AMERICAN UNIVERSITY OF BEIRUT

RAMMED EARTH CONSTRUCTION DEVELOPMENT IN LEBANON

by
ELIE MILED ALKAREH

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ELIE MILED ALKAREH

Approved by:

Prof. Aram Yeretzian, Assistant Professor Department of Architecture and Design	Advisor
Dr. Mounir Mabsout, Professor Department of Civil and Environmental Engineering	Co-Advisor
Dr. Salah Sadek, Professor, Department of Civil and Environmental Engineering	Member of Committee

Date of thesis defense: Tuesday February 18th, 2020

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AN ABSTRACT OF THE THESIS

Elie Miled AlKareh for Master of Engineering
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As a construction method, rammed earth makes use of raw earth, with little to no additives as a building material. Buckets of soil are placed into a mold and compacted in layers to build load-bearing walls. Once construction is complete, the molds can be removed immediately and the structure becomes ready for further construction steps. Rammed earth structures come with little material costs due to the common and immediate availability of earth as a resource on construction sites. They produce less carbon dioxide emissions throughout their life cycle and are completely recyclable, thus reducing environmental harm to a minimum. The simplicity with which rammed earth structures are built, coupled with the finishes that can be provided, make earth an accessible building material to fit many project costs, quality, and aesthetic requirements. Earthen homes also provide healthy living environments with regards to indoor temperature and humidity. This research aims to optimize the construction methods and material mixes to best fit the East Mediterranean region's climatic conditions and soils, while developing an efficient and reusable formwork system. Two sets of six test walls with varying soil, sand, and additive ratios were built, one located in the Advancing Research and Enabling Communities (AREC) facility of the American University of Beirut (AUB), in Lebanon's arid Bekaa Valley. The second set, located on AUB's main campus in Beirut's humid climate. The walls are instrumented with soil moisture and temperature sensors and sample cylinders representing the different mixes were tested for compressive strength. It was found that the sampling method used to make the test cylinders directly impacts test results and using the tools used on site to make the cylinders produced the most reliable results. The decrement factor and heat flux time lag of the walls were calculated using the temperature data gathered, and were shown to be impacted by the ambient external conditions. Construction quality was studied by monitoring workmanship and determining productivity and quality of work, through in-situ wall density measurements, determined to be a reliable method to monitor achieved wall density.

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CHAPTER I

INTRODUCTION

Rammed earth, “the man made equivalent of sedimentary rock” (Hall, et al., 2012), made up some the first homes humankind lived in after moving out of the caves. Excavations have uncovered rammed earth structures dating back thousands of years in numerous locations around the world (Jaquin et al., 2008). With simple tools and materials available at the time, our ancestors were building strong and sturdy shelters that shielded them from the elements and relied on passive design to provide more comfortable living spaces (Chen et al., 2015).

In essence, rammed earth construction is a relatively simple process that uses natural soil, also called loam, and mechanical energy to mimic the sedimentation process that occurs in the earth’s crust. The building process, illustrated in ***Figure 1***, starts with placing a 15 to 20 cm layer of soil into a mold and compacting it by hand using a manual or pneumatic tamper, shown in ***Figure 2***, until it reaches its maximum density. When completed, a second layer is placed and compacted. The process is repeated until the total height of the structure is reached and the formwork, also shown in ***Figure 2***, can be removed immediately.

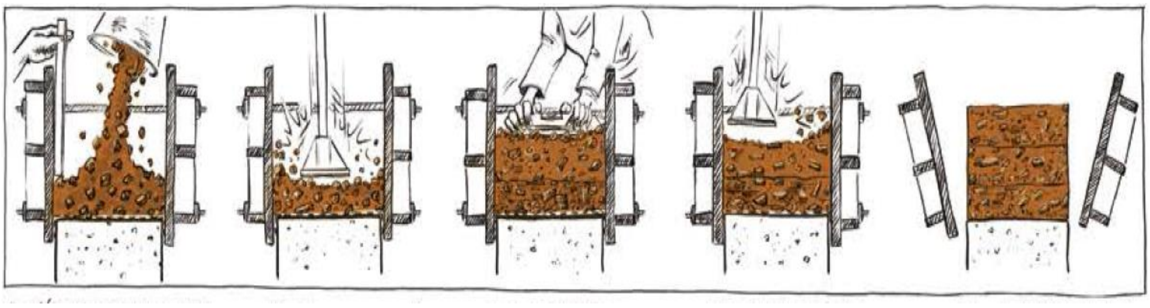

Figure 1 - Rammed Earth Compaction Process (Illustration by - Pauline Sémon, TERRA Award)

