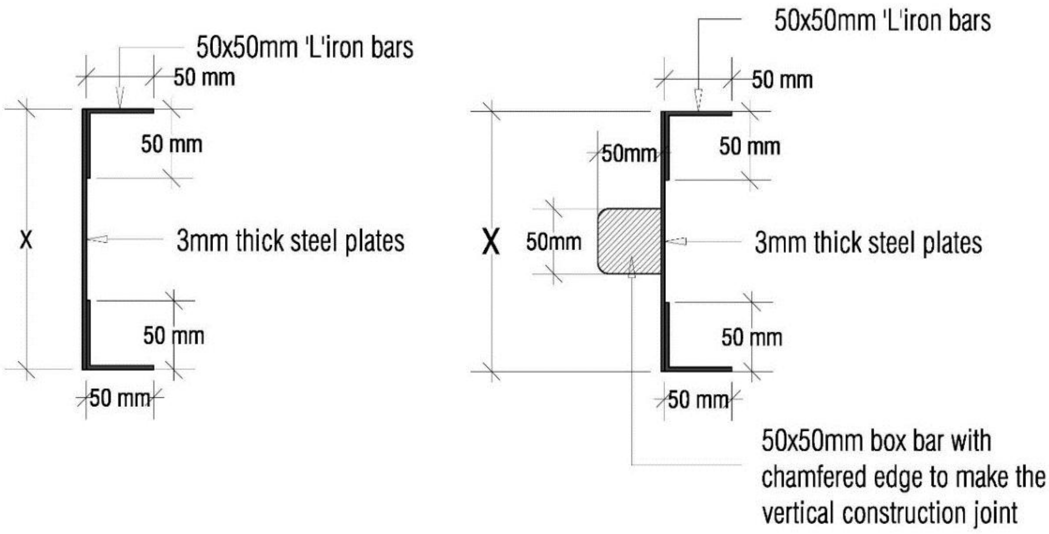


Figure 64: Formwork arrangement of end plates – PLAN VIEW

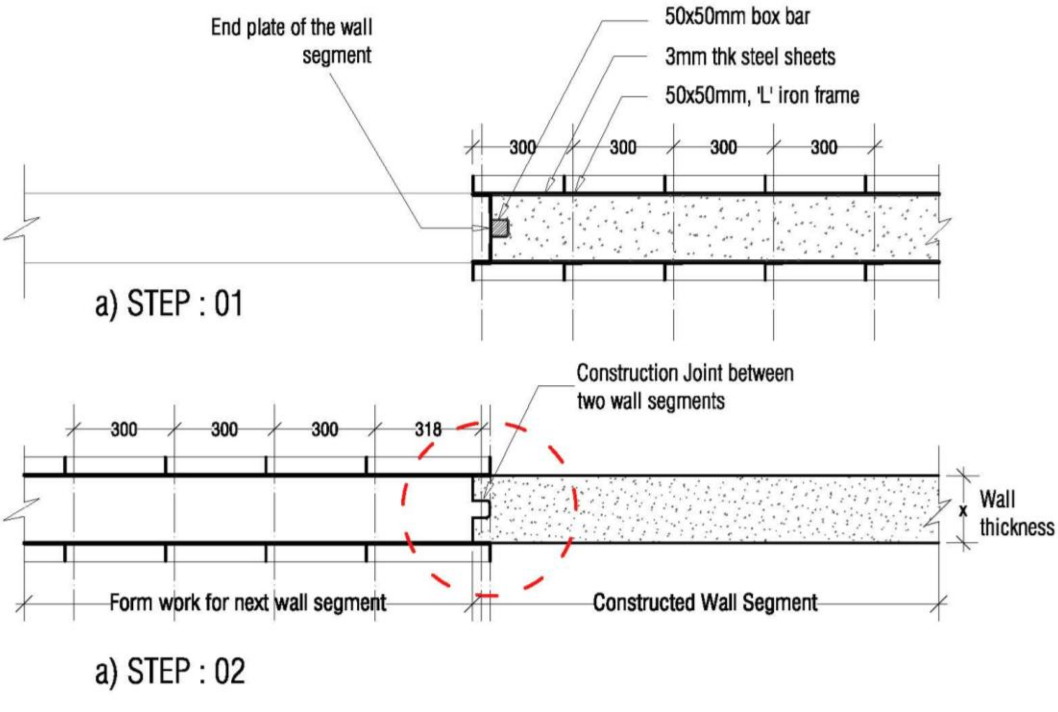


Figure 65: Construction Joints between wall segments – PLAN VIEW

B. Formwork at wall corner

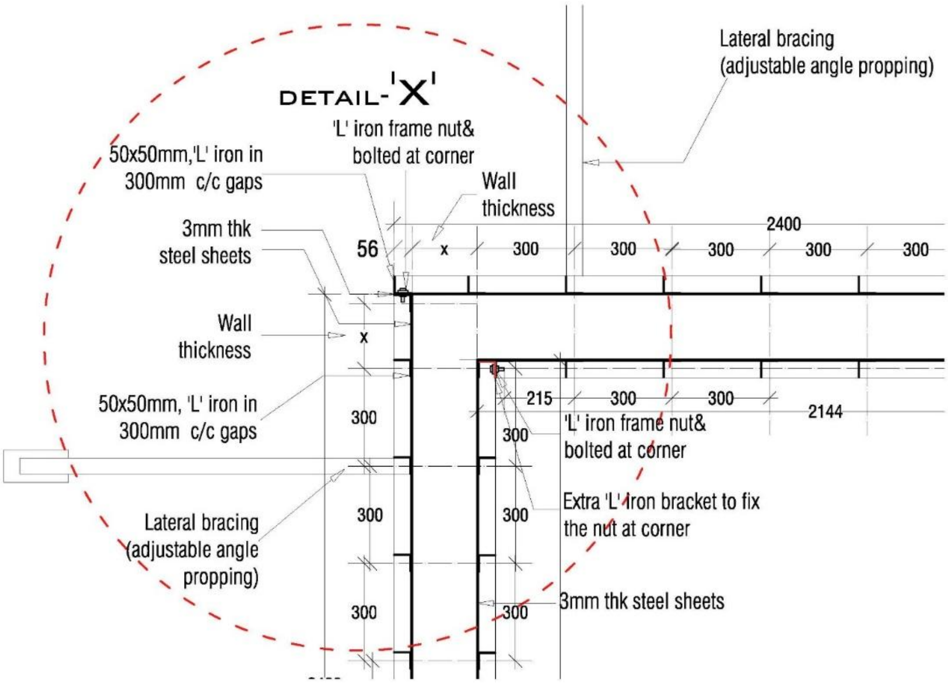


Figure 66: Corner formwork – PLAN VIEW

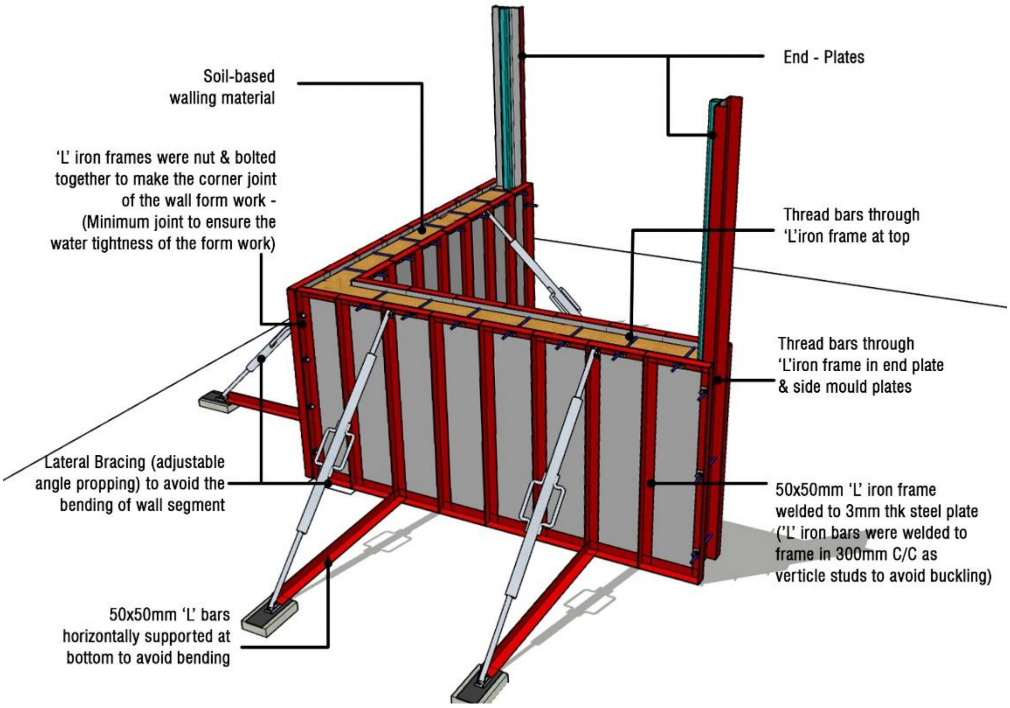


Figure 67: Corner Formwork – Outer View

As per the results of finite element modelling the designing principals were same to the above conditions of typical wall segment. Here the attempt is to optimize the minimum materials which could use for a corner formwork in construction. Thus, the same mould plates in 1200mm (height)x 2400mm (width) steel sheet welded to 50mmx50mm, 'L' iron frame and 50mmx50mm 'L' iron steel studs welded in each 300mm was used to fabricate the corner formwork. In this system, corners were ensured in watertight with minimum material usage (Figure 66, Figure 67 and Figure 68).

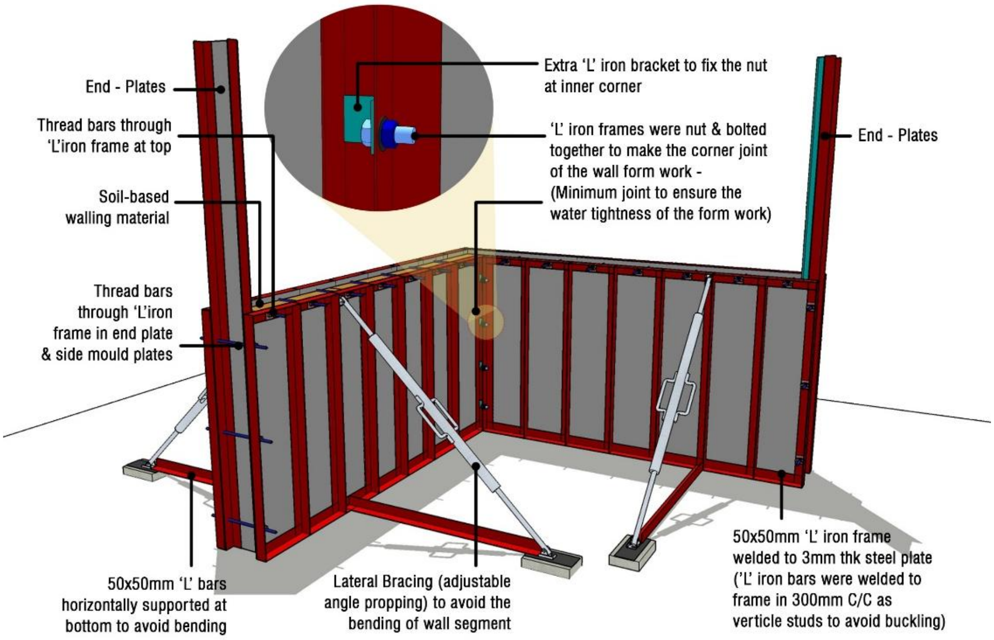


Figure 68: Corner Formwork - Inner view

C. Formwork at window opening

When the walling materials were filled up to the sill height level of the window, then the formwork for window opening (A frame made out of end plates similar to the sizes of window opening) needed to place within the mould plates. Then that frame needed to fix to the 'L' iron frame from the top in the side mould plates, to keep the alignments of the structure. There's no any through ties were used to fix this frame (formwork for window opening) to side mould plates. Thus the typical wall formwork could use in any component in wall construction (Figure 69, Figure 70, Figure 71 and Figure 72).

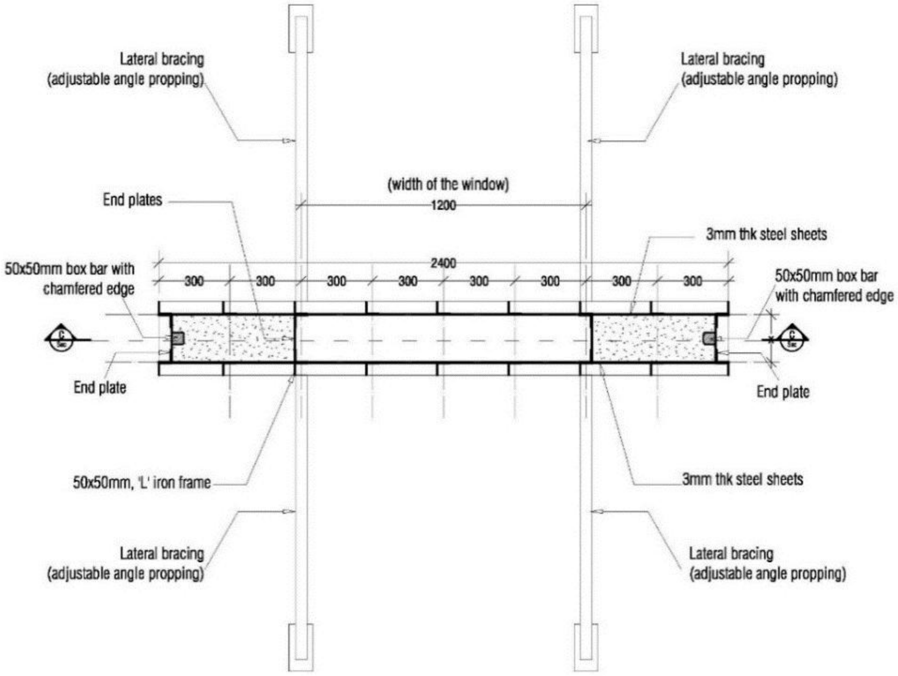


Figure 69: Formwork at window opening - PLAN VIEW

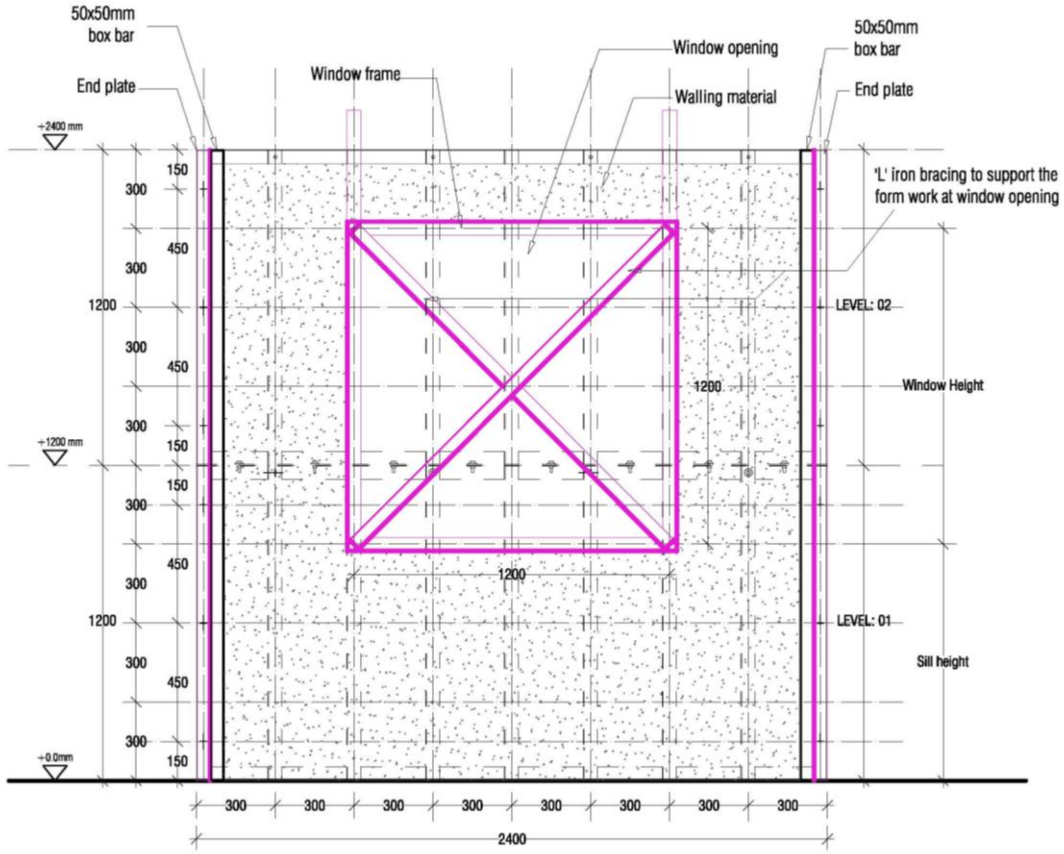


Figure 70: Formwork at window opening - ELEVATION

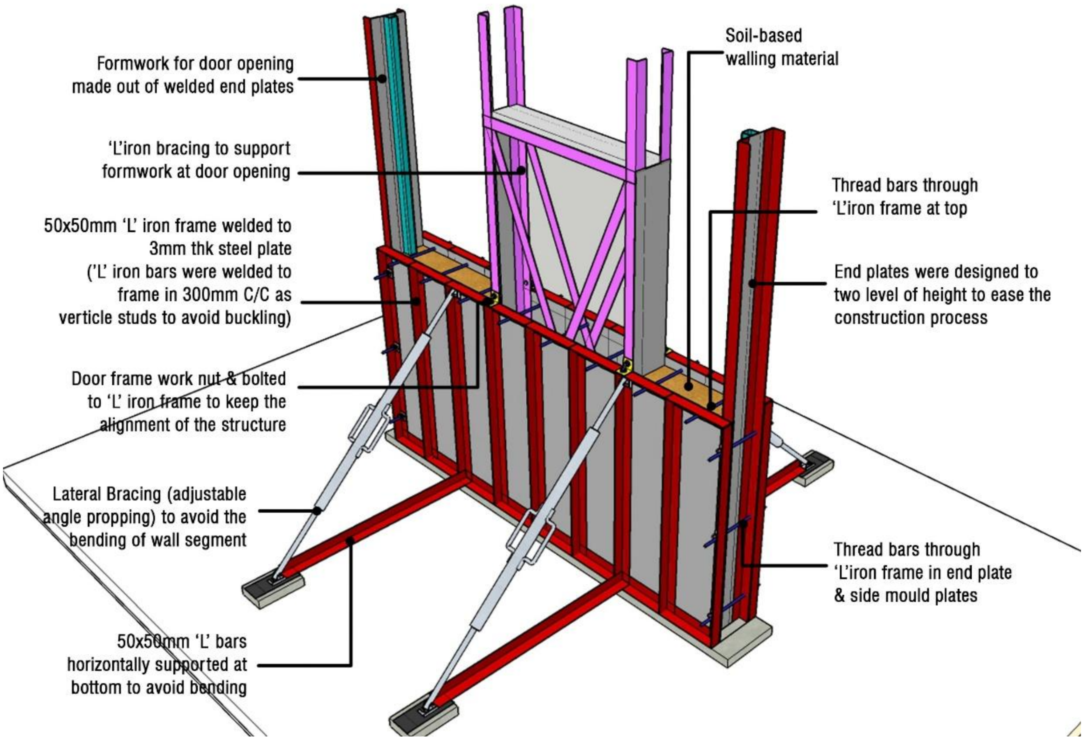


Figure 71: Formwork at window opening- Step: 01

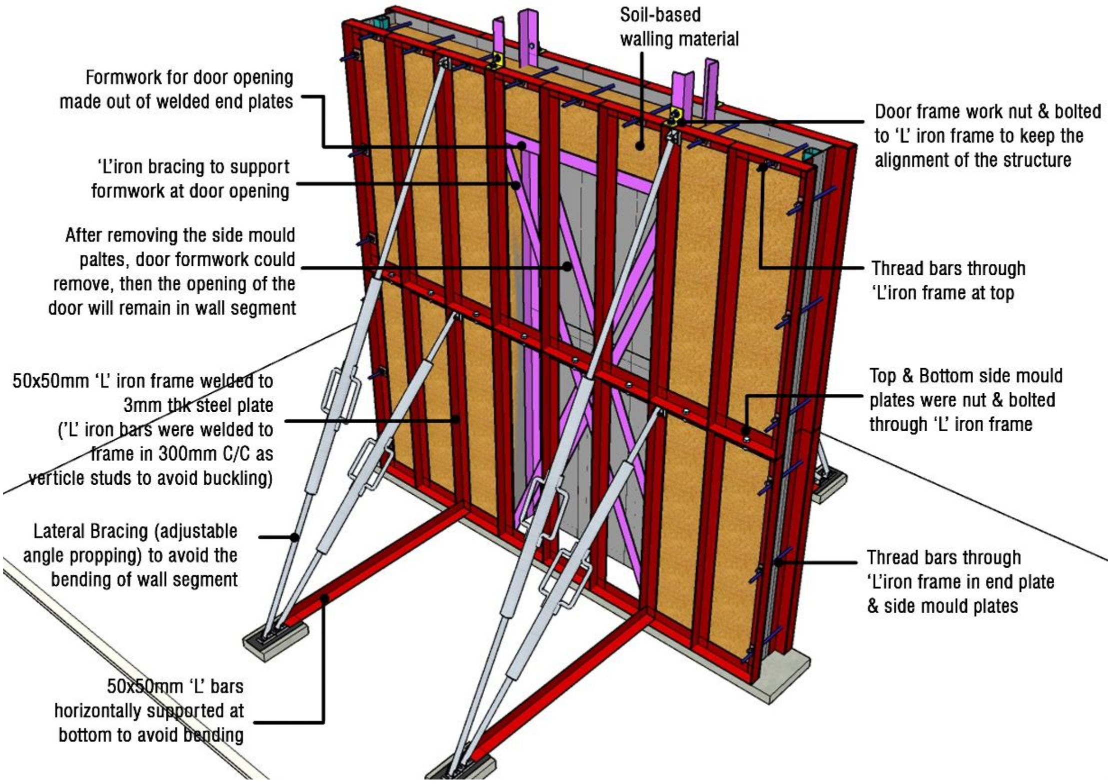


Figure 72: Formwork at window opening- Step: 02

D. Formwork at door opening

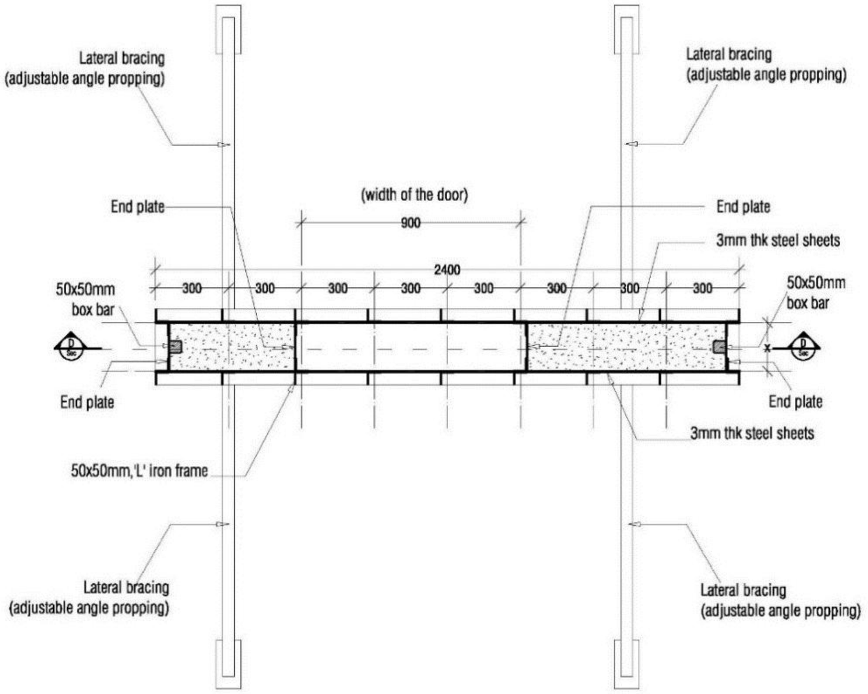


Figure 73: Formwork at door opening - PLAN VIEW

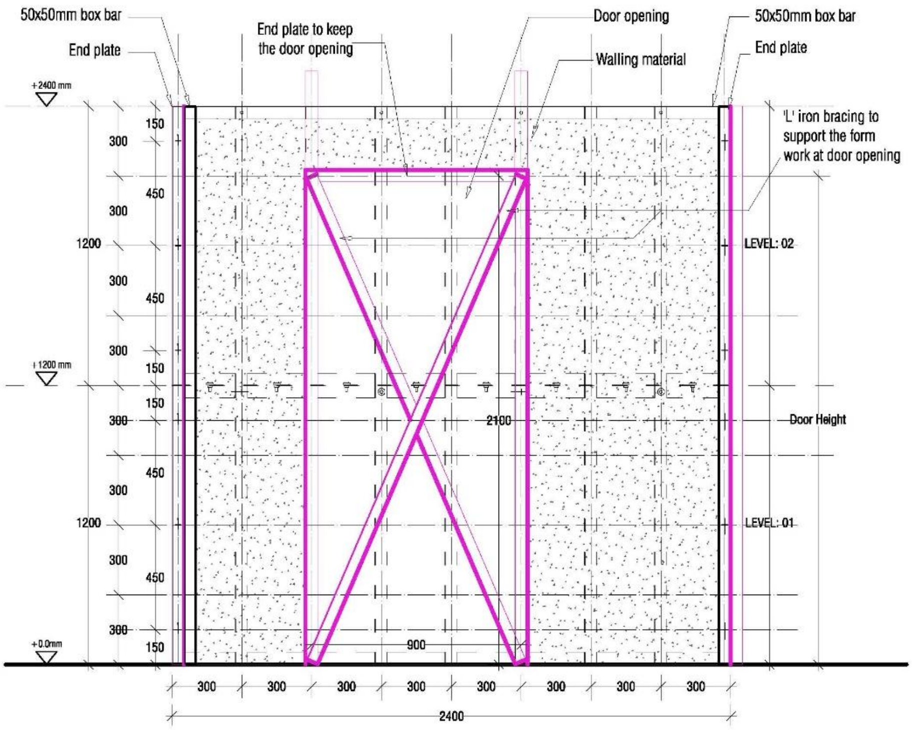


Figure 74: Formwork at door opening - ELEVATION

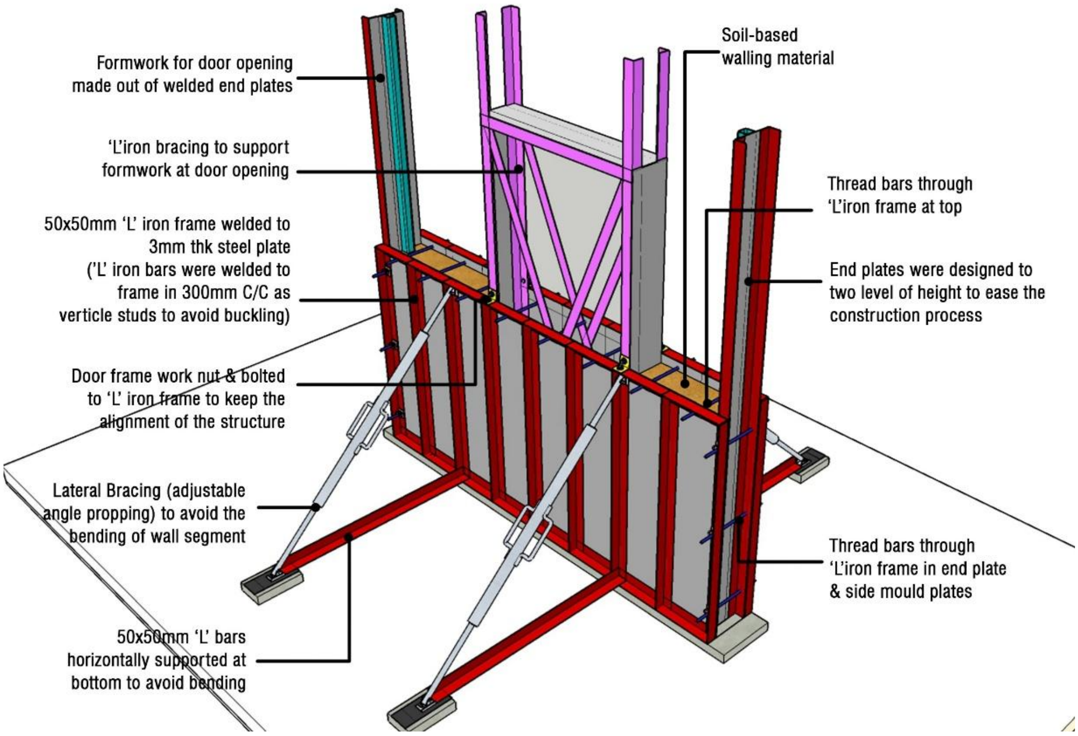


Figure 75: Formwork at door opening- Step: 01

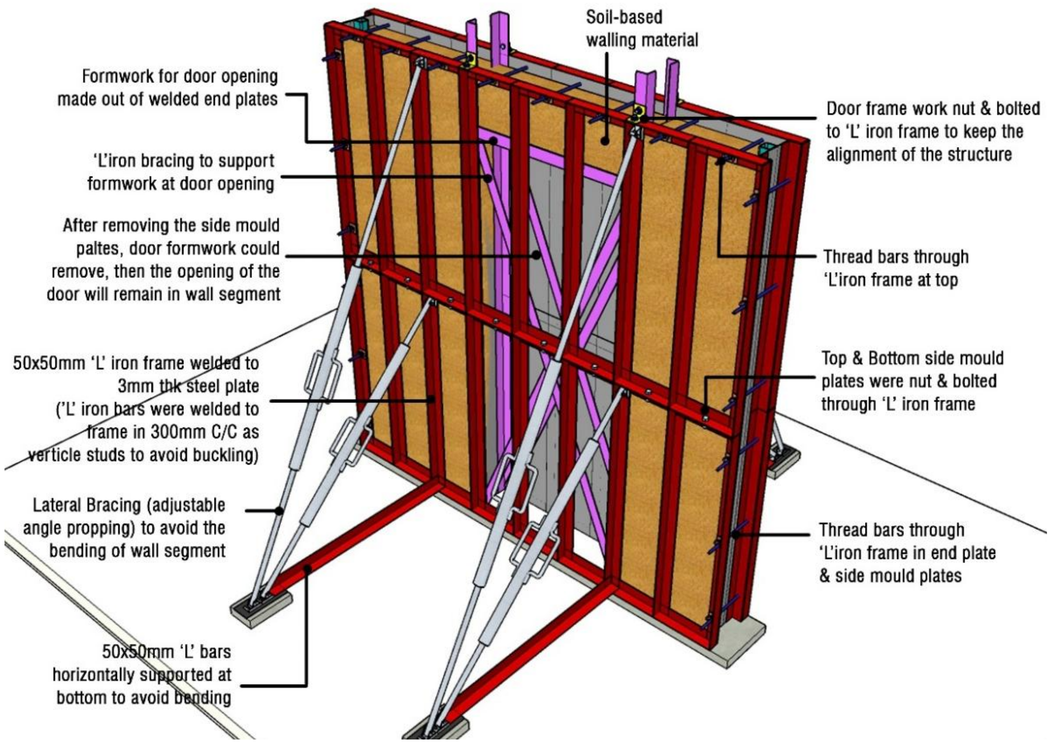


Figure 76: Formwork at door opening- Step: 02

When the mould plates were assembled, in the next step the formwork for door opening has to be installed. This formwork at door opening is a frame made out of end plates which similar to the size of the door opening. After positioning in the correct place that door frame needed to fix to the ‘L’ iron frame from the top in the side mould plates, to keep the alignment of the structure. Similar to the window frame there’s no any through ties were used to fix this door frame to side mould plates. Thus, the water-tightness of the structure was ensured, and the typical wall formwork could use in any components in wall construction (Figure 73, Figure 74, Figure 75 and Figure 76).

Figure 77: Fabricated modular formwork system - ex: Corner formwork

Figure 77 shows an example of actually fabricated corner formwork. There are few special characteristics of the developed formwork system (18879, 2016). Those are as follows;

- Easy to erect
- Easy to dismantle
- Keep continuity of the structure

- Watertight structure with minimum joints
- No wall through holes to fix the mould plates
- Simple construction joints; Provisions were already kept in form work for joint preparation between wall segments
- Simple supporting arrangement
- Dimension accuracy
- Flexibility of changing wall thickness; No ramming or external compaction were required
- High quality surface finishes are possible with the system
- The requirement of skilled labour is reduced due to the simplicity of assembly and disassembly.
- Increased speed and efficiency in construction
- Reduced material and manufacturing cost per m^2
- Reduced maintenance cost

4.3. Investigation of optimum lifting height of MCW

The optimum construction height of an in-situ cast wall can be affected by different factors such as segregation of material when increasing the wall height, the workmanship available at the site, the techniques used for handling and fixing formwork/mould of the wall, etc. Whilst introducing a new in-situ cast load-bearing walling material, it is important to check the strength variation with the height of the wall. Similarly, this optimum construction height of the wall will govern the speed of the construction process. As recorded in literature, the testing of optimum lifting height of Stabilized Rammed Earth (SRE) wall was done in two (02) methods (Lombillo et al., 2014; Ciancio & Gibbings, 2012). First one is moulding sample from the same mixture of casted wall and testing the compressive strength variations of the block or cylinder moulds. The second one is core the casted wall and get the cored sample to check the compressive strength variations. Recorded results depict that moulded samples are almost two times stronger than the cored samples of SRE. Horizontally cored samples are slightly stronger than the vertically cored samples of SRE. Ciancio and Gibbings (2012) assume this difference may be occurred due to the intersection of coring samples with ramming lines. However, the main objectives in this research are to investigate comfortable, an optimum lifting height of MCW.

4.3.1. Core testing

a) Finding the existing particle size distribution of used sub-soil samples

Gravelly laterite soil was used to commence the investigations. Soil samples were obtained from a homogeneous layer; 600mm-900mm below the top of the soil to get the good composition of soil and to avoid the organic particles in the soil samples. Three (03) random air-dried soil samples were used to conduct the sieve analysis tests to understand the existing particle size distribution of the soil while minimizing the errors. Liquid limit, plastic limit and plastic index were obtained by conducting Atterberg limit tests (Table 62). The average values of gravel 40.85%, sand 47.49% and fine 1.66% was available in existing soil samples (Figure 78). Then the soil was developed up to the achieved best mix design of MCW.

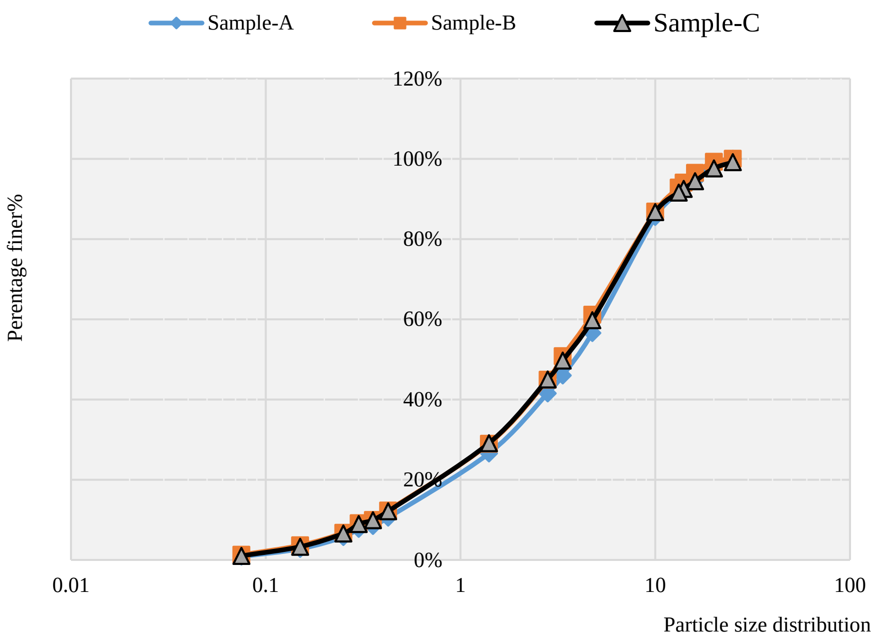


Figure 78: Particle size distribution of virgin soil

Table 62: Physical properties of selected virgin soil

Properties	**Values**
Liquid limit	35.99%
Plastic limit	21.78%
Plasticity index	14.95%
Dry density (soil gravel)	1600 -1800 kg/m^3
Wet density (soil gravel)	1800 - 2100 kg/m^3

b) Developing the soil and casting the wall specimen

The sieve analysis results were used to develop the virgin soil up to the achieved best mix by adding needed gravel and sand while keeping the 5% fine content in the total mix (Table 63). Four (4%) percent minimum cement quantity was used in geo-polymerization of MCW. Wall specimens were cast in optimum segment size (obtained results of the questionnaire survey were used) of 1200mm height, 1200mm width and 150mm thickness for the purpose of core testing. Table 63 shows the needed total soil quantity and the added gravel and sand to cast a single wall segment.

Formwork was removed after 24 hours and curing procedure was started soon after formwork dismantling. Wall specimen was cured for 14 days using wet gunny bags at room temperature (± 25 ºC Temperature, ± 75% Relative humidity).

Table 63: Needed soil quantities for one wall segment and developing the soil ac-cording the best mix of Mud-Concrete wall

<table>
<tr><td colspan="7">Total weight of the mix to cast a one wall segment – size 150mm(thick), 1200mm(width), 1200mm(height) (To keep 5% fine from the total weight of the mix)</td><td>641.3 kg</td></tr>
<tr><td colspan="7">Added cement (4% of the total weight of the mix)</td><td>25.65 kg</td></tr>
<tr><td>Sample No: (ex.)</td><td>Sample weight of the soil (kg)</td><td colspan="3">Existing proportions and weight</td><td colspan="3">Proposed proportions and weight</td></tr>
<tr><td rowspan="3">W1</td><td rowspan="3">275</td><td>Gravel</td><td>Sand</td><td>Fine</td><td>Gravel</td><td>Sand</td><td>Fine</td></tr>
<tr><td>40.85%</td><td>47.49%</td><td>11.66 %</td><td>45%</td><td>50%</td><td>5%</td></tr>
<tr><td>112.34kg</td><td>130.59kg</td><td></td><td>288.58kg</td><td>320.65kg</td><td>32.07kg</td></tr>
<tr><td colspan="7">Added gravel to keep the 5% fine in the mix (kg)</td><td>176.25 kg</td></tr>
<tr><td colspan="7">Added sand to keep the 5% fine in the mix (kg)</td><td>190.05 kg</td></tr>
</table>

c) Core cutting and compressive strength testing of cored samples

Wall specimen was cored using a core cutter machine to check the compressive strength of cored samples after 28 days (Figure 79 and Figure 80). The diameter of core specimen should be at least 94mm to determine the compressive strength in load bearing structural members (ASTM, 2004). Because the preferred minimum core diameter is three (03) times the nominal maximum size of the coarse aggregate (ASTM, 2004). The core locations were marked on the wall in different heights prior to take the samples (Figure 79). The blade of the core cutter machine kept perpendicular to the wall surface while obtaining cored samples from the MC wall in different height (Figure 81). The faces of some samples were damaged due to the practical issues occurred while drilling the MC wall (Figure 80). Therefore, a capping had to be applied on each faces of the cored samples to make the faces even and flat (Figure 83).

Table 64: Correction factors for L/D Values

Ratio of Length to Diameter (L/D)	Strength correction factor
1.75	0.98
1.50	0.96
1.25	0.93
1.00	0.87

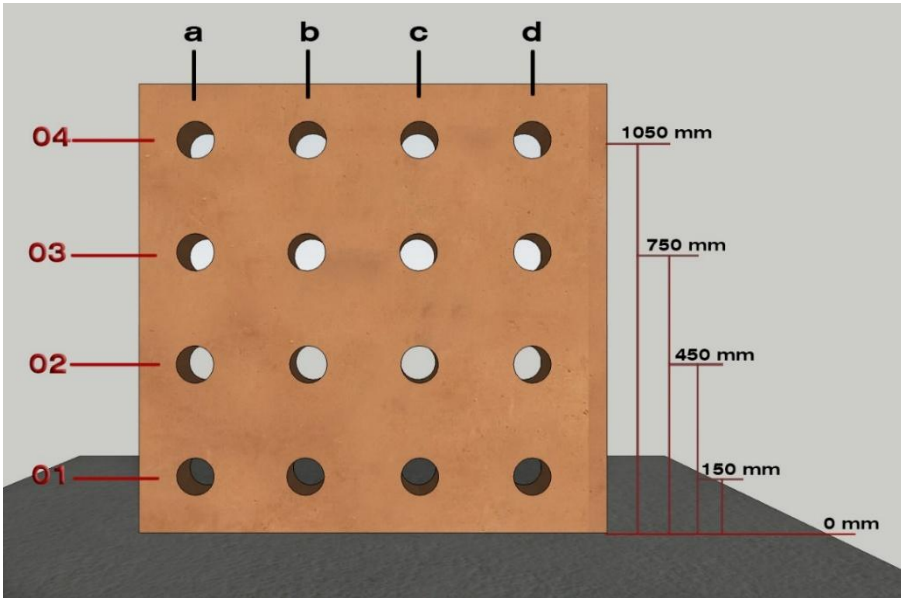


Figure 79: Cored locations along the MC wall

Figure 80: MC core samples

Figure 81: Obtaining MC core samples

Figure 82: Checking the compressive strength of MC sample

Figure 83: Applied capping on both side of MC sample

Obtained core samples were stored in separate plastic bags (seal to prevent moisture loss) and kept at ambient temperature and protected from without exposing to direct sunlight. A 5mm thick capping was applied to maintain flat surface from both ends (ASTM, 2004). Cores were crushed using an electronic load testing machine (Figure 82). Calculate the compressive strength of each specimen using the computed cross-sectional area based on the average diameter of the specimen. Then compressive strength of the cored samples extracted in different heights along the MCW was plotted to see the compressive strength variation. The preferred length of the capped or ground specimen should between 1.9 and 2.1 times the diameter. If the ratio of the length to the diameter (L/D) of the core exceeds 2.1, reduce the length of the core so that the ratio of the capped or ground specimen is between 1.9 and 2.1. Core specimens with length-diameter ratios equal to or less than 1.75 require corrections to the measured compressive strength (Table 64). A strength correction factor is not required for L/D greater than 1.75. A core having a maximum length of less than 95 % of its diameter before capping or a length less than its diameter after capping or end grinding shall not be tested (ASTM, 2004).

d) Compressive strength testing of moulded samples

Same MC mix (which is used to cast the MC wall) was used to cast the 150mm x 150mm x 150mm MC blocks to check the dry compressive strength of moulded samples. Six (06) similar samples were cast and cured for 14 days using wet gunny bags at room temperature (± 25 ºC Temperature, ± 75% Relative humidity). The dry compressive strength of the blocks were tested after strength gain in 28 days.

e) Results and discussions

Results show that increasing the height of the wall does not reduce the compressive strength of the MCW (Table 65 and Figure 84). Therefore, there is no height restriction for constructing a MC wall segment. Thus, the required total wall height can cast once, since there is no height restriction in achieving the strength of the wall. However considering the comfort of the workers, the size of optimum size of a MC wall segment was finalised as 1200mm (4'-0") in construction. Correspondingly this data was forwarded to use the formwork fabrication and optimisation in the next level of the research.