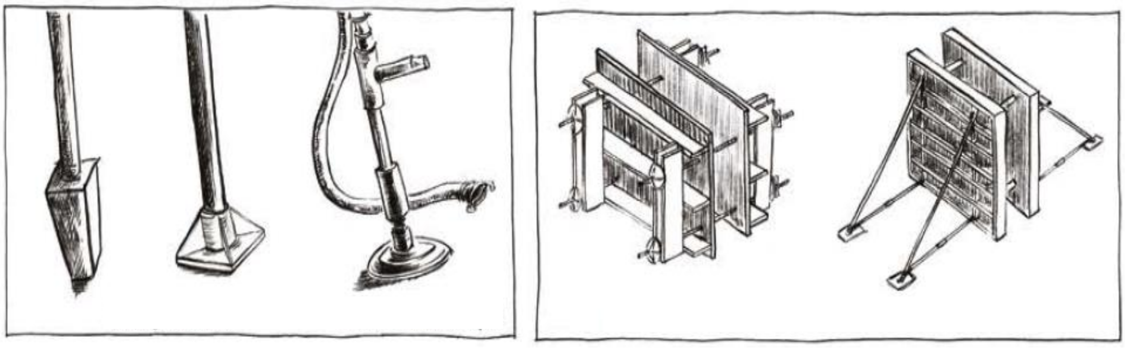

Figure 2 – Left: Tampers Used in Rammed Earth, Right: Forms Used in Rammed Earth (Illustration by - Pauline Sémon, TERRA Award)

A. Background

In order to build strong and stable walls, granular soil with specific characteristics must be used. The process relies on the presence and harmony of the four main components of soil: gravel, sand, silt and clay, but most importantly on sand and clay (Minke, 2013). Clay plays the role of mortar in the soil matrix and depending on its plasticity and concentration in the soil, dictates the amount of sand required. The balance between clay and sand is of utmost importance to maintain due to the plastic property of clay. In other words, although clay is responsible for providing rammed earth with most of its strength, it expands and contracts with the addition and evaporation of water. These volume changes produce cracks within the structure of rammed earth that drastically weaken it. As such, a certain range of clay content must be maintained in the rammed earth mix in order to provide the material with the necessary strength without compromising its integrity.

Since soil is not a manufactured material, its content and characteristics change depending on where it is sourced (Rauch et al., 2013).

Burroughs (2008) details the multiple criteria considered for the appropriate selection of a mix and focuses on a compressive strength of 2 MPa or higher as a good indicator of overall mix performance.

By compiling a large number of previous studies conducted on this topic, Burroughs identified a convergence on several key parameters indicative of suitable strength results, detailed in ***Table 1***:

Table 1 - Key Parameters for Appropriate Rammed Earth Mix (Burroughs 2008)

Indicator	Value
Clay	5-25%
Clay/Silt	30-35%
Plasticity Index (PI)	<15
Linear Shrinkage (LS)	<6

As such, it is advisable to use loam with a clay content less than 25% by weight and a plasticity value below 15. If a certain soil presents parameters that are much higher than the ones recommended, mixing it with sand or a different low clay soil will help lower the clay content and plasticity of the resulting mix. Additionally, compressive strength tests must be conducted on any trial mix to make sure it achieves the required performance.

To have a better idea of the different soils available, samples from different locations in different areas were acquired and tested in the lab for their composition and plasticity. Results obtained are shown in ***Table 2***:

Table 2 - Soil Samples Composition

Location	% by Mass				Plasticity Index
	Gravel	Sand	Silt	Clay	
Kfardebian #1	20	15.5	27.1	37.4	18.2
Kfardebian #2	2.5	81.4	8	8.1	Non Plastic
Klayaat #1	29.3	12.4	14.3	44.1	28.3
Klayaat #2	46.5	9.6	7.9	36	19.7
Klayaat #3	29.3	45.6	10.5	14.6	Non Plastic
Thoum #1	6.3	4.5	17.4	71.8	N/A
Thoum #2	9.3	10	28.7	52	24.5
Thoum #3	42.3	19.5	10.9	27.3	18.9

The rammed earth compaction process relies on the presence of moisture in the soil mix. An optimum moisture content will provide lubrication for the soil particles for more effective compaction, without taking excessive space within the compacted soil matrix. Excess water creates voids and reduces the overall density when the moisture evaporates. As such, the water content of the mix during compaction is critical for the end product’s structural performance and must be determined beforehand with the Standard Proctor Test.

Detailed in ASTM D698 (2012), the Standard Proctor Test (SPT) determines the optimum moisture content of a certain soil from the compaction of at least three samples with increasing moisture content. Since the highest density is achieved at optimum moisture, values above and below the optimum will result in samples with lower density. By plotting the densities achieved against their respective moisture content and drawing a best fit line, the optimum content is simply the maximum of the curve obtained as per ***Figure 3*** below.

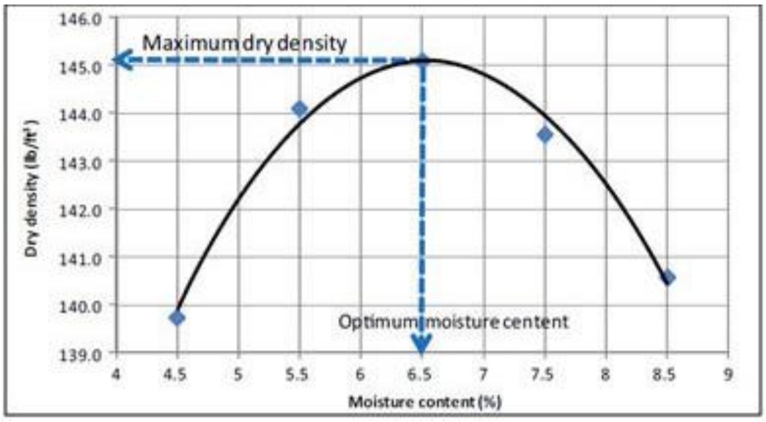

Figure 3 - Finding the Optimum Moisture Content Using the Standard Proctor Test (https://civilseek.com/modified-proctor-test/)

Once compacted, rammed earth structures provide a multitude of benefits for their occupants and the environment. Their environmental impact is much smaller than other construction methods since they are made from a natural and abundantly available resource. The extraction and use of soil, considered a waste product on construction sites, reduces the demand of manufactured materials, such as steel and cement, and over-exploited natural materials such as rock and sand.

On one hand, sand is the most exploited resource worldwide after water, it is estimated that 50 billion tons are mined each year. Additionally, desert sand is unusable in construction due to its smooth edges eroded by the wind, meaning that the sand needed is sourced mostly from rivers, lakes and beaches. The intense demand has seen these sources ravaged, making sand mining far from sustainable and very straining, especially since sand is a non-renewable resource (Beiser, 2018).

On the other hand, quarrying activities in the Mediterranean region are putting pressure on limited resources of soil and water, altering natural ecosystems, hydrological and hydro- geological processes. Additionally, the large majority of quarries excavated in Lebanon are not rehabilitated meaning their ecosystems are unlikely to recover and more likely to accentuate land degradation and desertification (Darwish et al., 2010).

The carbon footprint of a rammed earth building is also very small over its lifecycle, in fact, the preparation, transportation and handling of loam on site demands about 1% of the energy needed for similar procedures with reinforced concrete (Minke, 2013). Additionally, the material itself being natural and unprocessed means it is completely recyclable and can be disposed of or reused with no concern for environmental harm.

Indoors, rammed earth buildings reduce temperature fluctuations due to their thick walls. Thermal mass allows the walls to act as a heat store, absorbing the sun's energy during the day and releasing it during the night, effectively reducing the extent of temperature fluctuations between day and night and reducing the need for artificial heating and cooling. Stone et al. compiled a large number of sources and created a compacted set of thermal properties for a 30 cm thick rammed earth wall, shown in ***Table 3*** below:

Table 3 - Thermal Properties of a 30 cm Thick Rammed Earth Wall (Stone, Katunský and Bagoňa, 2013)

Property	Value
Thickness (cm)	30
Thermal Resistance R (K/W)	0.025
Overall Heat Transfer Coefficient U (W/m^2K)	40
Thermal Storage (KJ/m^3K)	1830

Moreover, soil being a granular material means it can absorb water into its pores when humidity levels are high and release it when levels are low. Studies have shown that rammed earth walls are effective in keeping indoor humidity levels well within the World Health Organization's range for indoor humidity levels (Minke, 2013), depending on the ambient environment.

With regards to fire resistance, loam is a non-combustible material, even with the presence of organic content, it does not degrade or lose strength when exposed to prolonged fire and heat (Ciancio and Beckett, 2015).

From a socio-economic point of view, rammed earth construction provides great communal benefits. The difference in the requirements of rammed earth, means that the economics of the project vary greatly. When using industrial materials, a large part of the cost is usually spent on material procurement, but when using earth, it is mostly spent on workmanship, since the process is labor intensive and soil is freely available. This entails a transfer of cash flow from multi-million-dollar industries into the worker class, providing it with more empowerment and consequently increasing the activity of local economies.

B. Research Significance

As climate change's impact is becoming increasingly visible, public and private initiatives are undertaken around the world in order to find short and long-term solutions for this crisis. Two approaches are discussed to fight climate change (Climate Change: Vital Signs of the Planet, 2020):

1. Mitigation: Reducing emissions of greenhouse gases
2. Adaptation: Adapting to climate change that has already begun

The modern construction industry relies heavily on energy intensive processes for the manufacture of construction materials and goods, to the point where it has become the third largest producer of anthropogenic carbon dioxide (Andrew, 2017). As such, the introduction of rammed earth into the East Mediterranean region's construction market for buildings with low structural demand will help reduce the large environmental costs of construction and mitigate climate change.

The reduction is worthwhile due to the relatively insignificant energy requirements of rammed earth construction, its very low carbon footprint throughout its lifecycle and its complete recyclability, making rammed earth buildings sustainable from cradle to cradle. In other words, rammed earth would help alleviate the atmosphere of unnecessary emissions by replacing manufactured materials.