Table 65: Obtained compressive strength values for cored samples taken from different heights through Mud-Concrete load bearing wall

Core Number	wall height(mm)	Compressive strength(N/mm^2)
01/a	150	1.38
01/b	150	1.50
01/c	150	-
01/d	150	1.45
02/a	450	1.38
02/b	450	-
02/c	450	1.59
02/d	450	1.44
03/a	750	1.45
03/b	750	1.53
03/c	750	1.40
03/d	750	-
04/a	1050	1.35
04/b	1050	1.55
04/c	1050	1.36
04/d	1050	1.50

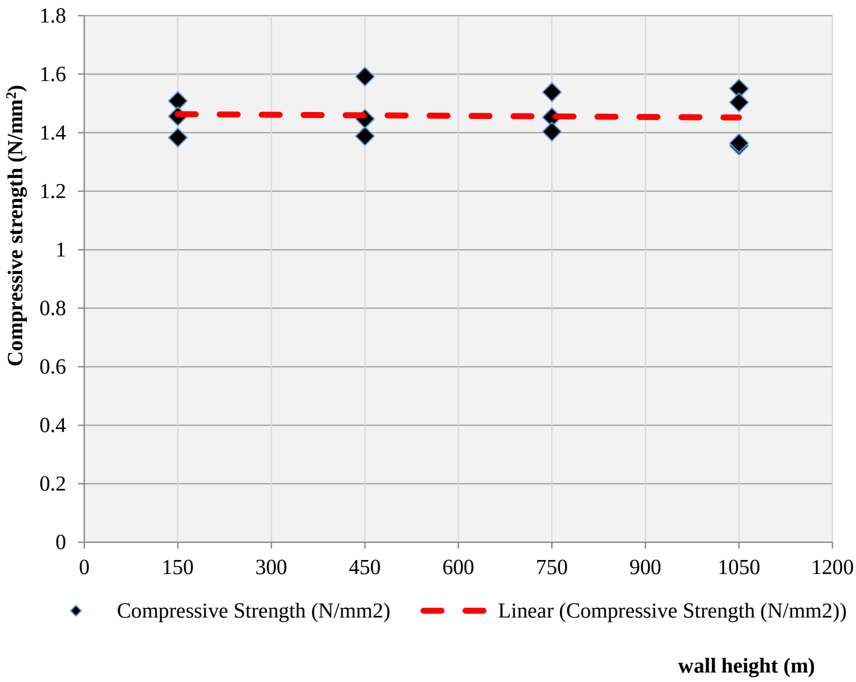


Figure 84: Behavior of the compressive strength variation along the height of the Mud-Concrete load bearing wall

Table 66: Average dry compressive strength values of moulded samples and comparison of average values of cored samples

Dry Compressive Strength (N/mm^2) of MC with 4% cement							
S:01	S:02	S:03	S:04	S:05	S:06	Average Values of moulded samples	Average values of cored samples
3.05	3.10	3.02	3.0	3.15	3.03	3.05	1.45

Table 66 shows the average compressive strength values of MC moulded samples. The values depict that compressive strength of moulded samples are always greater than the compressive strength of cored samples. Further the results confirmed that MC moulded samples are stronger than MC cored samples more than two times. MC cored samples are giving less compressive strength, because bonding between the gravel particles are getting weaker due to cutting and vibration in coring process.

Identifying the optimum height of a MCW segment is important to reduce the repercussion in construction. Because this optimum construction height of the wall will govern the speed of the construction of the wall and quality of the overall work presented at the end. The optimum construction height of a wall can be affected by different factors such as segregation of material by increasing the wall height, the workmanship available at the site, the techniques use for handling and fixing formwork/mould of the wall and etc.

The experiment results confirmed that moulded MC samples are stronger than the cored MC samples. Further, the results demonstrated that increasing the height of the MCW does not reduce the compressive strength of the wall. Therefore, there is no height restriction for constructing an in-situ cast MC wall segment. However then again the comfortable height of pouring concrete to formwork was found as 1200mm (approx.4'-0") through the questionnaire survey conducted among 400 construction workers in different construction sites. Therefore, the formwork to cast a one wall segment was optimized up to 1200mm height. Since there is no height restriction, the total wall height (1200mm – height of a one wall segment) can be casted at once without proposing any joints.

4.4. Investigation of linear drying shrinkage of MCW segment

Clay shrinks and swells with the loss and addition of moisture(Latha & Venkatarama Reddy, 2016). The deterioration of earth walls occurs from contraction and expansion due to cyclic weather conditions. This problem can be limited by the construction of raised footings or eave overhangs. However, it was of importance to determine the value of drying shrinkage for a specific material and for the construction of movement joints. As per the Walker's record, the drying shrinkage of compressed stabilised earth blocks was primarily governed by the plasticity index of the soil which is used for the block manufacturing. For soil plasticity index below 20, the drying shrinkage steadily increases with increasing clay content. Drying shrinkage at low plasticity also noticeably increases with cement content (Walker, 1995c). According to Jayasinghe, (Jayasinghe, 2007) shrinkage strain of 150mm thick rammed earth wall made out of gravelly laterite soil decrease by increasing the curing period from 7 days to 28 days. Literature shows the maximum drying shrinkage should not be greater than 0.5% (for composite load bearing) under typical minimum performance specifications for rammed earth walls (Walker et al., 2010a). After compaction, as the material dries from around 8-14% moisture content (by dry mass) to around 1-5% in ambient conditions, rammed earth walls shrink vertically, laterally and longitudinally. The rate at which the material loses moisture and the final moisture content depend on factors such as shelter, environmental conditions and material characteristics. The level of shrinkage depends on the soil grading, clay content, initial and final moisture content and rate of drying (Walker et al., 2010a). Horizontal drying shrinkage may be accommodated by the inclusion of movement joints. Vertical shrinkage is a principal concern where load-bearing rammed earth shares structural support with other elements such as timber or steel. In such cases, quantifying the extent and rate of drying shrinkage is important (Walker et al., 2010a).

Drying shrinkage limits are typically specified when shrinkage or associated cracking can impair the intended functionality or reduce service life. Drying shrinkage is not a problem if the mixture of the material is free to move. If the material is restrained in any way, drying shrinkage will introduce tensile stresses which if they exceed the tensile strength of the clay, will cause the wall to crack. Shrinkage cracks are opposed to flexural cracks. Linear drying shrinkage is the change in linear dimension of the test specimen due to drying from a saturated condition to an equilibrium weight and length under specified accelerated drying condition (ASTM C426 - 16, 2012). Linear shrinkage of a rammed earth wall is expressed as the ratio of change in length to original datum length and tests were performed according to recommendations given by Walker *et al*. in 2005 (Walker et al., 2010a). When it comes to an in-situ cast load bearing wall it is an important factor to check the drying shrinkage, because if the crack takes place in a wall segment, it could be propagated up to the openings of the wall (door/window) and it could be a reason for the collapse of the building. Thus, it is important to investigate and make standard specifications for newly introduced material, because it will always help to reduce repercussions in the process of construction on site. The material may also be deemed to be unsuitable if the drying shrinkage is excessive, compared to minimum performance specifications.

The primary objective of this section is to check the influences of curing time on drying shrinkage of self-compacting in-situ cast Mud-Concrete load bearing wall. There are plenty of recommendation and standards to test the drying shrinkage of masonry materials. However it is difficult to justify all those standards and recommendations directly to local construction industry due to the prevailing different construction techniques and environmental conditions (Nandapala, Peiris, Senavirathna, & Nanayakkara, 2014). In order to achieve the objectives of this section of research, the methodology was designed through three (03) steps and recommendations were given by analyzing the results.

1. Step: 01– Checking the effective curing period which gives the required minimum compressive strength.
2. Step: 02 – Measuring the vertical and horizontal linear drying shrinkage of MC wall segment within the effective curing period and assessing the material suitability.
3. Step: 03 – Investigating the effective methods of reducing the drying shrinkage further with different curing periods (7,14,21 and 28 days)

Same stock pile was used (see section 2.3) and ordinary Portland cement (Type I, strength class 42.5N) was used as the stabilizer in entire research.

4.4.1. Step: 01 - checking the effective curing period which gives the required minimum compressive strength

a) Developing the soil according to the achieved optimum mix and sample manufacturing

Using the results of sieve analysis, the soil was developed according to the achieved optimum mix by adding needed gravel and sand while keeping the 5% fine content in the total dry mix. Table 67 gives an example method of developing the existing soil. Five sets of soil samples were prepared and named according to the expected curing periods as C-0, C-7, C-14, C-21 and C-28. Twelve blocks were cast in each sample to check both dry and wet compressive strength and total 60 cubes were cast as test specimens. Blocks were cast by adding and mixing developed soil, 4% Cement and 20% water from the dry mix.

Table 67: Method of developing the available soil samples according to the achieved best mix (ex: C-0 sample)

Sample Block series No: (ex.)	Existing proportions and weight			Proposed proportions and weight			Sample weight (kg)
	Gravel	Sand	Fine	Gravel	Sand	Fine	
	40.85 %	47.49 %	11.66 %	45%	50%	5%	
C-0	8.17kg	9.49kg		20.9 kg	23.3kg	2.3kg	
Required (raw) virgin soil							20
Added gravel to keep the 5% fine in the mix							12.89
Added sand to keep the 5% fine in the mix							13.82
Added cement (4% of the total weight of the mix)							1.87
Total weight of the mix to cast 12 nos. of blocks in one set of specimens (To keep 5% fine from the total weight of the mix)							46.7

150mmx150mmx150mm size prism moulds were used to cast the MC blocks. Five sets of samples (C-0, C-7, C-14, C-21 and C-28) were cast to check the compressive strength within 0, 7, 14, 21 and 28 days. The cubes were removed from the moulds in 24 hours of casting. Curing procedures were commenced immediately after removing the moulds. Surfaces of MC block were covered using wet gunny bags and cured one time a day with the use of hand to pour water on the surface. Cubes were cured each day until the recommended curing period of 7, 14, 21 and 28 days and compressive strength was checked after the 28 days using an electronic load testing machine and the average compressive strength was computed.

4.4.2. Step: 02 – Measuring the vertical and horizontal linear drying shrinkage

a) Developing the needed soil samples according to the achieved optimum mix using the sieve analysis results

Table 68: Needed soil quantities for one wall segment and developing the soil according to the best mix of Mud-Concrete wall

<table>
<tr><td rowspan="3">Sample Wall No: (ex.)</td><td colspan="3">Existing proportions and weight</td><td colspan="3">Proposed proportions and weight</td><td rowspan="4">Sample weight (kg)</td></tr>
<tr><td>Gravel</td><td>Sand</td><td>Fine</td><td>Gravel</td><td>Sand</td><td>Fine</td></tr>
<tr><td>40.85%</td><td>47.49%</td><td>11.66%</td><td>45%</td><td>50%</td><td>5%</td></tr>
<tr><td>W1</td><td>112. 4kg</td><td>130.6kg</td><td></td><td>288.6 kg</td><td>320.7</td><td>32.1kg</td></tr>
<tr><td colspan="7">Sample weight of the used virgin soil</td><td>275</td></tr>
<tr><td colspan="7">Added gravel to keep the 5% fine in the mix</td><td>176.3</td></tr>
<tr><td colspan="7">Added sand to keep the 5% fine in the mix</td><td>190.1</td></tr>
<tr><td colspan="7">Added cement (4% of the total weight of the mix)</td><td>25.65</td></tr>
<tr><td colspan="7">Total weight of the mix to cast a one wall segment – size 150mm(thick), 1200mm(width), 1200mm(height) (To keep 5% fine from the total weight of the mix)</td><td>641.3</td></tr>
</table>

Required total soil samples were prepared to cast the 1200mm (height) x 1200mm (width) x 150mm (thickness) size wall segment at the beginning of the test. Thus, the needed gravel and sand samples were sieved and prepared according to the needed quantity of the total mix. Table 68 shows the needed total soil quantity to cast a single wall segment (ex: W1 specimen). Cement was added by 4% from the weight of the total dry mix. The mixing was done in section by section due to the limited mixing capacity of the concrete mixture machine. Therefore, the 50kg weight of samples were prepared and mixed per cycle to pour in the formwork of wall. Table 69 shows the proportions of ingredients used to mix in 50 kg limited weight mixture machine. Water 20% (10 litres) from total dry mix was added to keep the self-compacting quality of the MC mix.

Table 69: Method of developing soil according to the allowable weight limit of concrete mixture

Sample Wall No: (ex.)	Existing proportions and weight of in fraction of soil			Proposed proportions and weight of in fraction of soil			Sample weight (kg)
	Gravel	Sand	Fine	Gravel	Sand	Fine	
	40.85%	47.49%	11.66%	45%	50%	5%	
W1	8.8 kg	10.2 kg		22.6 kg	25.1kg	2.5kg	
Sample weight of the used virgin soil							21.5
Added gravel to keep the 5% fine in the mix							13.78
Added sand to keep the 5% fine in the mix							14.86
Added cement (4% of the total weight of the mix)							2.01
Total weight of the mix to cast a one wall segment – size 150mm(thick), 1200mm(width), 1200mm(height) (To keep 5% fine from the total weight of the mix)							50

b) Casting the wall specimens

Prior to cast the wall specimens, the pre-fabricated steel formwork was assembled on a levelled floor. This modular steel formwork was already developed within the research process and patented under the Sri Lankan intellectual property act No.36 of 2003 (18879, 2016). Specimen wall size was defined according to the standard segment size (optimum lifting height) found during the research process. Specimen size is 1200mm (Height) x 1200mm (Width) x 150mm (Thickness). Before assembling the formwork, mould oil was applied to the internal surfaces of the formwork. After assembling the steel formwork, the MC mixture was poured into the formwork. After 24 hours of casting, formwork was dismantled, and the wall was prepared to curing. Wet gunny bags were used to cover the walls and water was poured once a day on the surface for curing the MC walls. The walls were cured up to 07days (according to the results received in step: 01) only. Three specimens of walls (W1, W2 and W3) were used to take the data. Total set up was covered to protect from the weather conditions. ±30 °C temperature and ±75% relative humidity was maintained in the room.

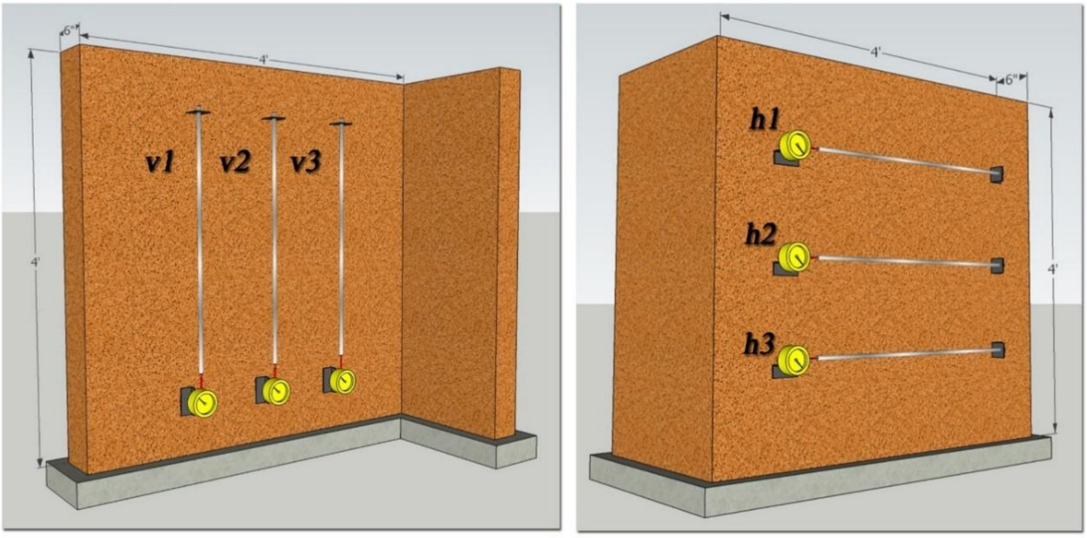


Figure 85: Apparatus arrangement of measuring horizontal and vertical drying shrinkage

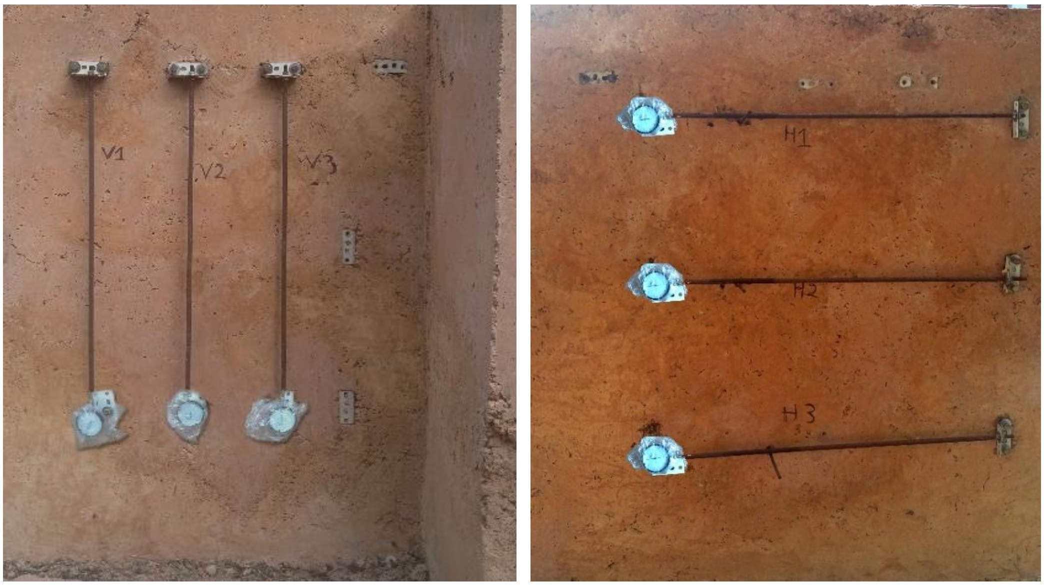


Figure 86: Reference images of measuring the shrinkage strain on Mud-Concrete wall

Linear shrinkage was measured by using a stainless-steel rod fixed to the Mud-Concrete wall segment with dial gauges at one end (Figure 85 and Figure 86). Three stainless-steel rods were used to check the horizontal shrinkage and another three stainless-steel rods were used to check the vertical shrinkage measurements on one wall. At the same time, temperature and humidity in the room were measured to maintain stable environmental conditions (± 75% Humidity, ± 30 ºC Temperature).

Total apparatus set up on the wall was kept until the gauge readings remain at the same value where the wall reaches its maximum strain. Average values were used to show the relationship between age of the wall and the shrinkage strain. (Table 70)

Table 70: Average value calculations of vertical and horizontal shrinkage

Description	Equation	Description	Equation
Wall no. 01 (W1) average vertical shrinkage	$\frac{v1+v2+v3}{3}=VW1$	Wall no. 01 (W1) average horizontal shrinkage	$\frac{h1+h2+h3}{3}=HW1$
Wall no. 02 (W2) average vertical shrinkage	$\frac{v1+v2+v3}{3}=VW2$	Wall no. 02 (W2) average horizontal shrinkage	$\frac{h1+h2+h3}{3}=HW2$
Wall no. 03 (W3) average vertical shrinkage	$\frac{v1+v2+v3}{3}=VW3$	Wall no. 03 (W3) average horizontal shrinkage	$\frac{h1+h2+h3}{3}=HW3$
Total average vertical shrinkage	$\frac{VW1+VW2+VW3}{3}=VW$	Total average horizontal shrinkage	$\frac{HW1+HW2+HW3}{3}=HW$

4.4.3. Step: 03 – Effective methods of reducing the drying shrinkage with different curing periods (7,14,21 and 28 days)

This methodology was adopted to check the behaviour of shrinkage strain with increasing the curing period of MC wall. Even though the obtained results of shrinkage strain in MC wall is lower than the recommended limits (≤ 0.5% for earth walls), it is important to investigate the effective reduction rate while increasing the curing period of MC wall. The results would be useful to improve the quality of MC constructions. In order to achieve this task, rectangular blocks were used as specimens and only horizontal shrinkage was measured.

a) Developing needed soil samples up to the achieved optimum mix.

Table 71: Needed soil quantities to cast three nos. of rectangular block sections of Mud-Concrete and developing the soil according to the best mix of Mud-Concrete wall

<table>
<tr><td rowspan="3">Sample rectangular block No: (ex.)</td><td colspan="3">Existing proportions and weight of in fraction of soil</td><td colspan="3">Proposed proportions and weight of in fraction of soil</td><td rowspan="4">Sample weight (kg)</td></tr>
<tr><td>Gravel</td><td>Sand</td><td>Fine</td><td>Gravel</td><td>Sand</td><td>Fine</td></tr>
<tr><td>40.85%</td><td>47.49%</td><td>11.66 %</td><td>45%</td><td>50%</td><td>5%</td></tr>
<tr><td>B1</td><td>8.88 kg</td><td>20.98kg</td><td></td><td>11.54 kg</td><td>12.44kg</td><td>2.09kg</td></tr>
<tr><td colspan="7">Sample weight of the used virgin soil</td><td>18</td></tr>
<tr><td colspan="7">Added gravel to keep the 5% fine in the mix</td><td>7.35</td></tr>
<tr><td colspan="7">Added sand to keep the 5% fine in the mix</td><td>8.55</td></tr>
<tr><td colspan="7">Added cement (4% of the total weight of the mix)</td><td>1.68</td></tr>
<tr><td colspan="7">Mix weight needed to cast three no. of rectangular block sections in one set of specimens. (To keep 5% fine from the total weight of the mix)</td><td>42</td></tr>
</table>

Existing virgin soil was developed up to the achieved optimum mix by adding the required amount of gravel and sand while keeping the 5% fine content in the total dry mix. Table 71 shows the required quantities of ingredients in sample preparation. Cement was added 4% of the total weight of dry mix. Water was added 20% (8.5 litres) of the total weight of dry mix.

b) Casting the rectangular block specimens and measuring the horizontal linear drying shrinkage

MC rectangular block sections sized 300mm (length) x 150 mm (width) x 150mm (depth) were used to measure the shrinkage strain. Cast iron moulds were prepared and mould oil was applied to the internal surfaces of the mould prior to pour the MC mix. The prepared MC mix was poured into the mould and top surface was levelled. After 24 hours, the moulds were dismantled, and curing was started. Wet gunny bags and carpets were used to cure the specimens at controlled room temperature at ±30 ºC and relative humidity at ±75%. Three samples were tested for each curing period; 7days, 14 days and 21 days respectively. Altogether, nine (09) no. of MC rectangular block specimens were cast to get the readings. Decisions were taken to measure the horizontal shrinkage only. Because the result of step two (02) defines that horizontal shrinkage strain has a slight increase than the vertical shrinkage strain. Thus, we had conducted the test for the critical conditions. Soon after removing the moulds, two dial gauges were fixed from both sides of the specimen as shown in Figure 87 and Figure 88. A gauge reading of both sides was measured continuously to calculate the shrinkage strain of the rectangular MC block sections. Shrinkage strain of each MC specimen was calculated using the equation 4.