The impact of this introduction also extends into the human component in two ways: health and social justice. Firstly, due to their natural ability to regulate temperature and humidity indoors, rammed earth buildings are some of the healthiest buildings to live in. Secondly, the relative simplicity with which this technique is applied makes it easy for people to learn and adapt it to their needs. This in turn makes construction more accessible and better tailored to people who are less well-off and can thus serve them to make strong and reliable shelters without the need for large investments of time and money.

C. Research Objectives

Many books and studies are written on rammed earth construction; however, they do not allow for the process to be simply applied to the context of Lebanon due to the novel nature of the material.

The process is made more difficult given the high variability at play when using soil as a construction material. Soil can contain varying amounts of different components with different properties, meaning that every mix is different and cannot be taken for granted. As such, the first objective of this research is to determine the characteristics of the soil brought in from the Advancing Research and Enabling Communities (AREC) facility of the American University of Beirut (AUB) and assess its use as rammed earth construction material.

Secondly, when building with rammed earth, experience plays an important role. In fact, multiple steps like the ball drop test or the sound that signals the completion of a layer's compaction, rely on the experience of rammers to be properly judged. As such the second objective of this research is to develop the necessary experience in rammed earth construction that will allow for future more complex works to be done. Proper construction practices will relieve future efforts from the hassle of learning a new construction method and allow them to focus on their intended work more quickly and effectively. The experience collected will include mix design, structural behavior of rammed earth cylinders, formwork design and assembly, ramming procedure and quality control.

The third objective is to measure the thermal and humidity fluctuations of the walls relative to the environment they are placed in. These measurements indicate the different ways rammed earth walls react to external changes in temperature and humidity, and help improve the overall design process of rammed earth buildings, by profiting as much as possible from their properties.

D. Thesis Organization

This thesis is made up of four chapters in total, the first one being this introduction chapter that covers the background information on rammed earth as well as the research’s significance and objectives. The second chapter presents the methodology used to develop the research and includes all steps conducted for testing and construction. The third chapter details the findings of all aspects of the research. Chapter IV, finally, summarizes and concludes the thesis and lists a set of proposed recommendation for future works.

CHAPTER II

METHODOLOGY

To complete the objectives, two sets of six walls were built in different locations. The first, AREC-AUB. The second set, on AUB's main campus behind the Raymond Ghosn Building (RGB), in Beirut near the coast.

A. Choice of Location

The two locations were chosen due to their different climatic conditions and accessibility. The Beqaa region is known to be characterized by an arid climate and moderate rain with occasional freezing temperatures during winter, while the Beirut coastal area is characterized by a hot and humid climate during summer, and humid and rainy climate during winter. The different climatic conditions would help better understand how rammed earth behaves relative to its environment.

B. Soil Selection

To properly conduct the necessary tests and comparisons, all the walls had to be built using the same soil. The soil chosen was from AREC, due to its abundance and open access. It was sieved on site using a large 5 cm sieve, shown in ***Figure 4***, in order to remove large stone fragments. The sieved soil was put into small bags and transported from AREC to AUB.

Figure 4 - Five-centimeter Sieve, On-site at AREC

C. Soil and Mix Selection

A soil sample was taken to classify the soil using sieve (ASTM C136, 2019), hydrometer (ASTM D7928 – 17, 2017) and Atterberg limits (ASTM D4318, 2017) tests before construction began. The results found led to the selection of the following six mixes:

Table 4 - Composition of Sample Mixes

Wall	Composition
1	Soil Only
2	75% Soil + 25% Sand
3	75% Soil + 25% Sand + 1% Cement + 1% Lime
4	75% Soil + 25% Sand + 5% Cement
5	75% Soil + 25% Sand + 5% Lime
6	75% Soil + 25% Sand + 4% Cement + 4% Lime

The results found and the mix selection process are further discussed in chapter III section A.1.

The base mix used for the project was 75% soil and 25% sand. One mix used soil alone in order to evaluate the impact sand had on the mix. The other four mixes add varying percentages of two additives: cement and lime. These additives were chosen due to their availability and relatively low cost.

Cement is a globally known and used manufactured mortar that relies on a hydration reaction, creating a strong cementitious bond (ACI Concrete Terminology, 2013). Lime, also known as hydrated lime, is also used as mortar in construction and develops its bonding strength from a hydration reaction. The cementitious bond of lime is much weaker than that of Portland cement. However, its manufacturing process produces less CO_2, making it a more environmentally friendly alternative, when the higher strength of cement is not needed (Anon, 2020).

The tests conducted on the selected sample mixes were limited to compression strength for its role as a good indicator of the performance of the mix overall (Burroughs, 2008). The test was done according to ASTM C39 (2018) using an automated hydraulic press shown in the figure below. The hydraulic press, shown in ***Figure 5***, also provided the stress-strain curves of the tested samples, allowing for a graphical assessment of the structural behavior of the cylinders under compression, presented in chapter III section A.1.

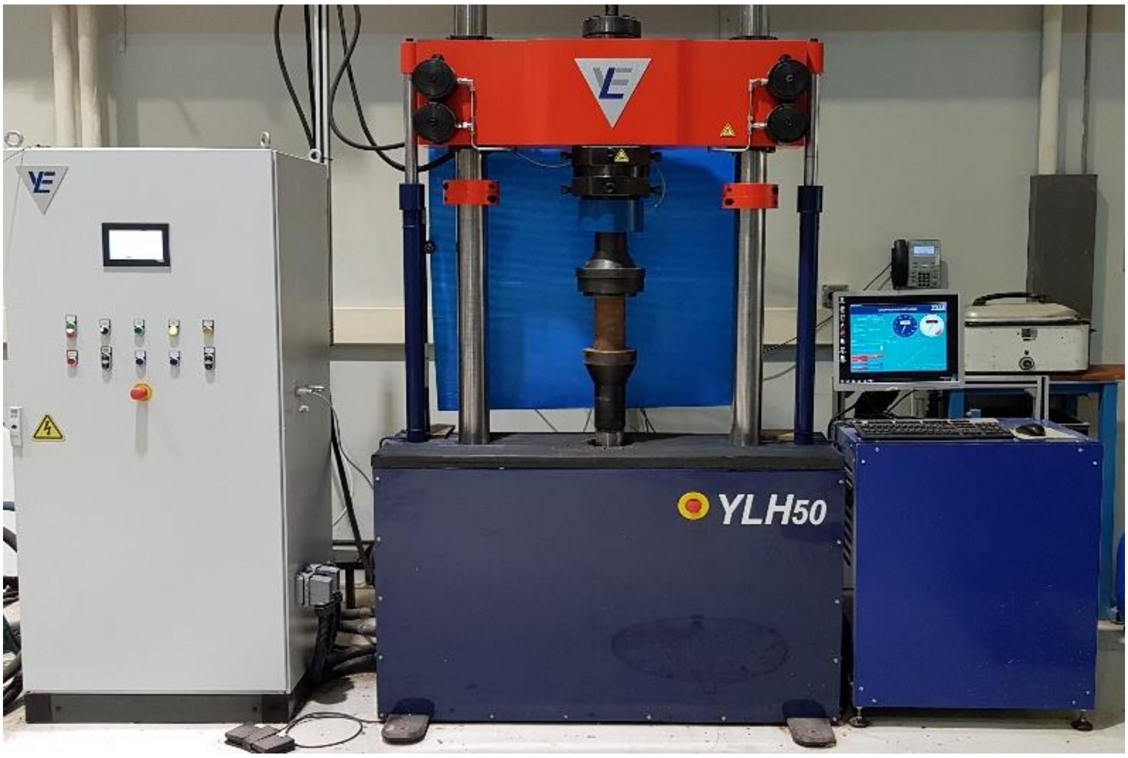

Figure 5 - Hydraulic Press Apparatus

D. Construction Process

The six walls were all of the same dimensions: 2x1x0.4 meters for height, width and thickness respectively. The walls were constructed following the same procedure at AREC and AUB, on a 0.2x1x0.4 meters reinforced concrete footing, shown in ***Figure 6***, to limit the risks associated with settlement that might lead to wall cracking. The concrete slabs had four, one-meter long starter bars coming out of them to make sure there was a good connection between the concrete footing and the wall on it. With the footings ready, construction began by the assembly of the lateral and first set of formwork panels, as shown in ***Figure 7***.