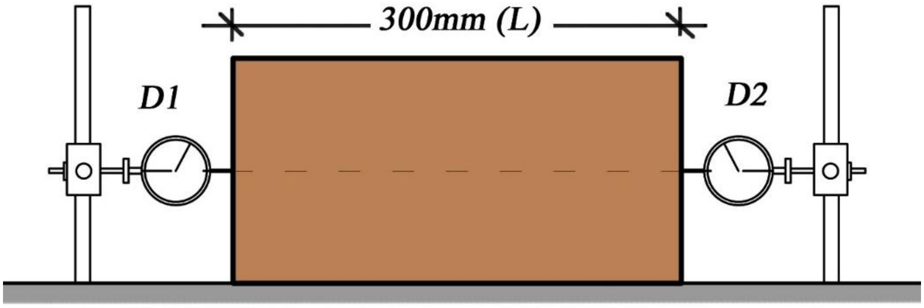


Figure 87: Apparatus arrangement to measure horizontal drying shrinkage

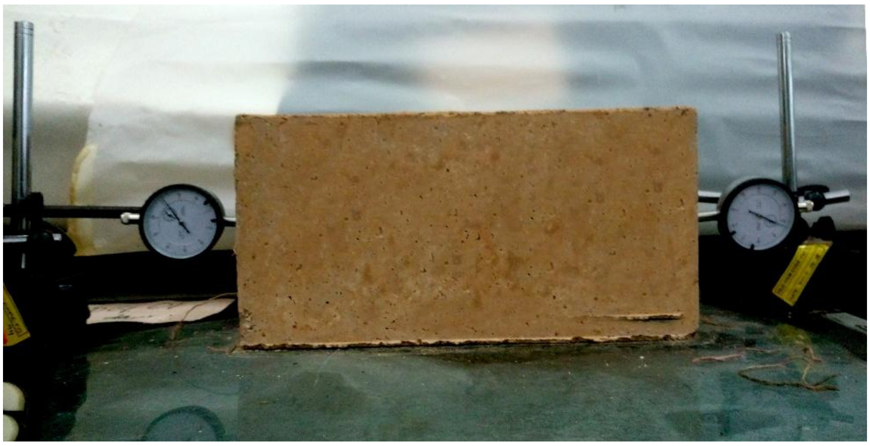


Figure 88: Reference images of measuring the horizontal shrinkage strain of MC rectangular sections with different curing periods

$\frac{D1+D2}{L} = Shrinkage\ strain\ of\ the\ MC\ rectangular\ block\ section$.......... (4)

Where,

D1 = Reading of dial gauge 01; D2 = Reading of dial gauge 02; L = Length of rectangular section

4.4.4. Results and discussion

a. Checking the effective curing period which gives the required minimum compressive strength of in-situ cast Mud-Concrete load bearing walls. (Step: 01)

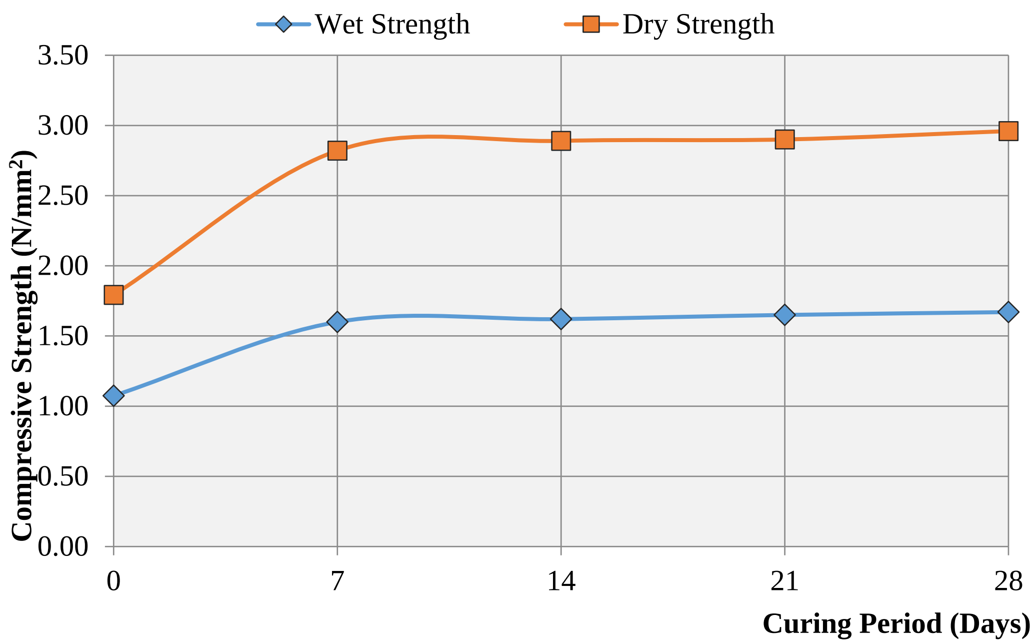


Figure 89: Behaviour of compressive strength of Mud-Concrete material with different curing periods

The plotted results in Figure 89, it is clear that increasing the curing period helps to increase the compressive strength of the MC material. However after seven days of curing period, the strength increment of MC is considerably slow. The results show that MC walling material is achieving its standard requirement of wet and dry compressive strengths for load bearing soil based materials (wet compressive strength = 1.0 N/mm^2, dry compressive strength = 2.0 N/mm^2) after 07 days of curing (Walker, 1995b). Thus, we can conclude 07 days is an effective curing period for MC load-bearing walling material in terms of achieving its minimum compressive strength requirements.

b. Measuring the vertical and horizontal linear drying shrinkage of Mud-Concrete wall within the effective curing period (Step: 02)

In this step the objective is to investigate whether this achieved 07 days curing period is effective in terms of drying shrinkage of MC wall or not. The results show the maximum horizontal shrinkage strain of the wall is approx.0.0023 (0.23%) in 35 days and the maximum vertical shrinkage strain of the wall is approx. 0.0022 (0.22%) in 28 days (Figure 90). Further it shows that horizontal shrinkage stain is slightly higher than the vertical shrinkage strain of the MC wall. However, the obtained results for shrinkage strain in MC wall is lower than the recommended level of shrinkage strain 0.005(0.5%) of in-situ cast rammed earth walls (Walker et al., 2010a).

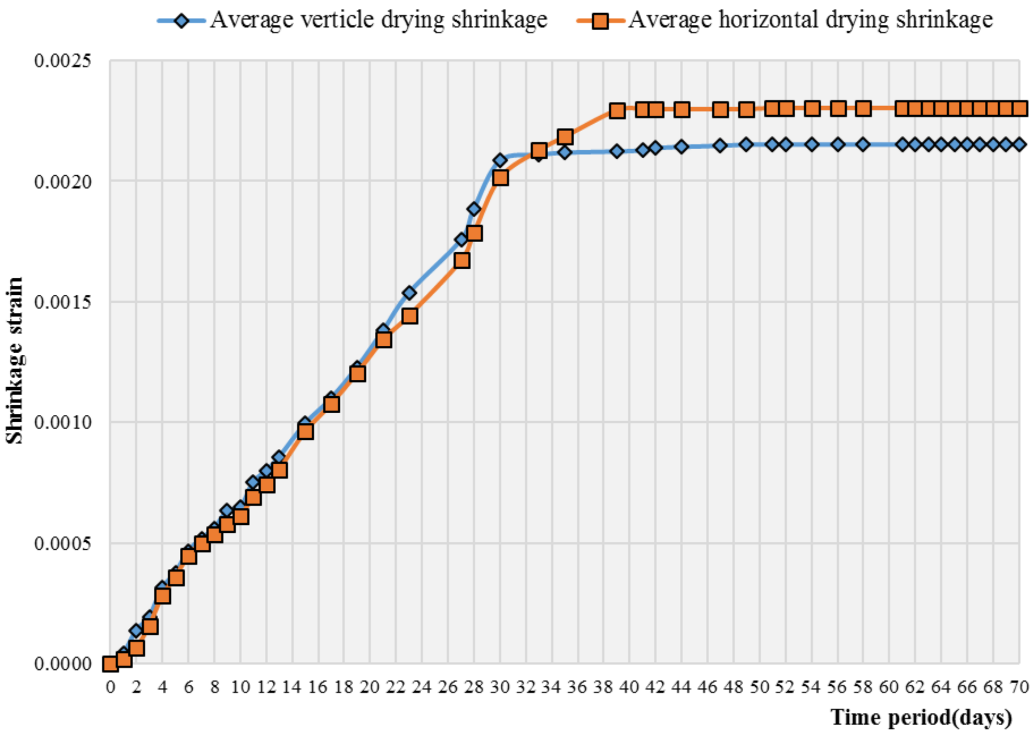


Figure 90: Average vertical and horizontal drying shrinkage strain of in-situ cast Mud-Concrete load-bearing walls

c. ***Investigating the effective methods of reducing the shrinkage strain with different curing periods (Step: 03)***

Figure 91, shows that increasing the curing period helps to reduce the shrinkage strain of MC load-bearing walling material. The linear shrinkage strain can reduce from 0.0023 (0.23%) to 0.0015 (0.15%) with the 14 days curing period and it is 65% of reduction rate of shrinking in MC wall. With the 21 days curing period, the linear shrinkage strain can reduce from 0.0023(0.23%) to 0.0013 (0.15%). When comparing the 14 days and 21 days curing, 14 days curing is much effective than the 21 days curing period; because there's no significant reduction in shrinkage strain between the results obtained in14 days and 21 days curing. Further, the results show the wall starts to shrink soon after stopping the curing process and until that the length of the wall has increased (swell) while curing the wall.

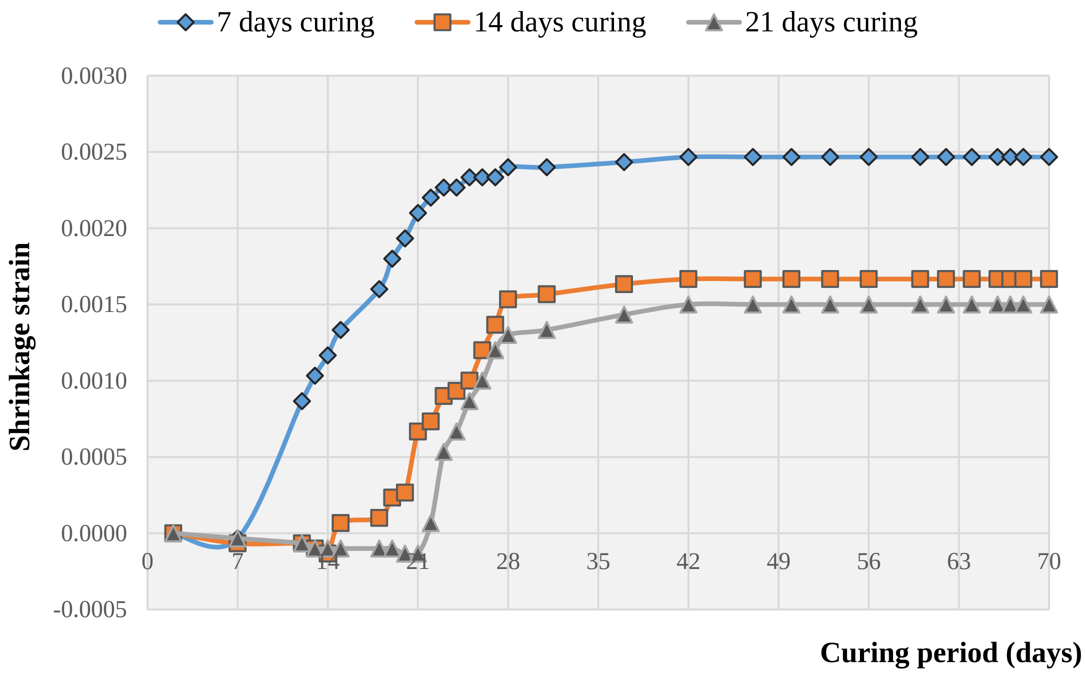


Figure 91: Horizontal shrinkage strain of Mud-Concrete with different curing periods

4.5. Investigation of crack development between possible construction joints of MCW segments

"Construction Joints" are used in circumstances where two consecutive placements of concrete meet(Cement Concrete & Aggregates Australia, 2002).Construction joints are normally placed at the end of the day or be placed when concrete pour has been stopped for longer than the initial setting time of concrete. These joints can achieve through a bond and continue reinforcement through a construction joint. There are plenty of importance in keeping construction joints in a wall construction. Few points were highlighted as follows;

- Unreinforced concrete will tend to develop larger cracks at irregular intervals wherever the tensile strength of the concrete is exceeded by the stresses induced by drying shrinkage. To prevent such cracks, **contraction joints should be installed at appropriate intervals**. It may also be more economical to install contraction joints in reinforced concrete than to rely on reinforcement to control shrinkage stresses.
- The location of contraction joints is a matter for the designer, however normally they will be situated where the greatest concentration of stresses due to drying shrinkage are to be expected: **at openings; at sudden changes in cross-section and in long walls** where they are used to divide the concrete into approximately square bays.

Different type of construction joints uses in the construction field. In this experiment few typical (possible) joint types were considered to see the strength variations and the crack development between the wall segments. There are as follows:

1. Tongue & groove joints between wall segments
2. Chipping the wall edges between wall segments
3. Chipping the wall edges and pouring the cement slurry between the wall segments

Objective of this experiment is to investigate the structural behaviour in possible construction joints between MCW segments. Therefore, the methodology was adopted to compare selected joint types with a normal MCW segment (with no joints).

4.5.1. Methodology

a) Developing the soil and casting the MCW specimens

Same stock pile of gravelly laterite soil (see section 4.3.1) was used to proceed the investigations. According to that, average value of gravel 40.85%, Sand 47.49% and Fine 1.66% was available in existing soil samples. Then the soil was developed according to the values finalized for the best mix for MCW.

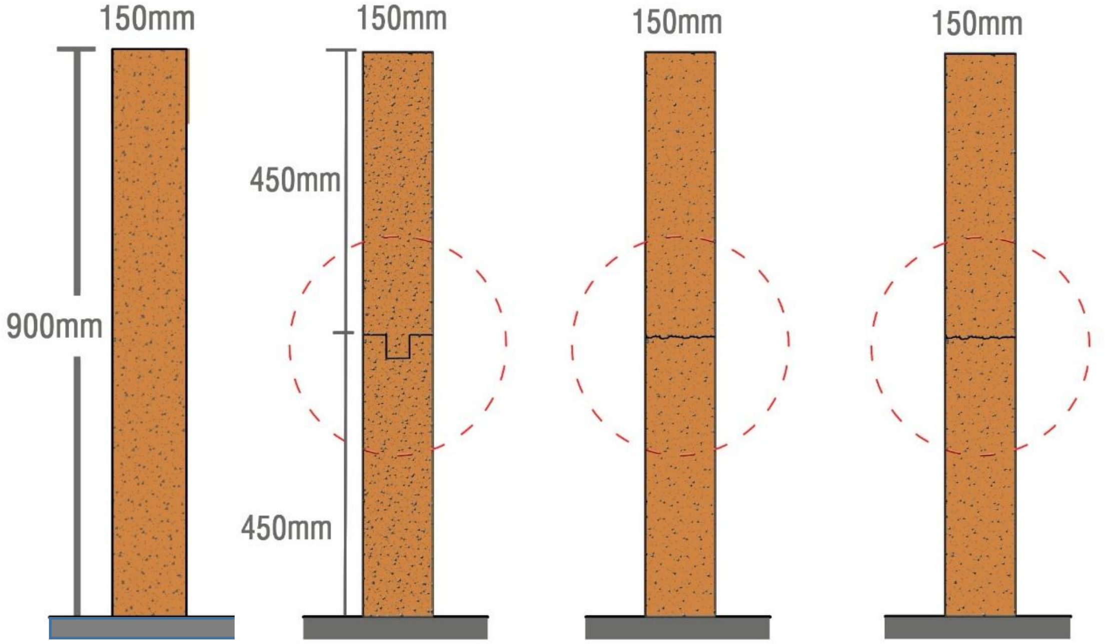
In this research, 900mm height, 600mm width and 150mm thickness walls were used in testing due to the easiness of handling purposes in load testing. Table 72 shows the needed total soil quantity to cast a single wall segment. Thus, the needed gravel and sand samples were sieved and prepared according to the needed quantity of the total mix.

Table 72: Needed soil quantities for one wall segment and developing the soil according to the best mix of Mud-Concrete wall

Total weight of the mix to cast a single wall segments – size 150mm(thick), 300 mm(width), 450 mm(height) (To keep 5% fine from the total weight of the mix)						42 kg
Added cement (8% of the total weight of the mix)			3.36 kg			
Sample weight of the soil (kg)	Existing proportions and weight			Proposed proportions and weight		
	Gravel	Sand	Fine	Gravel	Sand	Fine
18kg	40.85%	47.49%	11.66%	45%	50%	5%
	7.4kg	8.5kg	2.1kg	18.89kg	20.99kg	2.1kg
Added gravel to keep the 5% fine in the mix (kg)			11.54 kg			
Added sand to keep the 5% fine in the mix (kg)			12.44 kg			

Three (03) number of wall samples were casted to check each joint type to keep the accuracy of results (Figure 92). All together 12 number of MCW specimens were tested to get the compressive strength values.

After pouring a one segment up to 450mm next segment was poured after 24 hours of the time. Total formwork was de-moulded after 24 hours of casting the MC wall specimen. Curing was started just after de-moulding the formwork within 24 hours using wet gunny bags. After curing 14 days wall specimens were kept for 28 days strength gain.



A) Normal wall

B) Using Tongue & groove joints between wall segments

C) Chipping the wall edges between segments

D) Chipping the wall edges pouring the cement slurry between segments

Figure 92: Selected joints types to check the structural behaviour

b) Compressive strength testing of MCW specimens

Crack development of joints between walls segment were visually observed until conduct the load testing after the period of 28 days age of the MC wall. After 28 days strength gain, load testing was conducted to check compressive strength variations of each arrangement of joints. The MCW was loaded with a calibrated proving ring to measure the applied load and the deflection was measure with a dial gauge. The experiment setup used was shown in Figure 93 and Figure 94. Both readings (Applied force and deflection) were continuously taken down till the system failed. The crack patterns along the walls were observed and recorded while crushing the wall segments (Figure 95).

Figure 93: Conducting the load-testing

Figure 94: Conducting the load-testing

Figure 95: Observing the pattern of crack development between joints

4.5.2. Results and discussion

The applied force (kN) and all the crack patterns were recorded while doing the load testing. Figure 96 shows the crack patterns appeared along the wall while applying the load. This result confirms that keeping a joint between the wall segments will not affect to its load bearing characters.

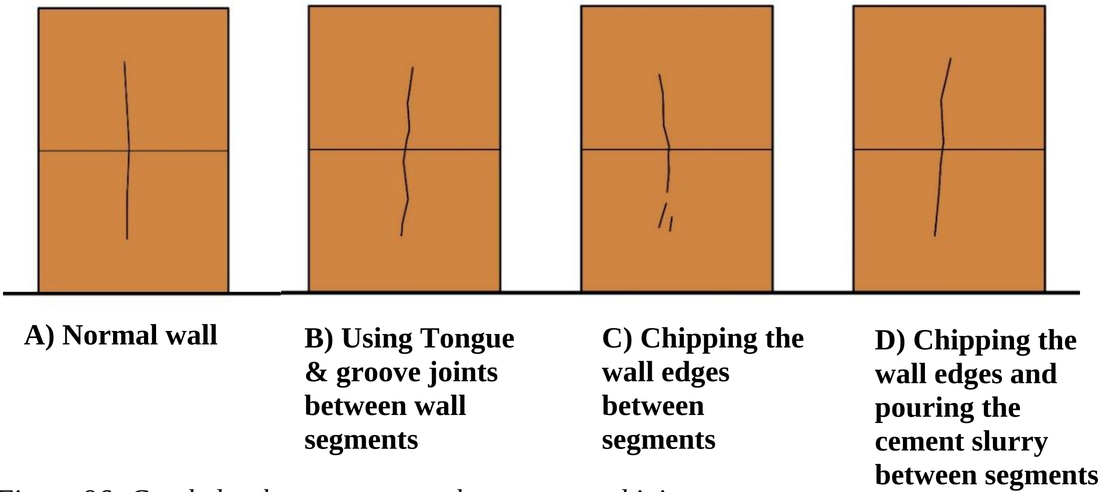


Figure 96: Crack development pattern between tested joint types

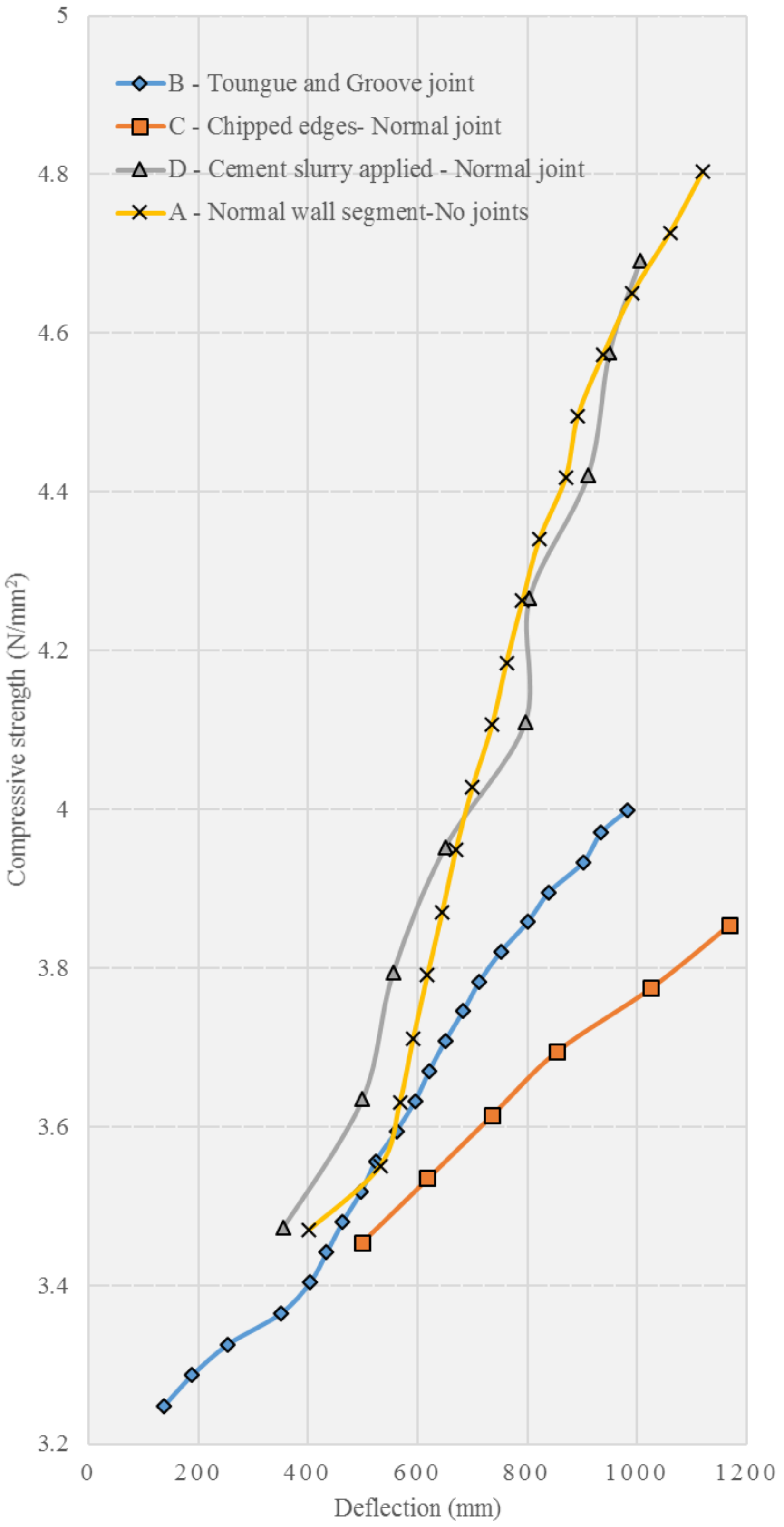


Figure 97: Compressive strength vs. Deflection – Between different joint types

Table 73: Average compressive strength results obtained from load testing

Joint type	Average compressive strength (N/mm^2)
A- Normal wall	4.80
B- Tongue and groove joint between wall segments	3.99
C- Chipping the wall edges between wall segments	3.85
D- Chipping the wall edges and pouring the cement slurry between wall segments	4.69

Table 73 and Figure 97 show the average compressive strength variations between the selected joint types. According to the results the higher compressive strength value was recorded in the type (A) normal wall. It is noted that keeping a joint between wall segments reduces the compressive strength of a MC wall. However introducing a proper construction joint does not affect to the load bearing characteristics of the MC wall. The joint type (D): adding cement slurry between wall edges has given a higher compressive strength value among the three (03) types of possible joints, because cement helps to make a continuous bonding between the wall segments. Therefore, if a joint were to be introduced between MC wall segments, it is strictly recommended to keep the continuity between the joints. Thus, in every 1200mm height proper horizontal joint should be introduced in in-situ cast process to reduce the crack development.

4.6. Concluding remarks

This research section of system development is mainly focused on optimizing the construction technology of MCW in the field. Then the flexible cost effective formwork was developed using quantitative and qualitative analysis.

This formwork system compromised of two mould plates and one or two end plates, which may be combined in various configurations to provide an end stop of adjustable width, which will produce walls of various thickness. All the joints were fixed according to ensure the water tightness of the system. This system has no walls through ties to hold the side panels together. The same end panel system used to prepare the frame for formwork at the openings in the wall without disturbing the structural requirement and the water tightness of the system. This Formwork system was flexibly developed to cater the different components in a wall construction.

The core testing proved that there is no height restriction for constructing an in-situ cast MC wall segment. However, the comfortable height of pouring concrete to formwork was found to be 1200mm (approx.4'-0"). Therefore, the formwork to cast a one wall segment was optimized up to 1200mm height. Since there is no height restriction, the total wall height (1200mm – height of a one wall segment) can be casted at once without proposing any joints.

Fourteen (14) days curing period could be recommended to reduce the drying shrinkage of MCW and the curing should commence soon after dismantling the formwork system. In addition it is highly recommend to keeping a continuous construction joint in between two MCW segments.

5. CHAPTER FOUR – THERMAL PERFORMANCES

5.1. General

Improvement in the thermal performance of buildings has the potential to reduce building operational energy and its associated negative impact on the environment. Thus checking and improving the thermal performance of a newly introduced material is important as to compare the advantages of the material usage with other available materials in the market. Hence this chapter discusses the thermal performance, structural optimization and the moisture buffering capacities of the MCW system.

5.2. Investigation on thermal performances

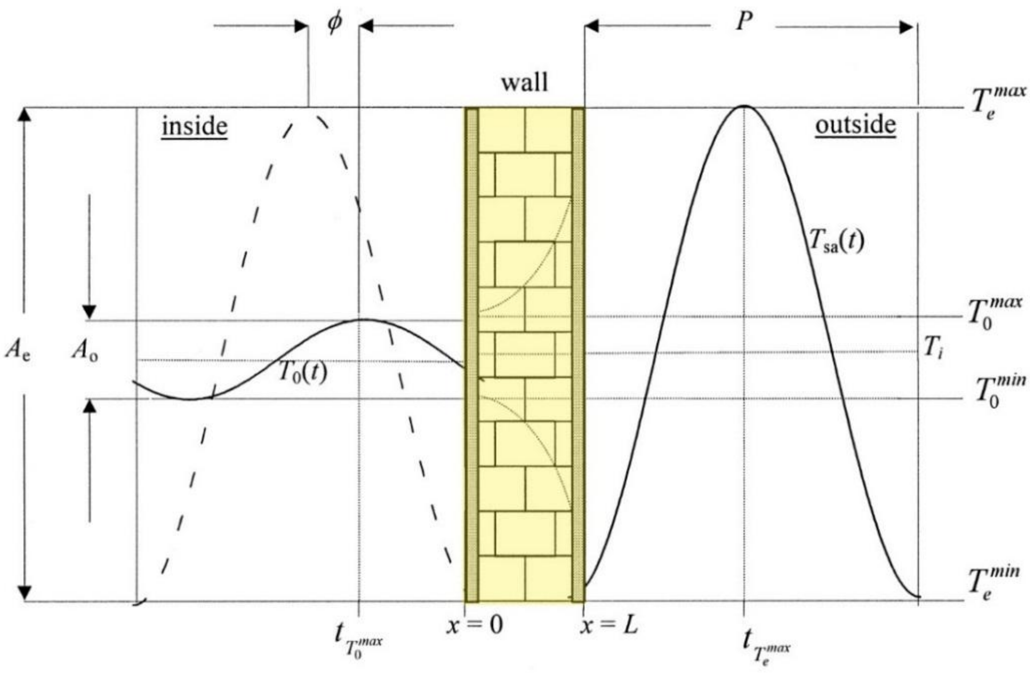


Figure 98: The schematic representation of time lag (Ø) and decrement factor (f)

Source: (Asan & Sancaktar, 1998a)

$$\text{Time lag } (\emptyset) = \begin{cases} t_{To^{max}} > t_{Te^{max}} \Rightarrow \quad t_{To^{max}} > t_{Te^{max}} \\ t_{To^{max}} > t_{Te^{max}} \Rightarrow \quad t_{To^{max}} > t_{Te^{max}} \quad + P \\ t_{To^{max}} = t_{Te^{max}} \Rightarrow \quad P \end{cases}$$

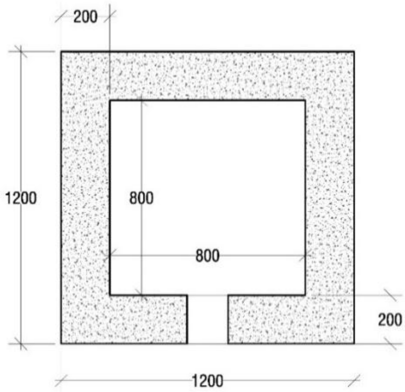
$$Decrement\ factor\ (f) = \frac{A_0}{A_e} = \frac{T_0^{max}}{T_e^{max}} - \frac{T_o^{min}}{T_e^{min}}$$

Thickness of the material and type of the material have a very profound effect on the time lag and decrement factor (Asan, 2006). The time it takes for the value it heats wave to propagate from the outer surface to the inner surface is named ‘time lag’ (Ø). Decreasing ratio of its amplitude during this process is named a ‘decrement factor’ (f). Single and combined effects of the thickness and thermo-physical properties have a very profound effect on the time lag and decrement factor (Asan & Sancaktar, 1998). Thermal resistance increases linearly with the wall thickness (El Fgaier, Lafhaj, Chapiseau, & Antczak, 2016). Thus, this experiment is mainly focussing to optimise the wall thickness and optimise the structural performance according to the thermal performance of Mud-Concrete wall. Methodology was adopted to achieve the below objectives. Further, this section of research presents the evaluated results attained through actual scale physical model testing and computer simulations. Objectives of the of this section of research are,

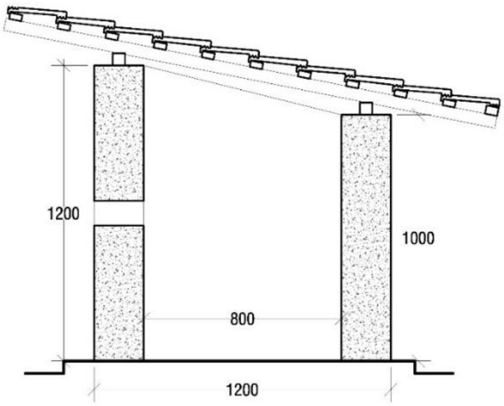
- Small scale actual model was casted to get the inside surface temperature and outside surface temperature of Mud-Concrete wall.
- Analyzed and interpret the thermal behavior of in-situ cast load bearing Mud-Concrete walls through computer simulations (Design builderV5).
- Thermo-Physical properties of Mud-Concrete wall will be analyzed (Decrement factor, Time lag, U-value, R-value)
- Changing the wall thickness of Mud-Concrete wall and analyses the effect on time lag and the decrement factor.
- Optimizing structural capacity of Mud-Concrete wall according to thermo-physical properties of the wall.

5.2.1. Material and methods

An actual small-scale model of a house was constructed using mud concrete walls to get the actual temperature measurements (Figure 99). Inside and outside ambient temperature, indoor and outdoor surface temperatures of walls/roof of each model was measured using data logger and several thermo couples (Figure 100). An accurate data set for 24 hours period from recorded temperature values were used for data analysing.



Plan view of model house
(Dimensions in mm)



Sectional view of model house

(Dimensions in mm)

Figure 99: Construction of small scale model house to get on site temperature values

Decrement factor (f)' and 'Time lag (Ø)' for 200mm thickness of Mud-Concrete wall was identified by analysing data. Same actual scale model was modelled in DesignBuilderV5 computer software to analyse the thermo-physical properties of Mud-Concrete wall (Figure 101). Then simulated values of inside and outside ambient temperature was compared with measured values of the data logger. Then both values were calibrated until the simulated and measured values become same. Then properties of the material were recorded while calibrating the computer model.

According to the calibrated data, Thermo-physical properties (Thermal conductivity, Specific Heat Capacity, R- value and U- value) for MCW were obtained. After that, the wall thickness of Mud-Concrete wall was changed in DesignBuilderV5 model and analyse the effect on time lag and the decrement factor of the wall. Optimum wall thickness of Mud-Concrete wall was found according to the changed thermo-physical properties of the wall through computer simulations. R and U value of the MCW was compared with other load-bearing walling materials. Structural capacity of Mud-Concrete wall was optimised according to identified optimum wall thickness of the self-compacting in-situ cast Mud-Concrete load-bearing wall.

Figure 100: Thermal data measured using GL 820 Midi - data logger and thermo-couples

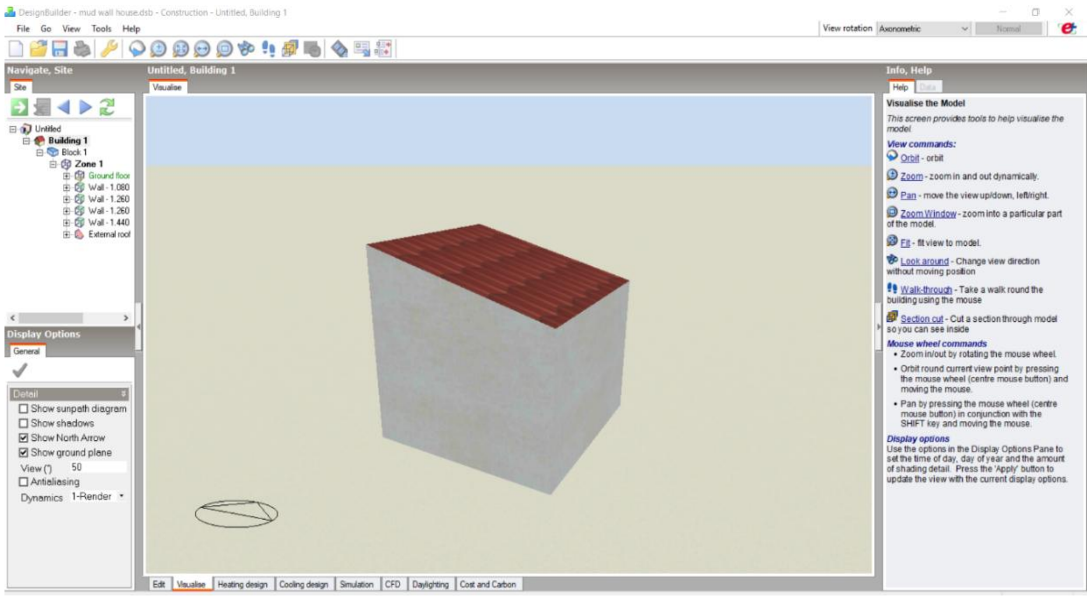


Figure 101: DesignBuilder model of the mini scaled –house made at site

5.2.2. Results and discussion

Obtained inside and outside wall surface temperature values of actual scale model was plotted in Figure 102, Figure 103, Figure 104 and Figure 105.The results were shown according to the wall oriented directions of north, south, west and east.

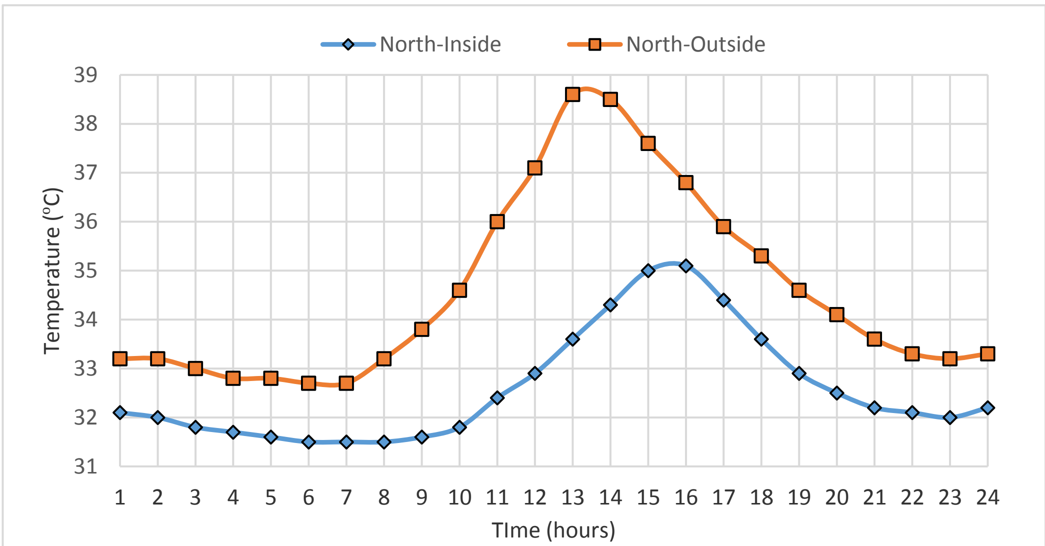


Figure 102: Inside and outside temperature of North oriented wall

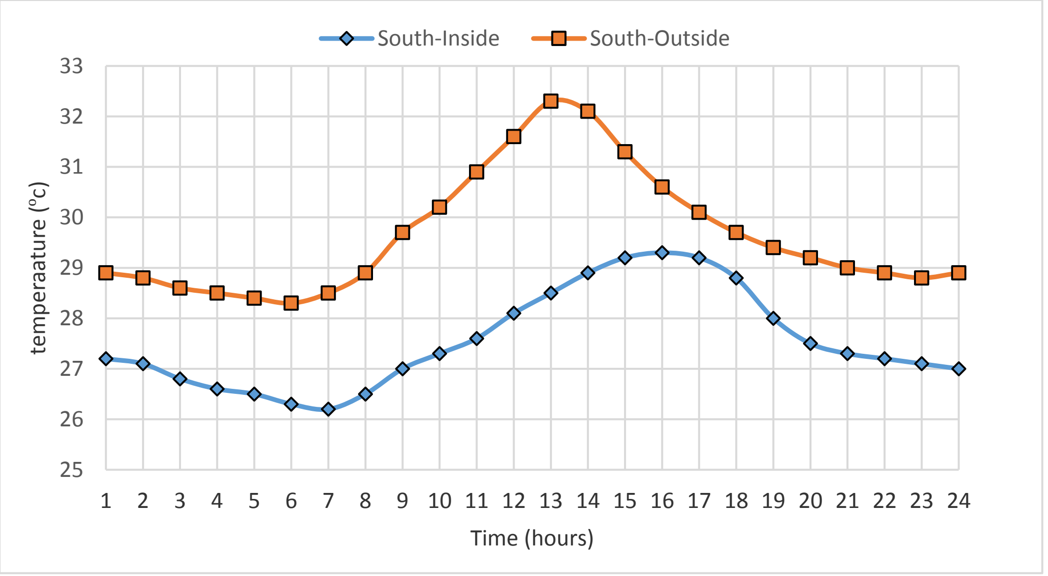


Figure 103: Inside and outside temperature of South oriented wall

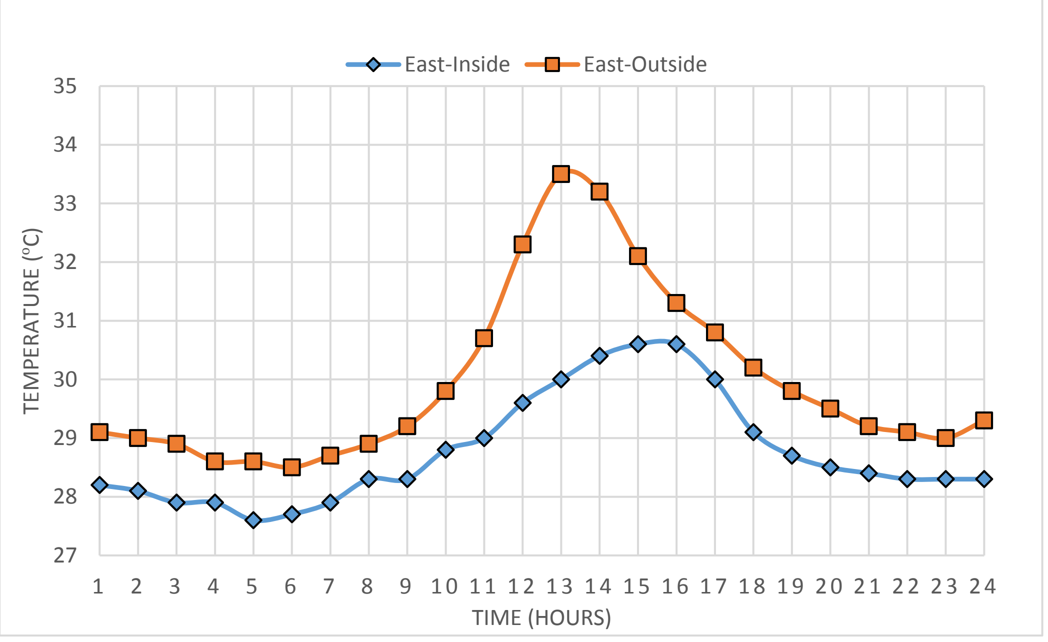


Figure 104: Inside and outside temperature of East oriented wall

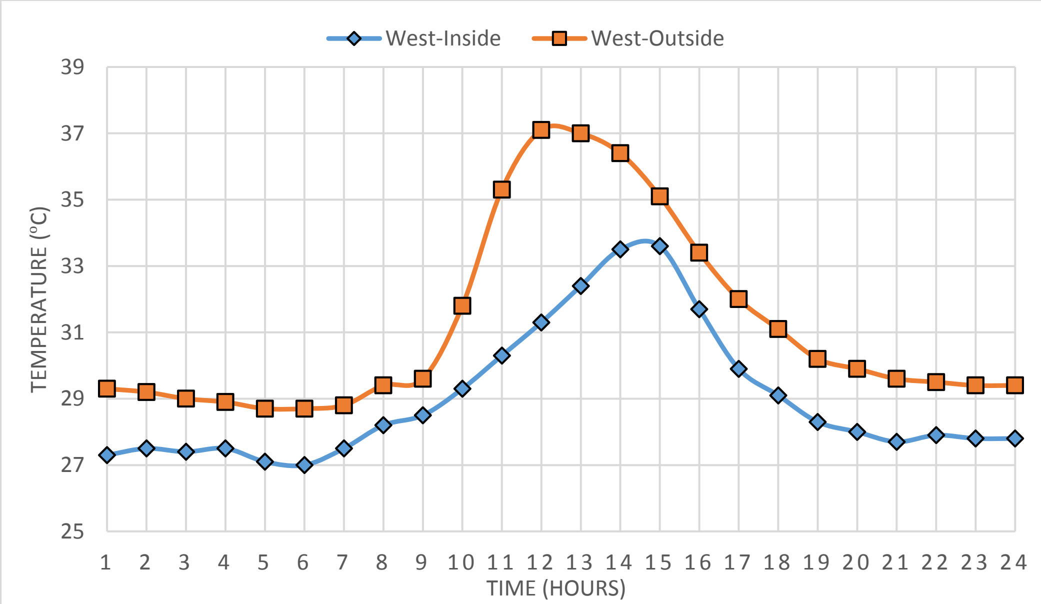


Figure 105: Inside and outside temperature of West oriented wal

Using the obtained results decrement factor of each wall (oriented to four (04) directions were calculated. The results show that 200mm thickness of Mud-Concrete wall has a 0.91 decrement factor and time lag was 3 hours (Table 74).

Table 74: Decrement factor and the time lag of 200mm thickness, Mud-Concrete wall

Properties	**Symbol**	**For 200mm thickness of MC wall**
Decrement Factor (f)	f	0.91
Time Lag (h)	Ø	3

After identifying the time lag and decrement factor, it was a need to identify the other thermo-physical properties of Mud-Concrete wall and how these time lag and the decrement factor change according to the different wall thickness. Therefore, as mentioned in methodology the same actual scale model was built on Design Builder V5 software. After that, the computer generated model was calibrated according to the actual thermal data and relevant properties were identified by matching the curves of actual thermal data and calibrated data (Figure 106).