Figure 6 – 0.2x1x0.4 meter Reinforced Concrete Footings with Four Starter Bars

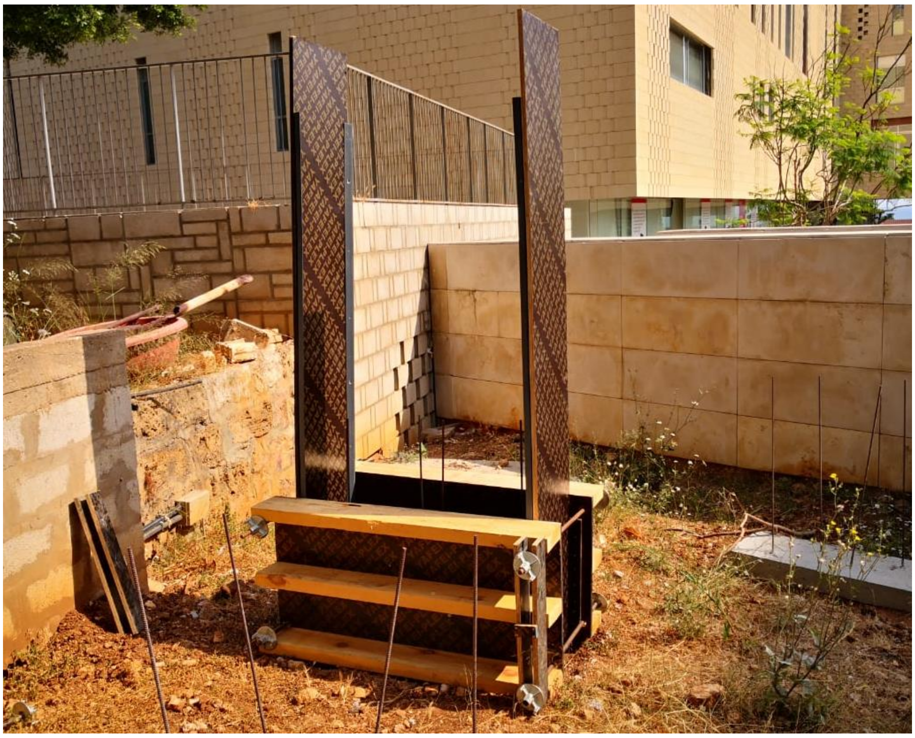

Figure 7 –Lateral and First Set of Formwork Panels Assembly

Once the formwork is ready, the soil mixing process shown in ***Figure 8*** begins. The required quantities of the different components are measured and placed on the ground for dry mixing. When the mix becomes homogenous, it is spread out and water is sprayed evenly over it while mixing begins again. The ball drop test, further discussed in chapter III section D.1., is conducted to assess the dosage of water. When the moisture content is suitable, the soil is transferred into the forms.

Figure 8 - Mixing Process

The required amount of soil is placed in the mold, as shown in ***Figure 9***, spread by hand and the compaction process begins. For the process to go smoothly and effectively, it was divided into three steps. It starts with manual foot compaction, also shown in ***Figure 9***; this step saves time by having someone walk over the loose layer of earth and effectively packing it. This means that a significant portion of the required compaction is made with relatively low effort, reducing the remaining compaction effort.

Figure 9 - Left: Soil Placing, Right: Manual Foot Compaction

The second stage is done using the manual tamper, as shown in ***Figure 10***. With the soil packed with the foot, manual compaction using the steel tamper will be easier and less time consuming. Skilled ramming using the manual tamper is the most reliable way to build good quality walls. Special attention must be given to the corners and edges of the wall to minimize honeycombing on the surface of the walls. Compaction is complete when the sound of the tamper hitting the soil changes from a deep thud to a high pitch ding, signaling the increased hardness of the material. It is important to note that the soil should not be sticking to the tamper, otherwise the clumps should be removed from the tamper and the water content must be reduced.

Figure 10 - Left: Manual Steel Tamper, Right: Manual Ramming

The third and final stage of compaction is done with two passes with the pneumatic tamper shown in ***Figure 11***. The choice of air compressor for the job is important. If the compressor is too weak or its volume capacity too small, the low air pressure will not be enough for the pneumatic tamper to work properly, thereby causing major delays in construction. Since there was no access to a strong enough air compressor for the job, two small electric compressors were used in alternance.

Once the layer is complete, the wall is ready for the next batch of soil and the process is repeated.

Figure 11 – Left: Pneumatic Tamper Used, Middle: Air Compressor Setup, Right: Ramming Using Pneumatic Tamper

The compaction process is repeated until the wall reaches a level around 15 cm below the end of the formwork panel, the second set of formwork is then assembled on top of the one present, as shown in ***Figure 12***. Details concerning formwork design and assembly are further discussed in chapter III section C.

Figure 12 - Formwork Setup

When the intended wall height is reached, the formwork is disassembled immediately and the wall exposed as shown in ***Figure 13***. The six walls at AUB and the seven walls at AREC are shown after construction in ***Figure 14*** and ***15*** respectively.

Figure 13 - Freshly Completed Rammed Earth Wall

Figure 14 - Six Rammed Earth Walls Constructed at AUB

Figure 15 - Seven Rammed Earth Walls Constructed at AREC

E. Temperature and Humidity Measurements

To better understand the heat transfer process, a sample bloc of dimensions 30x30x3 cm, shown in ***Figure 16***, was built using the soil-sand mix.

Figure 16 - Sample Preparation

The thermal properties of the material were measured using the guarded comparative longitudinal heat flow technique detailed in ASTM E1225 – 13 (2013), using the apparatus shown in ***Figure 17***. It must be noted that the heat flow used in the test was perpendicular to the direction of ramming.

Figure 17- Thermal Conductivity Measurement Apparatus

On site, the moisture and temperature content of the walls were measured using the logger and sensor shown in ***Figure 18***.

Figure 18- Left: TEROS 12 Soil humidity and Temperature Sensor. Right: ZL6 Advanced Cloud Data Logger (METER, 2020)

The devices were chosen for their relatively low price and ease of use. Each logger can take in data from a maximum of six sensors placed in the middle of each wall. Due to logistical delays in procurement, a large part of the sensors that were supposed to be installed during construction, shown in ***Figure 20***, were installed after the walls were completed. The procedure undertaken to install the sensors after construction, shown in ***Figure 19***, was by drilling holes into the middle of the walls, inserting the sensors into the earth and filling the hole back up in layers of loose soil placed by hand and sequentially compacted using the handle of a hammer.