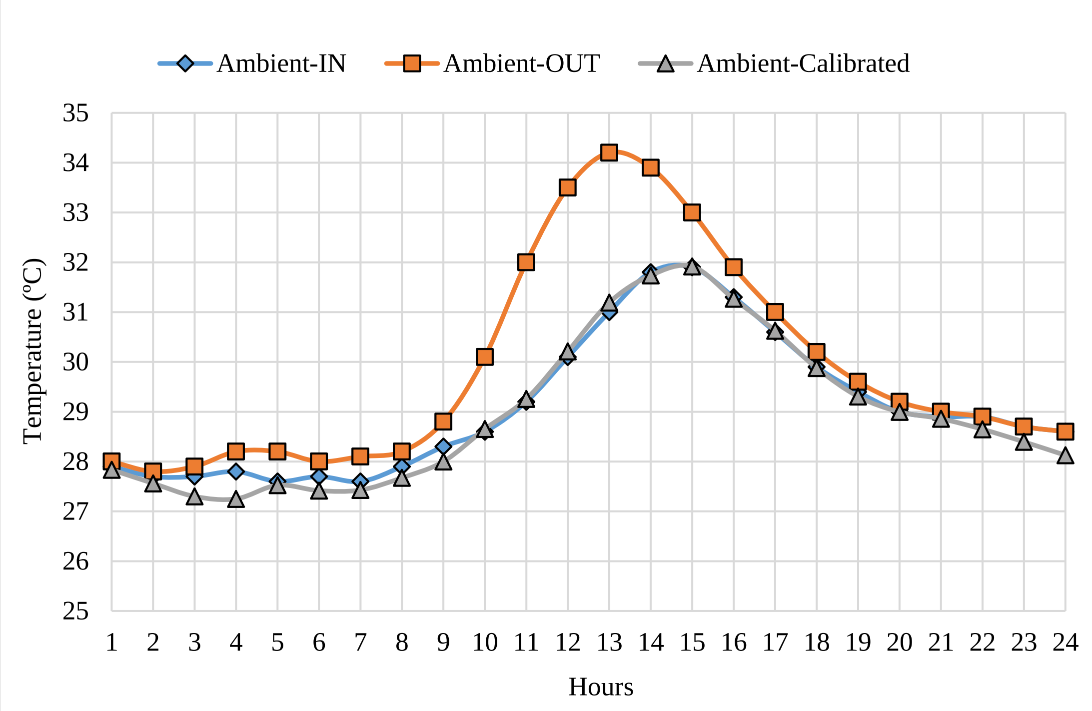


Figure 106: Matching the curves of actual data and calibrated data through Design Builder software

Thus, the data matrix used in calibrated model (Design Builder) was identified and extracted as the thermo- physical properties of Mud-Concrete wall (Table 75).

Table 75: Thermo-Physical properties of the Mud-Concrete wall

Properties	Symbol	Units	Value
Conductivity	f	W/m.K	1.2
Specific Heat Capacity	Ø	J/kg.K	1440
Density	ρ	Kg/m^3	1540
R-Value	R	m^2. K/W	0.366
U-Value	U	W/m^2. K	2.17

As mentioned in methodology, the next objective is to investigate the behavior pattern of inside surface temperature in different thickness of Mud-Concrete wall. Thus, the same Design Builder model was used and temperature differences was calculated in 100mm, 150mm, 200mm, 300mm and 450mm of wall thickness of Mud-Concrete wall. As per the results shown in Figure 107 maximum inside surface temperature was decreasing with increasing the thickness. Figure 108 shows that decrement factor of the wall was decreasing with increasing the thickness of wall. Figure 109 shows that time lag of the wall was increasing with increasing the thickness of wall.

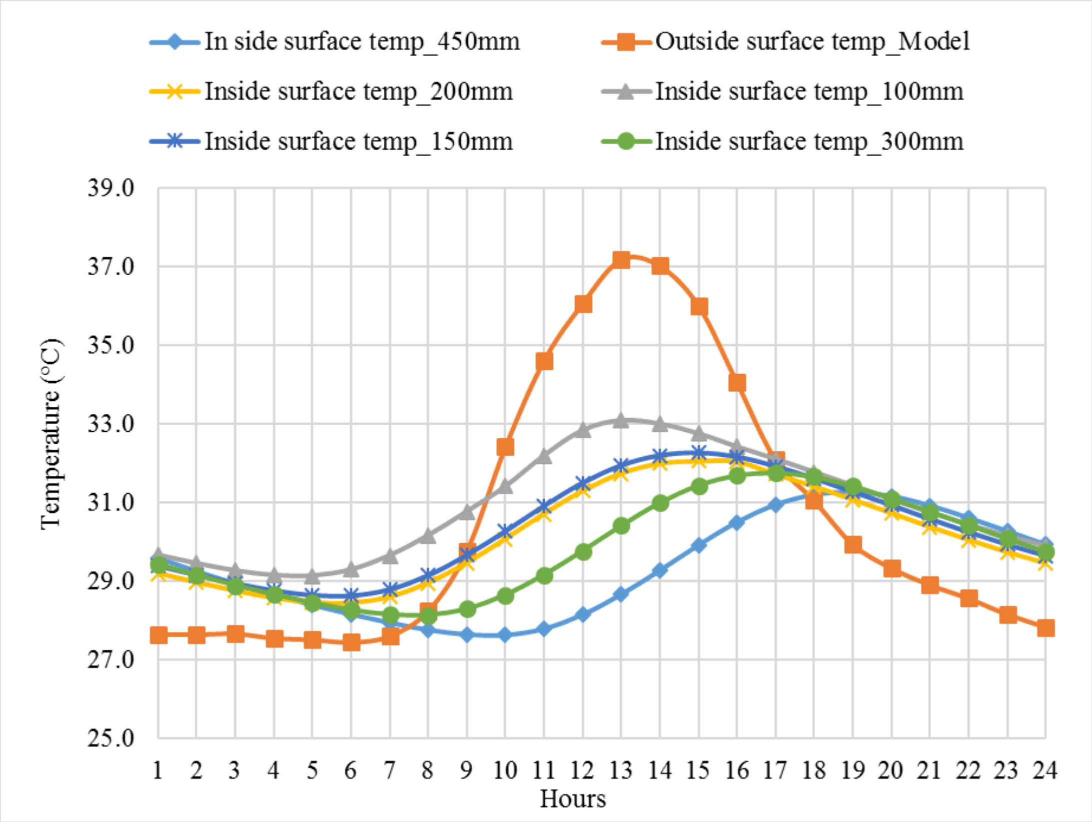


Figure 107: Surface temperature variations according to different thickness in Mud-Concrete wall

Results conclude that material of self-compacting in-situ cast Mud-Concrete load-bearing wall has 1.2 W/m.K of conductivity, 1440 J/kg.K of Specific Heat Capacity, 1540 kg/m^2 of density, 0.366 m^2.K/W of R-value and 2.17 W/m^2.K of U-Value. The time lag of the MCW was proportionate to the thickness of wall and decrement factor was inversely proportionate to the thickness. Thus, increasing the thickness of wall will help to create a good thermally resistive material through Mud-Concrete. But then again it is questionable as what is the most optimum wall thickness that can achieve the thermal comfortableness and minimum load-bearing capacities while reducing the LCC and EE.

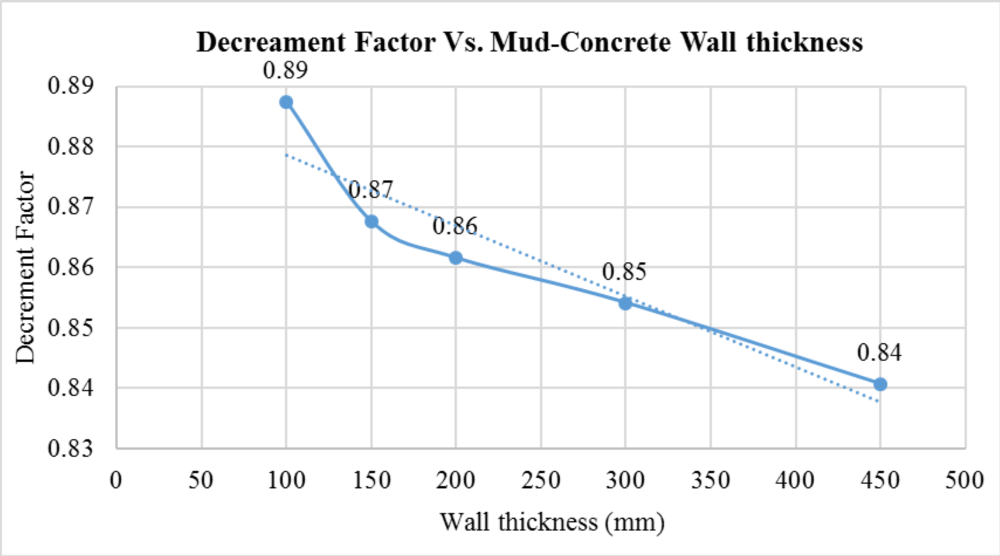


Figure 108: Decrement factor Vs. Mud-Concrete wall thickness

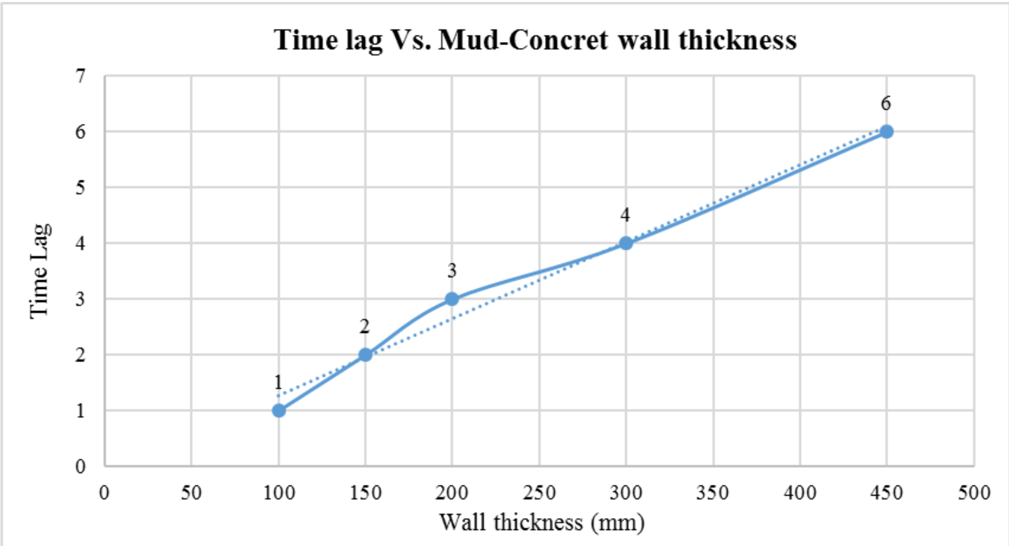


Figure 109: Time lag Vs. Thickness of Mud-Concrete wall

Hence the research was extended to investigate minimum thickness which can achieve the minimum load bearing capacities of MCW and the results will be used to calculate the LCC and EE of MCW.

5.3. Optimising the thickness of MCW segment

Increase in the thickness can change its thermal performances. Hence it is a need to find an optimum thickness to proceed with LCC and EE of the MCW analysis. The minimum structural requirement of the thickness was calculated for a typical two storied house by considering the possible load conditions. 5.0 m x 5.0 m spanned room was considered as the loading area and a two storied house with a roof top was considered as the model.

This study was mainly conducted in two combined process as quantitative and qualitative methods. In the first process manual calculations were done to identify the load acting on the MC wall.

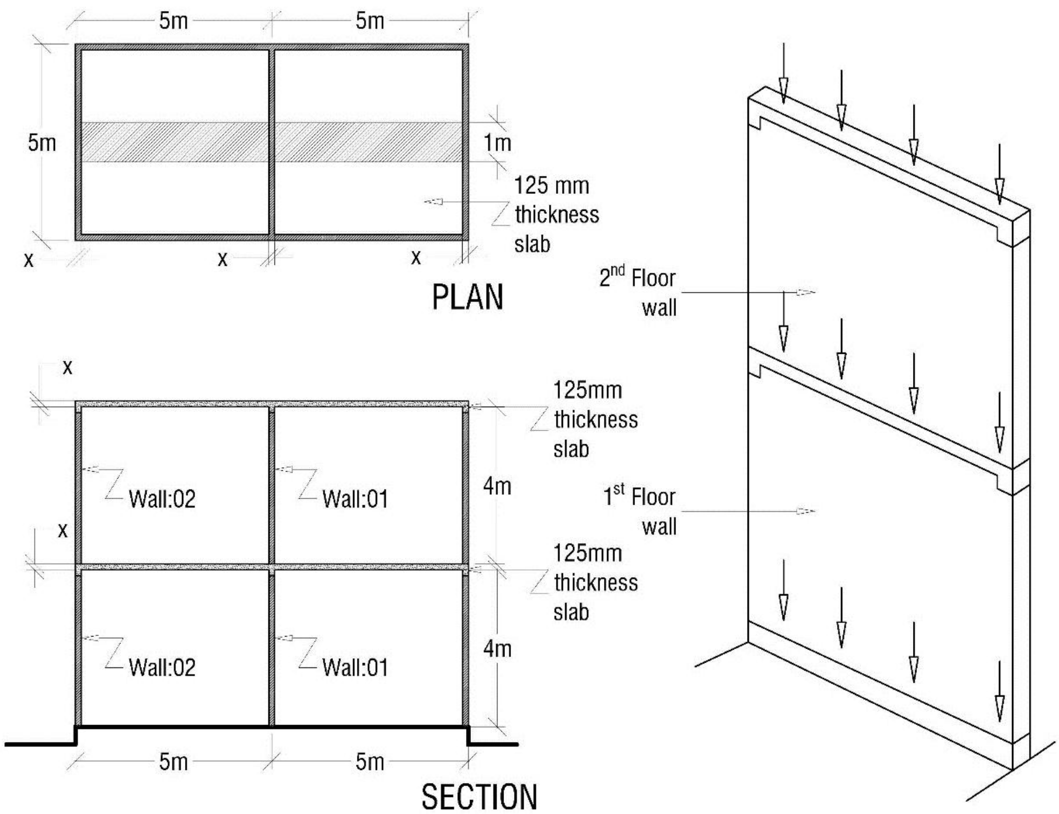


Figure 110: Selected case for calculate the load acting on the MC wall

Figure 110, shows the details of model house. Here, the '*x*' represents the thickness of the wall. Wall: 01 represents a middle wall and wall: 02 represents an edge wall. Allowance for finishes of slab was considered as 0.5 kN/m^2. Reinforced concrete slab thickness was considered as 125mm. Density of concrete was assumed as 24 kN/m^3. Density of MCW material was 15 kN/m^3 and it was taken from the results of previous section 5.2. Here the roof was considered as a concrete slab and imposed load of the roof slab was 3.0 kN/m^2. Imposed loads were taken from the code of BS 6399 (BS 6399-1, 1996) and applied for the adverse conditions. Thus, imposed load of the concrete roof slab was considered as 5kN/m^2 and imposed load of first floor slab was considered as 5kN/m^2. For the load calculation, 1m strip of the MC wall (wall: 01) was considered. The calculated dead load at the ground floor wall (bottom) from slab was 30 kN/m and dead load from finishes was 5.0 kN/m. The calculated dead load from MC wall was 6.0 kN/m. Then the total dead and live load at bottom of the MC wall was calculated. The values of loads for ultimate limit state were considered from BS 8110 (BS 8110, 1997). The values were applied to the adverse conditions. Thus the following equation (5) was used to calculate the combination of loads on the bottom of the MC wall.

$$1.4\,gk + 1.6qk \quad \ldots\ldots\ldots\ldots \quad (5)$$

Where, gk= dead load and qk = imposed load

Table 76: Load of MC wall: 01 vs wall thickness

Wall thickness (mm)	100 mm	150mm	200mm	300mm	450mm
Load combination of MC wall (kN/m)	1.46	1.03	0.81	0.60	0.46

According to Table 76, even 100mm thickness of the wall is enough to bear the loads of two storied construction. After identifying the satisfied limits of the MC wall thickness it was a need to find out the most applicable walling thicknesses and the most preferable walling thickness in an actual construction. Therefore a simple questionnaire survey was done among 242 people to identify the preferences of wall thickness using conventional walling materials (ex; Bricks, cement blocks, MCB) in the market. The selected sample was consisted with architects, engineers, contractors, mason basses and other randomly selected people (Figure 111). Figure 112 shows that considerable number of people prefer 225mm wall thickness due to structural and design considerations. However according to the cost aspects 225mm wall thickness was received the less preference.

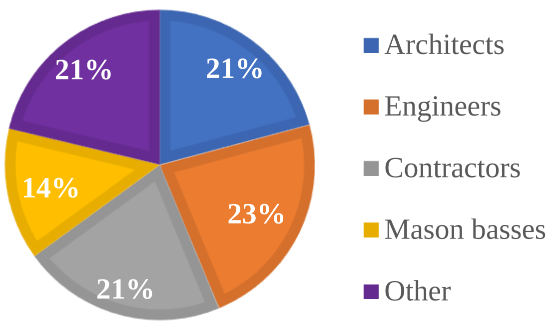


Figure 111: Responded sample % for the questionnaire

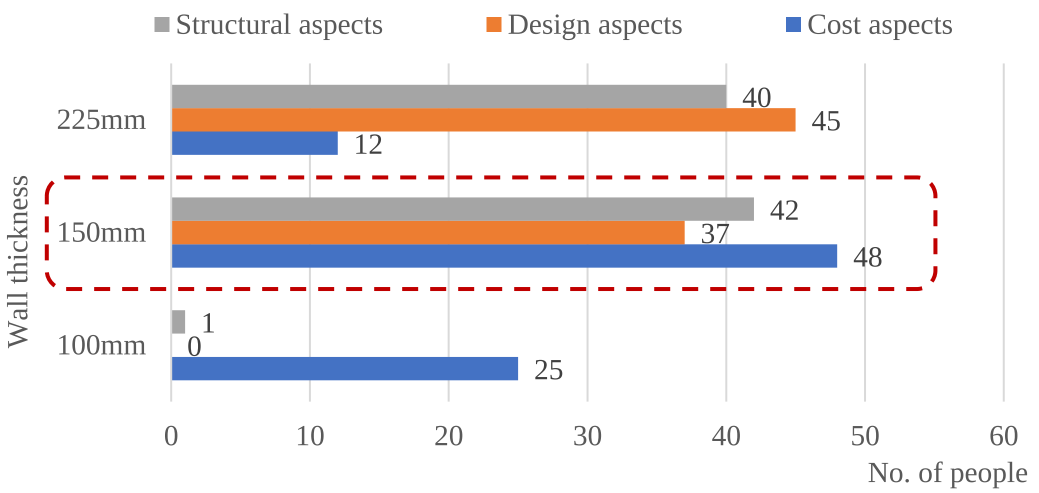


Figure 112: Preferences of wall thickness according to different aspects effects on the construction process

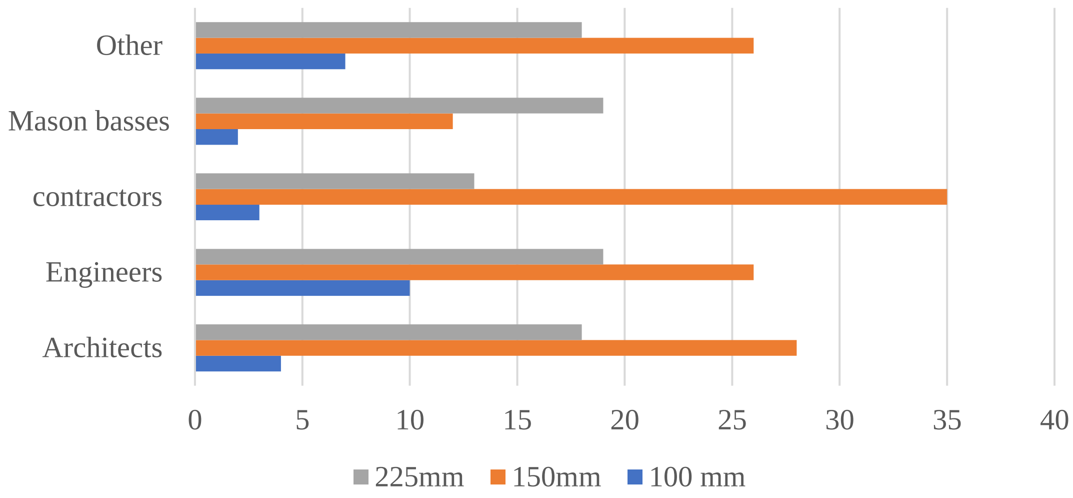


Figure 113: Preferences of selecting wall thickness according different professions which are relating to construction industry

However, Figure 112 shows an equal preference in three aspects, towards the 150mm wall thickness. According to Figure 113, most of the people relating to different fields preferred to use 150mm wall thickness. Among them contractors have showed a high preference, because they were more concerned about the cost of the work. Some architects were preferred 225mm wall thickness, because they were more concern about the final finish of the entire space and they prefer to match the wall thickness to column/beam (typical) sizes. However the structural engineers who preferred 150 mm thickness, were reasoned out that the structure can optimize (sizes of columns and beams) and match with 150mm thickness of the wall. Masons and contractors prefer to the 225mm wall thickness; because it increases the material and labour cost of the project. Another important finding was that most of the people didn’t prefer to select 100mm wall thickness. Those who selected 100mm wall thickness, considered the cost aspects and not the thermal properties of the wall. As a balanced approach we can consider 150 mm considered as the wall thickness in application of MCW construction. Accordingly, the life cycle costing (LCC) and embodied energy (EE) of MCW was calculated to the optimum walling thickness of 150mm.

5.4. Concluding remarks

MCW has 1.2 W/m.K of conductivity, 1440 J/kg.K of Specific Heat Capacity, 1540 kg/m^2 of density, 0.366 m^2.K/W of R-value and 2.17 W/m^2.K of U-Value. The time lag of the MCW was proportionate to the thickness of wall and decrement factor was inversely proportionate to the thickness. Thus, increasing the thickness of wall will help to create a good thermally resistive material through Mud-Concrete. However, it is questionable as what is the most optimum wall thickness that can achieve the thermal comfortableness and minimum load-bearing capacities while reducing the LCC and EE. According to the calculations, it is possible to use MCW with 100mm thickness to bear the downward thrust of a two storied building. But the results of questionnaire depict that most of the people prefer to go for 150mm thickness of walling. Thus as balanced approach the thickness of MC walling was optimized as 150mm and these values used in LCC and EE calculations.