Figure 19- Inserting Sensors After Construction

Figure 20 - Placing Sensors During Construction

The temperature and moisture measurements were taken to determine the mix's effect on the wall's humidity absorption and diffusion capacity, as well as the effect of the climate and sun exposure on the temperature within the walls.

After gathering the temperature data, two parameters used to evaluate the thermal performance of walls were calculated. The first is the heat flux time lag (φ_q), representing the time it takes for a temperature increase to travel through the wall. The second is the decrement factor (f_q), representing the decreasing temperature amplitude ratio between the indoor and outdoor temperatures. A wall with high time lag and a low decrement factor provides lower indoor temperature disturbance and higher thermal comfort for the occupants. (Jin et al., 2012). These parameters are defined by the following equations and ***Figure 21***.

$$\varphi_q = \tau_{qi,max} - \tau_{qe,max}$$

$$f_q = \frac{q_{i,max} - q_{i,min}}{q_{e,max} - q_{e,min}}$$

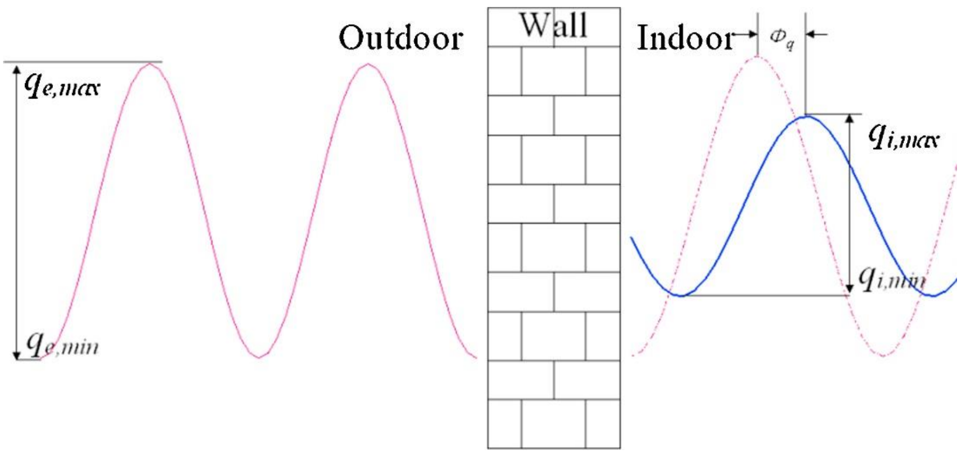

Figure 21 - Decrement Factor and Heat Flux Time Lag Representation (Jin et al., 2012)

F. Quality Control

Construction quality was studied by monitoring workmanship and determining productivity and quality of work. The time needed to finish a layer of rammed earth was the primary indicator for productivity. It was measured from the moment the previous layer was completed until compaction stops and included the time needed for pouring and spreading the soil within the form.

The height of the compacted layers indicated the quality with which the walls were rammed by following the process detailed below.

The amount of soil poured per layer was fixed to three buckets that provided a loose layer thickness of around 15 to 20 cm. A thicker loose layer will be significantly harder to compact and using two buckets instead of three will lower productivity.

By measuring the bucket's volume and its weight when filled with soil, the density of the soil placed were determined as follows:

$$Density_{Loose} = \frac{Mass}{Volume_{Loose}}$$

And by measuring the height of the compacted layers at different locations and averaging it, the volume of the layer, which is also the volume of the compacted soil, is found:

$$Volume_{Compacted} = Average\ height\ of\ layer\ \times 0.4\ m\ \times 1\ m$$

The compacted density of the layer was then calculated:

$$Density_{Compacted} = \frac{Mass}{Volume_{Compacted}}$$

The calculated densities of the different layers were compared to the densities achieved by the sample cylinders made for compressive strength testing.

CHAPTER III

FINDINGS AND RESULTS

A. Rammed Earth Mix

Before work began, the soil acquired from AREC needed to be assessed in order to determine the relevant parameters discussed by Burroughs, which indicated the effectiveness of the soil as rammed earth material. Sieve and hydrometer analysis as well as the Atterberg limit test were conducted and their results are shown in ***Table 5*** and ***Figure 22***.

Table 5 - AREC Soil Composition

Constituents	Percent by Weight
Gravel	23.4
Sand	13.7
Silt	35.6
Clay	27.4
Total	100