6. CHAPTER FIVE– LONG TERM PERFORMANCE AND COST EFFECTIVENESS

6.1. General

The main of this research is to develop a cost effective, environmentally friendly sustainable walling technology. Thus the LCC and EE of MCW was compared with other conventional walling materials frequently used in Sri Lankan construction industry. Hence this chapter covers the calculations of LCC and EE of MCW. Further, the research was showcasing how this novel in-situ cast walling system can save cost and energy during material production, construction process and maintaining in 60 years period of time.

6.2. Life Cycle Costing (LCC) of MCW

LCC can be defined as the total cost of an item through its life, including planning, design, acquisition, operations, maintenance and disposal, less any residual value (Schau, Traverso, Lehmann, & Finkbeiner, 2011). The total cost of both acquiring and maintaining a building over its life is the sum of the capital cost and the accumulated sum of maintenance costs, energy costs and other recurrent costs, less any disposal value at the end (Emmanuel, 2004):

$$LCC = Ic + (Mc + Ec + Cc + Oc) + Uc - Rv \qquad (12)$$

Where, Ic - Initial cost, Mc - Maintenance costs, Ec - Energy costs, Cc- Cleaning costs, Oc - Overhead and management costs, Uc - utilization costs, Rv - Resale value.

The sixty-year life span of the affordable house was defined by using British standards. The sixty-year definition helps the research to omit unnecessary calculation. However, all the selected walling materials have the life span more than sixty years, and therefore, the replacement cost of walling materials was neglected from the LCC calculation process. However necessary maintenance cost was included while calculating the total life-cycle cost of the building.

The initial cost (Ic) of the basic house was calculated by using Bills of quantity sheet considering 2017 market prices. Quantities were calculated by using TDS sheet. The walling materials changes and the quantity changes due to the change in walling material were added to BOQ. Maintenance cost (Mc) of the building calculated only for the walling material. Other maintenance works such as roof flooring etc. were omitted from the analysis in order to understand the cost changes due to walling materials.

By all means, basic houses in Sri Lanka don't use air conditioners to cool make their interiors comfortable. Therefore, the energy cost (Ec) is more or less zero. However in order to understand the thermal comfort factors and the cooling load acquired by differentiating walling material, assuming that all four types of different walling material used houses are using an air conditioner to cool those houses. The energy cost of cooling loads was calculated by using Design Builder software for a period of sixty years.

Table 77: U-values of different walling materials

Walling Materials	**U value** (W/m^2K)	**Thickness**	**Reference**
Brick	2.110	150mm	(Emmanuel, 2004a), (F. Hall,
Cement Block	2.617	150mm	(F. Hall, 1994a), (F. Hall, 1994b)
MCB	2.315	150mm	(C. Udawattha et al., 2016a)
MCW	2.170	150mm	(Measured and tested via simulation)

U-values, measure the efficiency of a walling material as an insulator for buildings. The lower the U-value is, the better the walling material is as a heat insulator for a tropical country (C. Udawattha et al., 2016a). For example, brick is a comparatively better heat insulator than cement block walls. Then brick U-value is lower than cement block U-value. Perhaps, the efficiency of walling materials can be easily compared by using u value. However at the same time, the thickness of the walling materials effect on U-value. U-values of different waling materials used in this study. Table 77 shows the needed U-values of brick, cement blocks, MCB and MCW.

Resale value (Rv) is the trade value of a building after using for a specific period. In this case, it is sixty years. However the problem is after sixty years a basic house has no resale value. Therefore, the reusability of materials is taken into consideration. Since this is about walling materials, walling materials resale value only taken into final comparison.

6.3. LCC techniques

Several methods of calculating the LCC exists in the industrial/business sectors. The three most common LCC methods are as follows (Emmanuel, 2004b);

- Simple Payback
- Net present value (NPV)
- Internal rate of return (IRR)

Between all three methods, the most preferred LCC technique in the construction industry is the NPV method; because simple payback is not widely used and IRR is a more comprehensive procedure (Emmanuel, 2004b). NPV is defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of an investment.

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{13}$$

Where Ct is the estimated cost in year t, r is the discount rate and T is the period of analysis in years.

The above equation makes allowance for interest receivable on the sum invested. In reality, the value of our investment will be eroded by the pernicious effects of inflation. Therefore, the above formula needs to be modi1ed by a factor which will take account of inflation. Inflation will increase the costs at year 'n' and therefore increase the present day investment level. The modi1ed factor is known as "net of inflation discount rate" (NDR):

$$NDR = \frac{1+int\%}{1+inf\%} - 1 \tag{14}$$

Where, int. % is the interest rate and inf. % is the inflation rate.

6.4. Real scale work study of calculating the unit cost MCW material

In this study, 16’-0” (4876.8mm) x 16’-0” (4876.8mm) room with a single sash 7’-0” (2133.6m) x 3’-0” (914.4mm) door and a one 4’’-0”(1219.2mm) x 4’-0”(1219.2mm) window(double sash) has been built up to see the needed optimum number of labour within a practical time frame. Figure 114 explains the manufacturing framework of MCW.

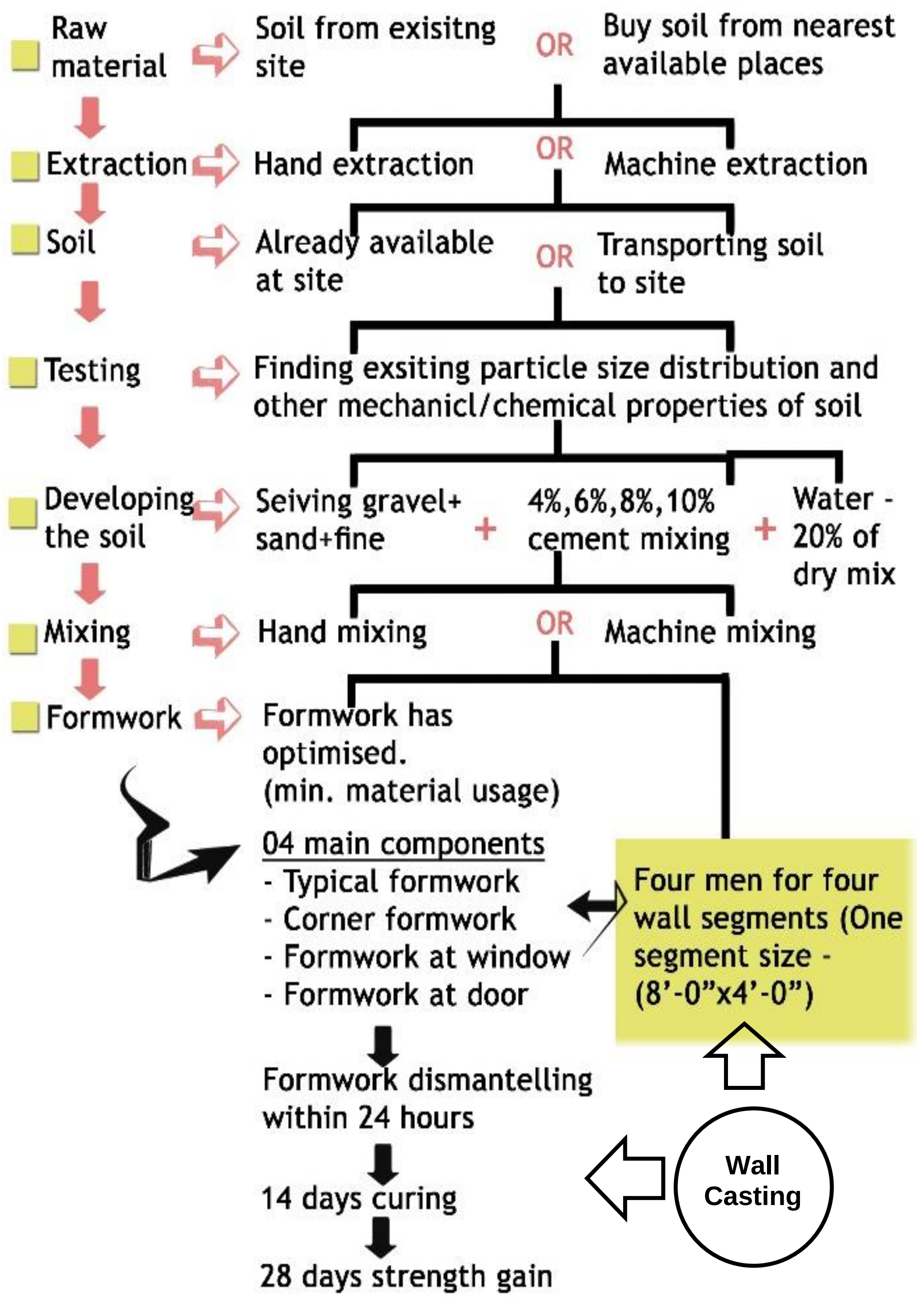


Figure 114: Manufacturing framework of in-situ cast MC wall (Seven stages)

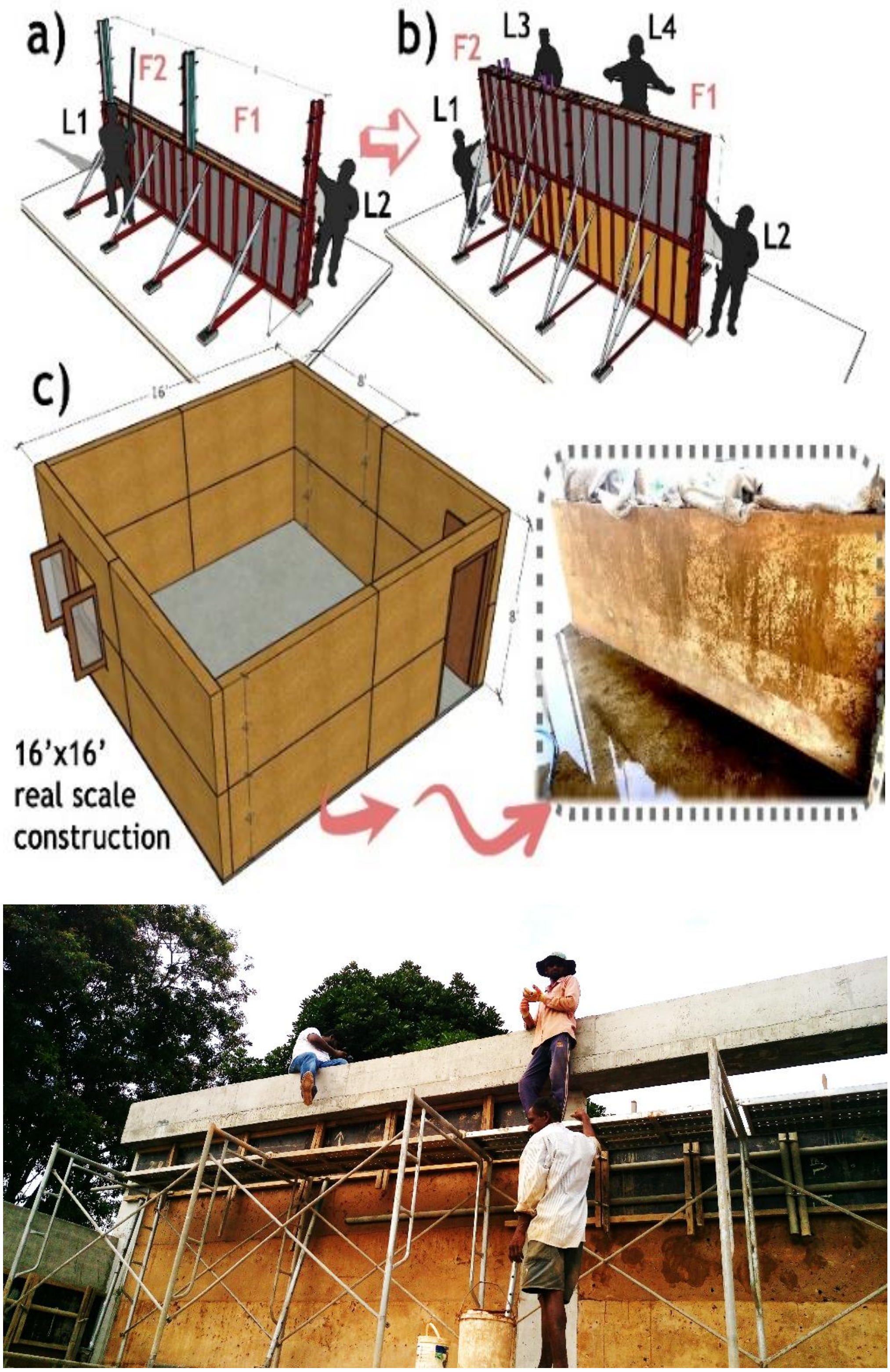


Figure 115: a)-Step one; Formwork (F) assembling for 16'-0" length and 4'-0" height. b) - Step two; bottom formwork dissembling and assembling the top formwork. 02 nos. of labour (L) required for formwork assembling and 02 labour (L) was required for mixing and pouring the MC mix.

Table 78: Work study to calculate the Mud-Concrete walling cost per sq.ft

Item	**Description**	**Amount (LKR)**	**Amount (USD)**
Material Cost	Formwork	7.18	0.04
	Mud-Concrete Mix	29.60	0.16
	Mould oil	0.50	0.0028
	Wall Curing	0.05	0.00028
Labour Cost	Formwork erecting	13.92	0.077
	Wall Casting	9.60	0.053
	Wall Curing	0.59	0.0033
Total Cost per sq.ft		**61.43**	**0.33638**

Figure 115 explains how the labour time was optimized using the process of the manufacturing framework of MCW. Four labourers were used to cast the MC walls of this 16’-0”x16’-0’ room using two sets of formworks. Optimum lifting height of a MC wall segment is 4’-0” (1200mm) and 0’-6” (150mm) thickness. In two steps 8’-0” height (2400mm) wall can be cast using the lifting formwork within two days. After 24 hours of casting, formwork can be dismantled and curing should be started soon after removing the formwork. This real scale work study has been used to calculate the rate per sq.ft value of MCW. Table 78 demonstrate how the material and labour cost values were added to calculate the unit cost of MCW. Thus the unit cost value of MCW is approximately LKR. 60 (USD 0.3) per square feet.

6.5. Selecting a basic house model for LCC calculation and energy accounting

The Ministry of Housing & Samurdhi in Sri Lanka has launched a hundred-day programme to develop hundred and fifty thousand houses in the country. Most of these house designs were built all over the country (Chameera Udawattha & Halwatura, 2017). These basic house models were given to poor locals by the Sri Lankan government as a manual of building their own house. The house manual was given to the general public with a costing sheet and a material sheet. The house design was published by the national housing development authority and Samurdhi division (Chameera Udawattha & Halwatura, 2017). The basic home was built on levelled land and it consists of 500 Sq. ft (46.4 m^2) of floor area, two bedrooms with open plan, living and dining, separate bathroom and shower. In addition, it consists 10 lights, seven power units, and three fans. Figure 117 shows the plan view of selected basic house model. Bill of quantities was prepared to understand the total initial construction cost of the selected houses with selected walling materials. Figure 118 shows the total construction cost vs. walling cost of selected basic house model. It was clear that MCW material gives the least construction cost among the selected walling materials. Then the selected basic house model was modeled on Design Builder V5 software (Figure 116) to calculate the cooling loads (Figure 119). Using these simulated results, energy cost was calculated. Every item of the BOQ was calculated up to the recommended years of LCC and final maintenance cost was calculated. Then the sum of the initial cost, the maintenance cost, resale value, energy cost and overheads of the each item were calculated to find the 60 years period of LCC of walling materials (Figure 120, Table 79 and Table 80). The reusability was considered basically after calculating the total life span of the building material. Not only for the walling materials but also for the other building elements life span was measured accordingly to calculate the total reusability of the building. It was assumed that the total lifespan of the building is sixty years and more than sixty-year life span building materials were multiplied by the reusability factor. However, the reusability was measured only for the similar usage in the future. The other alternative reuses or recycle were omitted because of their complexity in alternative reuses.

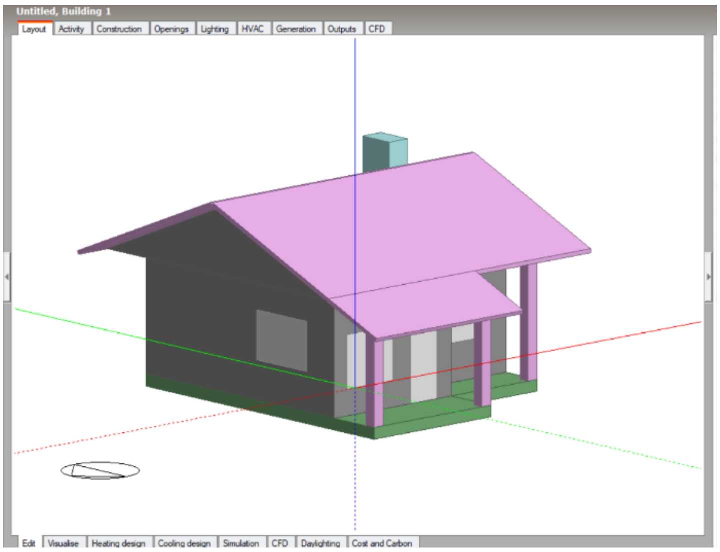


Figure 116: Modelled the basic house design on Design Builder software to calculate the cooling loads with different walling materials

Figure 117: Selected basic house model - PLAN

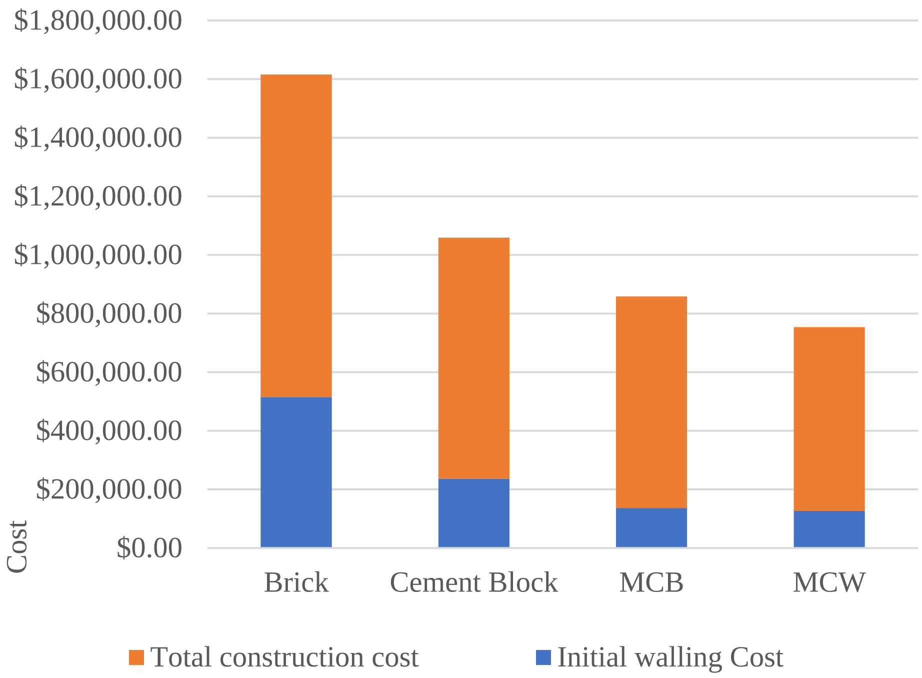


Figure 118: Total initial construction cost vs. walling cost

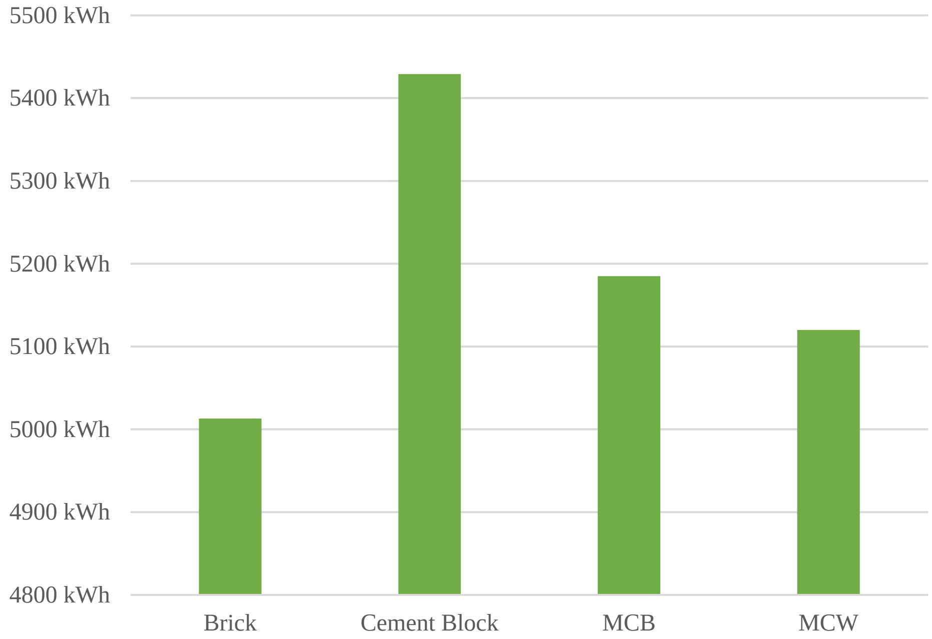


Figure 119: Cooling load calculation for 60 year

Table 79: Calculating initial cost and resale value of different walling materials

NPV as of January 2017 – Interest rate 8.0%					
Item & life span	Description	Brick	Cement block	MCB	MCW
Wall (Square feet 1460) >60 years	Initial walling Cost ($)	2810.3	1292.5	745.3	693.6
	Reusability factor	60%	70%	92%	96%
	Resale value ($)	1423.6	904.7	685.6	665.9

Table 80: Life cycle costing of 60 years in different walling materials

Basic House model with different walling materials	Brick	Cement Block	MCB	MCW
				
Total initial cost ($)	6001.9	4484.0	3936.8	3885.2
Total energy cost ($)	15382.5	16659.0	15910.3	15710.9
Over heads ($)	480.1	358.7	314.9	310.8
Life cycle cost ($)	23266.6	22903.8	21564.1	20560.2

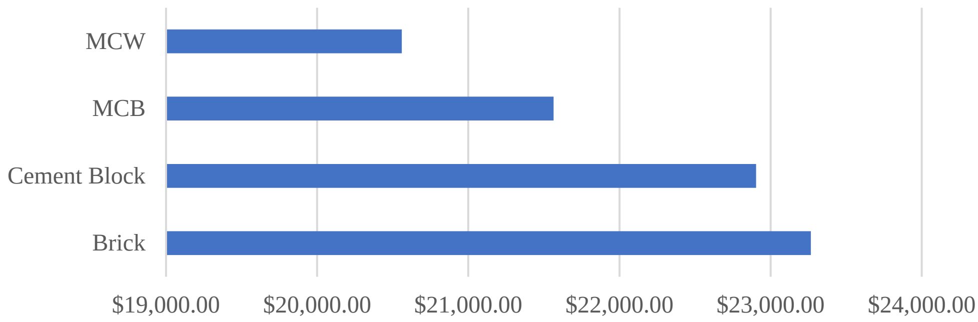


Figure 120: Life cycle cost of different walling materials (for 60 years) NPV as of 1st Jan 2017

6.6. Embodied Energy (EE) of MCW

The total energy for material at a given level becomes the embodied energy of the raw material, at next higher level. Apart from the items specialized in the BSR the data required to estimate the embodied energies are collected from building material manufacturers, contractors and merchants. Only three forms of energy are considered (Emmanuel, 2004b):

a) Level one: Energy embodied in raw materials;
b) Level two: Transport energy for raw materials and finished products;
c) Level three: Energy in construction.

Same basic house model and the calculated data used in LCC were used to calculate the Embodied Energy (EE) of MCW. In addition, a comparison study was done for brick, cement block, Mud-Concrete block (MCB) with self-compacting in-situ cast Mud-Concrete load-bearing (MCW) walls. Thus the EE calculation was done at different levels. 150mm (0'- 6") thick, 3m (10'-0") x 3m (10'-0") walls were considered in EE calculations. Embodied energy in selected walling materials calculated without the internal and external plasterwork. Plastering work was calculated separately to understand the materials contribution to the total embodied energy of the house. And it was assumed that all the walling material constructed with a similar smooth finish. In addition, stretcher bond was used to build all three types of walls excluding MCW. It was assumed that all the labour available within the site. The mortar was mixed at the same place where the brick wall was being built. Table

81 shows the energy consumed to build a hundred square feet wall of MCW. In addition, energy consumption of the machines was given in Table 82.

Table 81: Energy consumed to build a hundred square feet MCW – an example of EE measuring method

Requirement	The material requirement for 100 square feet wall							
	Area (sq.ft)	Soil (m^3)	Mortar (m^3)	Cement (kg)	Cement 50kg Bags	Sand (Kg)	Sand 40kg Bags	Water (L)
	100	10.5	0.00	114	3	0	0	6
Distance	Transport distance							
	Manufacturing (Level 01)		Transporting to the site (Level 2)			Construction of one square wall (level 3)		
	Soil	Water	MCW	Cement	Sand	MCW	Labour	Mortar
	20.0km	0.15km	0.00km	152.0km	0.0km	0.0km	0.0km	0.0km
Method	Soil	Water	MCW	Cement	Sand	MCW	Labour	Mortar
	01 tractor	100Pm	0 Lorry	01 Lorry	01 Lorry	0 Wheel Barrow	On site	0 Wheel Barrow
Level one (01)	Level one (Manufacturing MCW)							
	Raw material		Biomass	Fossil fuel		Electricity	Total Energy	
	Soil		0.00 kg	2.07 Litr		0.00 MWh	74.3122 MJ	
	Cement		0.00 kg	19.00 Litr		0.00 MWh	682.1000 MJ	
	Water		0.00 kg	0.00 Litr		0.20 MWh	720.1296 MJ	
	Molding		0.00 kg	2.00 Litr		0.000 MWh	72 MJ	
	Total energy for MCW production						1548.34179 MJ	
Level two (02)	Level two (Transporting material to the site)							
	Method		Biomass	Fossil fuel		Electricity	Total Energy	
	Uploading		0.00 kg	0.00 Litr		0.00 MWh	0 MJ	
	Transporting		0.00 kg	0.00 Litr		0.00 MWh	0 MJ	
	Unloading		0.00 kg	0.00 Litr		0.00 MWh	0 MJ	
	Cement (for mortar)		0.00 kg	0.00 Litr		0.00 MWh	0 MJ	
	Sand (for mortar)		0.00 kg	0.00 Litr		0.00 MWh	0 MJ	
	Total energy after producing and transporting materials to the site						1548.34179 MJ	
Level three (03)	Level three (Construction of one square MCW wall)							
	Method		Biomass	Fossil fuel		Electricity	Total Energy	
	Masonry		0.00kg	0.00Litr		0.00 MWh	0 MJ	
	Mortar mixing		0.00kg	0.00Litr		0.00 MWh	0 MJ	
	Constructing		0.00kg	0.00Litr		0.00 MWh	0 MJ	
	Total energy for construct hundred square feet MCW						1548.34179 MJ	

There were several assumptions considered for brick, cement blocks, MCB and MCW production. Soil extraction was done using human labour. It was considered the block making factory is 500m away from the construction site for brick, cement blocks and MCB. In MCW technology soil is directly transporting to the site because it is in-situ cast system and there is no transport cost form the factory to site. However it was considered the bricks, cement blocks and MCB were transported to the site by a lorry. Water was collected from a well 150m away using an electric pump (125 litres per minutes). Mould oil was used as a separator for formwork of MCB and MCW. All labour was available within the site. It was considered as mortar was mixed at the same place where the brick and block wall are being built. Also, mortar mixing was done manually; no machinery was used whatsoever while building the brick and block walls. There's no necessity of using mortar in MCW construction as wall segments can join using a tongue and groove joint or dowel bars.

Table 82: Energy consumption of machines

Description	Bricks	Cement blocks	MCB	MCW
Blocks per 100 sq.ft of single skin wall 150 mm	1150	80	302	Not applicable
Wheel barrow volume (l)	65	65	65	Not applicable
Weight of cement bag	50	50	50	50
Volume of bag of cement (l)	33	33	33	33
Volume of mortar per brick laid	0.00034	0.00034	0.00034	Not applicable
Cement bags per cubic meter of class I mortar	9.5	9.5	9.5	Not applicable
Volume of sand per cubic meter of class I mortar	1.23	1.23	1.23	Not applicable
Weight of 40 kg sand bag	30	30	30	Not applicable
Liters in a cubic meter	1000	1000	1000	Not applicable
Joint width on block work	10mm	10mm	10mm	Not applicable

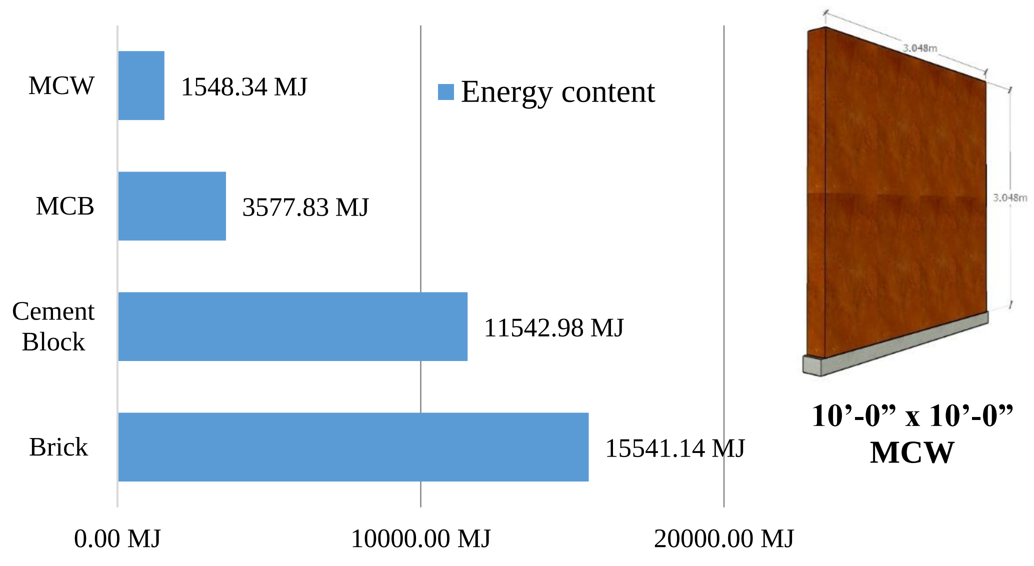


Figure 121: Energy content of building hundred square feet wall from different walling materials

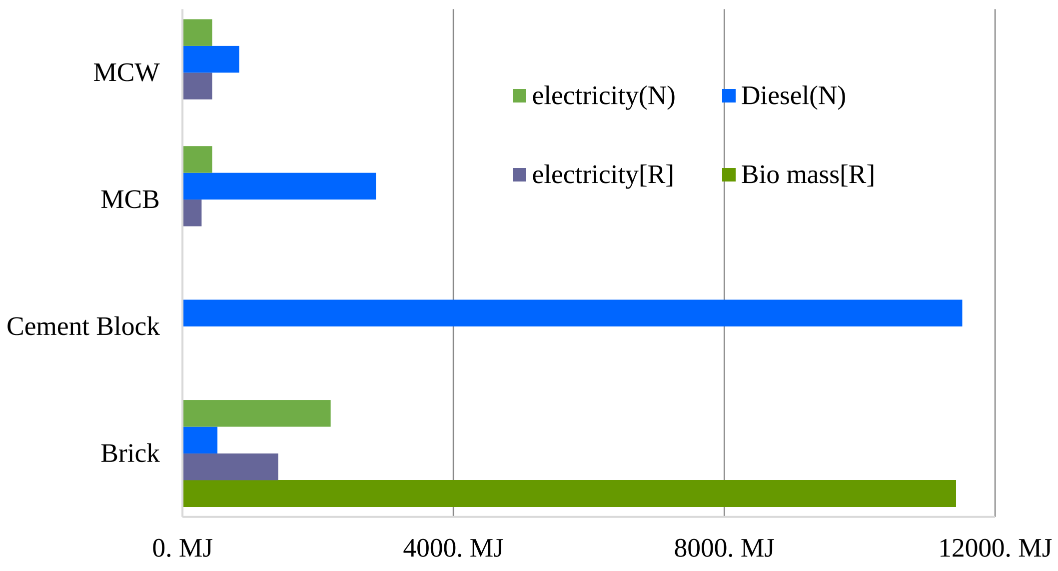


Figure 122: Comparison of the energy content of different materials (calculating energy source and energy type)

MCW has lesser embedded energy comparing to brick, cement blocks and MCB (Figure 121 and Figure 122). Because MCW is a self-compacting, in-situ cast, quick construction walling method. MCW can be made by soil extracted from a location near the site and no burning energy cost is added. All its highest energy content purely comes due to the embedded energy cost of cement production. However in MCW only for 4% cement is using as the total raw material cost. Though the MCB also produce similar material the LCC and EE differ due to the followed construction technology. In MCB production transportation cost and the labour cost is high than the in-situ method of MCW. Hence, the production of MCW and construction of MCW wall has lesser energy consumption comparing to brick, cement block and MCB.

Considering all the scales given to measure the suitability of different walling materials such as embedded energy, initial cost, operation cost and Life cycle cost; MCW is the best walling materials to build affordable houses. When comparing the cooling load calculation cement block is the worst material for the tropical condition. The brick wall has the highest energy content. Brick contain highest embodied energy due to its burning process. Cement block wall and MCB show intermediate energy consumption. However MCB has less energy consumption than cement blocks. Because cement block made of quarry dust need a lot more non-renewable energy to produce. The MCW has comparatively lowest embedded energy content due to its self-compacting methods, in-situ construction and less-labour usage in the construction process (due to optimised formwork system). Not only that MCW is 96% reusable. Its ingredient can be crushed and produce same walling material with an addition of cement ratio of 4%. Therefore, overall the MCW is one of the best alternative building materials to suit into tropical climate condition like Sri Lanka. However this will depend on the raw material availability of the context.

6.7. Concluding remarks

The construction sector has a meaningful contribution to the global scarcity of natural resources, as well as to impacts on the natural environment.

The concept of calculating LCC and EE is important to assess the cost effectiveness and the long term performance because it's a universal method of measuring the sustainability factor of building materials.

By definition, the embodied energy is the sum of all the types of energy consumed while producing a specific product or a service. The process analysis and hierarchical structure of energy consumptions were used to account the total embodied energy content. Ten feet (length) by ten feet (width) wall (hundred square feet) was used to compare the energy content. Considering all the scales given to measure the suitability of different walling materials such as embedded energy, initial cost, operation cost and Life cycle cost; MCW is the best walling materials to build affordable houses comparing to MCB, cement blocks and fired bricks.

7. CONCLUSIONS / RECOMMENDATIONS

This research was conducted to investigate a self-compacting in-situ cast load-bearing walling (MCW) material through Mud-Concrete (MC). The research was mainly focused on two different sections; finding the best mix design and optimum construction technology for MCW. In addition, durability, shrinkage characteristics, thermal performance and long-term cost effectiveness including LCC and EE were investigated.

Theoretically any soil type can be used in Mud-Concrete construction (Arooz et al., 2015); however gravelly laterite soil is effective because of its ease in making a well-graded soil sample in the mix (Arooz, Babilegedara, et al., 2017 ; Bandara et al., 2016). Thus, gravelly laterite soil was chosen in entire testing procedures.

The selected soil was air dried and sieve analysis was conducted prior to use in tests. In this study Ordinary Portland Cement (OPC)/ (Type I) (ASTM C150 -07, 2007)was used as the stabilizer in the mix and for the entire test. 150mmx150mmx150mm cast iron block moulds were used to cast the Mud-Concrete testing blocks. Blocks were cured for 14 days using wet gunny bags at room temperature (± 25 ºC Temperature, ± 75% Relative humidity).

To check the workability and the self-compacting consistency of the MC mix, custom methods were developed. MC mix can achieve the workability if it flows up to an approx. 500mm diameter circle on the flow table after giving 25 blows. Results show approx. 20% water of the dry mix gives the workable mix of Mud-Concrete.

The effective gravel range of self-compacting in-situ cast load bearing wall is 4.75mm-32mm, which means it is possible to use fine and coarse gravel ranges in MCW construction. Therefore, the soil use for the construction of MC walls must be sieved through the standard 31.5 mm (1.25 inch) sieve size to remove the large particle sizes from the soil mix. With minimum 4% of cement, 45% Gravel: 50%

Sand ratio gives the maximum wet and dry compressive strength for the mix design of in-situ cast MC load bearing wall.

- Fine - 5% (≤ sieve size 0.425mm)
- Sand (fine aggregate) - 50 % (sieve size 0.425mm ≤ sand ≤4.75 mm)
- Gravel (course aggregate) - 45% (sieve size 4.75mm ≤ gravel≤ 32mm)

Low quantities of fine (5%) were kept in mix to maintain the high compressive strength values of in-situ cast MC wall. Usable gravel range in soil for any Mud-Concrete construction is limited to 35%-55% and sand is limited to 60%-40% with 4% cement. Increasing gravel percentage does not lead to increase the compressive strength of MC at all times. Compressive strength of MC wall depends on the particle size distribution of developed soil, optimum gravel size and the optimum gravel: sand ratio of the mix.

Durability of MCW was checked in laboratory conditions and the results confirmed the Achieved mix design of MCW (with minimum 4% cement) deemed to satisfy the SLS standards 1382 (Sri Lankan Standard Institute, 2009).

Increasing the water content reduces the compressive strength of the MC mix. However, the behaviour of water in MC was ambiguous as it is difficult to keep the exact water percentage of the dry mix although the same volume of water was added in every sample while mixing. Therefore, data matrix was obtained through series of testing procedures and the phenomenological equation was developed to plot the exact grading curves in identified water percentage of dry mix in MC walls.

MCW is an excellent moisture buffering material. Increasing water content in the mix did not effectively increased the buffering potentials of the MC material, because MC wall can crack with the high water content in the mix. Although the low water content has given a better moisture buffering value of MC, practically it is difficult to keep the self-compacting quality of the material in construction. Thus, 20% optimum water content is recommended to be used in MC construction and it always deemed to satisfy the self-compacting quality, required strength and excellent moisture buffering capacities. Overall experimental results depicted that $MBV_{practical}$ values are higher than MBV_{ideal} values in all cases. Increasing the cement content increased the moisture buffering capacity of MC material due to its increased thermal conductivity and moisture capacity of the microstructural arrangements. This buffering potential of the MC material can be developed with optimizing the surface exposure and walling thickness in a given space while passively balancing the micro-climatic conditions.

After finalizing the mix design and grading characteristics of MCW material it was a need to identify a proper optimum construction technology. Thus, a flexible modular formwork system was developed. This formwork system comprised of two mould plates and one or two end plates, which could be combined in various configurations to provide an end stop of adjustable width, which will produce walls of various thickness. Chamfered box bars were welded inside the end plates to prepare the needed construction joints between the wall segments. All the joints were fixed accordingly to ensure the water tightness of the system. This system has no walls through ties to hold the side panels together. The same end panel system was used to prepare the frame for formwork at the openings in the wall without disturbing the structural requirement and the water tightness of the system. This modular formwork system was flexibly developed to cater the different components in a wall construction.

After designing the formwork, it is a need to identify the optimum height of a MCW segment to reduce the repercussion in construction. Because this optimum construction height of the wall will govern the speed of the construction and quality of the overall work presented. The optimum construction height of a wall can be affected by different factors such as segregation of material, the workmanship available at the site, the techniques use for handling and fixing formwork/mould of the wall. The experimental results confirmed that moulded MC samples are stronger than the cored MC samples. Further, the results demonstrated that increasing the height of the MCW does not reduce the compressive strength of the wall. Therefore, there is no height restriction for constructing an in-situ cast MC wall segment. However, the comfortable height of pouring concrete to formwork was found as 1200mm (approx.4’-0”) through the questionnaire survey conducted among 400 construction workers in different construction sites. Therefore, the formwork to cast a single wall segment was optimized up to 1200mm height. Since there is no height restriction, the total wall height (1200mm – height of a single wall segment) can be casted at once without proposing any joints.

Understanding the drying shrinkage characteristics with different curing times is important to keep the quality of construction of MCW in the field. To understand the value of drying shrinkage, methodologies were adopted step by step. Obtained results show that in-situ cast MCW load-bearing wall can reach for its required (load-bearing) minimum compressive strength after 07 days of curing period. Thus, 07 days of curing period was identified as an effective curing period for self-compacting load-bearing MC walls. The values of horizontal linear shrinkage and vertical linear shrinkage of the MC load bearing wall is almost the same. However, the maximum horizontal shrinkage strain of the MC wall is approx.0.23% in 35 days and maximum vertical shrinkage strain of the wall is approx. 0.22% in 28 days. Considering both horizontal and vertical shrinkage strains of the MC wall, the values have always been below the recommended maximum standard limits of the shrinkage of earth walls. Therefore, the achieved optimum mix of MC load bearing wall was deemed to satisfy the standards of construction and minimum 07 days curing period can be recommended to reduce the shrinkage cracks in MC wall construction. Nevertheless, the results were always below the recommended limits of drying shrinkage (value of drying shrinkage ≤ 0.5% for load bearing earth walls), further testing was carried out to check the behaviour of shrinkage strain in different curing periods of MC load-bearing walls. Results of the testing justify that increasing the curing period is always reducing the shrinkage strain of the in-situ cast MC load-bearing walls. Therefore, increasing proper curing procedure can reduce the shrinkage strain of in-situ cast MC load- bearing wall and reduce the repercussion in construction. When increasing the curing period from 07 days to 14 days the linear shrinkage strain reduced from 0.23% to 0.15%. With the 21 days curing period, the linear shrinkage strain could be reduced from 0.23% to 0.13%. Thus results depicted that 14 days curing is much effective than the 21 days curing period. Therefore, to minimize the shrinkage cracks further in construction, 14 days proper curing period is recommended for in-situ cast MC load-bearing walls.

Furthermore, it is important to introduce a proper construction joints in between two MCW segments to reduce the crack development in walls while construction. Thus, in every 1200mm height proper horizontal joint should be introduced in in-situ cast process. The results show that introduced joint should keep the maximum continuity in between the wall segments. Three types of possible and practical joints were tested. Among those adding cement slurry between two wall segments has given a higher compressive strength value. In addition, the result confirmed that keeping a joint between the wall segments is not affecting to its load bearing characters of MC walling system.

Self-compacting in-situ cast Mud-Concrete load-bearing wall has 1.2 W/m.K of conductivity, 1440 J/kg.K of Specific Heat Capacity, 1540 kg/m^2 of density, 0.366 m^2.K/W of R-value and 2.17 W/m^2.K of U-Value. The time lag of the MCW was proportionate to the thickness of wall and decrement factor was inversely proportionate to the thickness. It is clear that increasing the thickness will help to create a good thermally resistive material (both thermal mass and insulation characters) through Mud-Concrete.

The long-term performance of MCW walls are calculated using two different indices. One is the embedded energy of the walling materials and second one is the life cycle cost incurred due to change in different walling materials. Self-compacting in-situ cast Mud-Concrete load-bearing walling materials (MCW) have the lowest embedded energy (EE) considering all the other walling materials (fired bricks and cement blocks) and it has the lowest life cycle cost (LCC). However, subcomponents such as mortar and sand were not considered in this study. Exterior plastering is not necessary in walling materials such as Mud-Concrete block (MCB) and MCW. In addition, MCW reduces the labour cost due to its quick in-situ construction technologies. Thus the LCC and EE of MCW show low values than MCB. Moreover, MCW material is 96% reusable. Its ingredients can be crushed and use to produce the same walling material with an addition of cement ratio of 4%.

Thus, newly invented MCW material has satisfied all the appropriate standards and proved as a sustainable environmentally friendly construction material.

8. FUTURE WORK

Few future work has been planned through this research process as follows;

- Investigation on alternative stabilizers and natural additives to remove cement consumption in MCW
- Durability study of MCW in long-term environmental conditions (3-5 years)
- Fire resistance study of MCW in laboratory conditions
- Experimental study on (confinement study) MCW for 3D concrete printing
- Investigation on fabric formwork, fabric MCW construction to remove material wastage and develop novel architectural elements
- Investigating the shell structures and thin vaulting through MCW

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