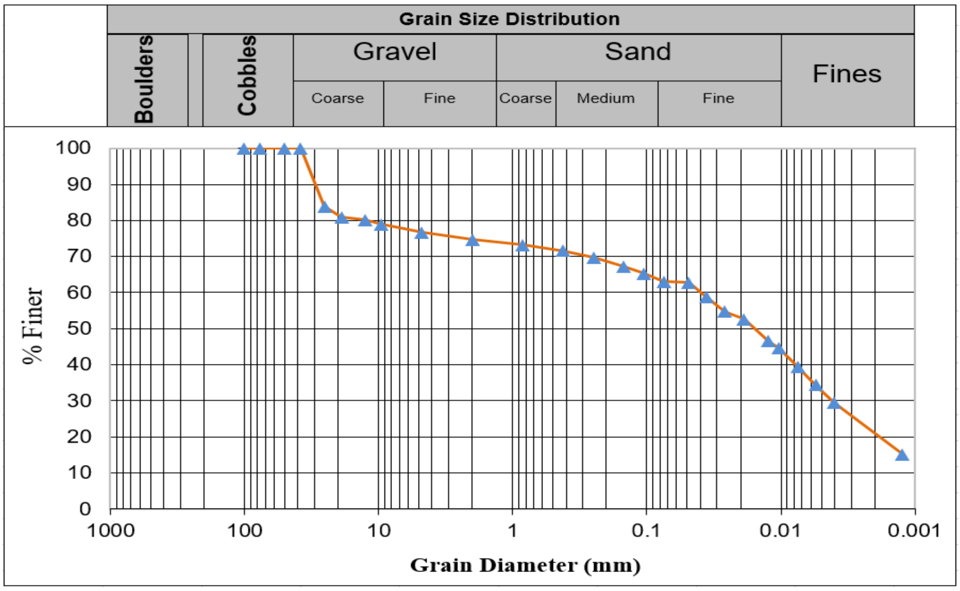

Figure 22 - Grain Size Distribution Graph of AREC's Soil

The sieve and hydrometer analysis determined that the clay content is above Burroughs' recommended maximum of 25% and the combined clay and silt content of 63% is much higher than the recommended maximum of 35%. The Atterberg limit test determined that the clay's plasticity index is 9.1, an acceptable but relatively high number considering the high clay content. Together these values clearly indicate a need to reduce clay content in the final mix in order to avoid cracking when the mix loses moisture. The addition of sand to the mix was proposed to mitigate the problem.

The volumetric approximation of three parts soil and one part sand was used for its practicality on site and the resulting mix constituents are shown in ***Table 6***:

Table 6 - Mix Composition of Soil with Added Sand

Constituents	Percent by Weight
Gravel	17.5
Sand	35.3
Silt	26.7
Clay	20.6
Total	**100.0**

The resulting mix contains 20.6% clay, placing it within the recommendations of Burroughs, but the combined clay/silt content remains high. However, considering the acceptable plasticity of the clay, the availability of the soil and not wanting to rely on adding more sand, compressive strength tests were conducted on the resulting mix.

The tests conducted gave positive results that will be discussed in details in chapter III section B.2.

B. Behavior Under Compressive Loads

1. Sampling and Compaction Method of Rammed Earth Cylinders

In order to assess the structural performance of a proposed rammed earth mix, compressive strength testing must be conducted on sample cylinders at the preliminary stages of design.

The testing procedure is the same as the one used for testing concrete cylinders, but with major variation in sample preparation. The compressive strength test was conducted on the hydraulic press machine according to ASTM C39. Rammed earth cylinders are rammed into the forms and can be tested in a relatively short amount of time (enough for the mix's humidity to normalize). The compaction method used to make the cylinders was investigated for potential impact on cylinder strength.

A common procedure used to compact soil into cylinders is the Standard Proctor Test. However, it was not certain that the Standard Proctor Compaction Machine could reach the same efficiency of compaction achieved on site using the pneumatic tamper. Therefore, a comparison of cylinders compacted in 10 cm loose layers was conducted, first using the Standard Proctor Compaction Machine, with a set number of blows, and second using the same pneumatic tamper used for the construction of the walls, by applying 5 to 10 seconds of compaction per layer.

On one hand, three samples were compacted by the tamper and tested. On the other hand, after compacting the first cylinder with 30 blows per layer, as per the regular machine settings, the density of the sample made was too low, it was decided to check whether any improvement could be made by increasing the number of blows to 40 and 50 blows per layer respectively.

Results obtained from the compressive strength tests and measurements of density were compared and are shown in ***Table 7***.

Table 7 - Compressive Strength and Sample Density Relative to Compaction Method

Compaction Method	**Pneumatic Tamper**			**Proctor Machine**		
Sample	**S1**	**S2**	**S3**	**S4-30b**	**S5-40b**	**S6-50b**
W% at preparation	11.03	11	10.74	11	8.53	9.75
W% at testing	4.87	4.46	4.13	4.2	2.08	3.3
Density at preparation (kg/m^3)	1925	1995	2048	1733	1739	1779
Average Density (kg/m^3)		1990		1733	1739	1779
Density at testing (kg/m^3)	1806	1864	1913	1611	1627	1664
F'c(Mpa)	1.15	1.68	1.63	0.45	0.48	0.6
Average F'c		**1.49**		**0.45**	**0.48**	**0.60**

Results from the tests show a significant variation in strength and density when comparing both methods. In fact, using the tamper provided an increase of 148% in compressive strength and 12% in density compared to the Proctor machine with 50 blows per layer.

Furthermore, the stress-strain behavior of the cylinders was recorded by the hydraulic press apparatus and is shown in ***Figure 23***.

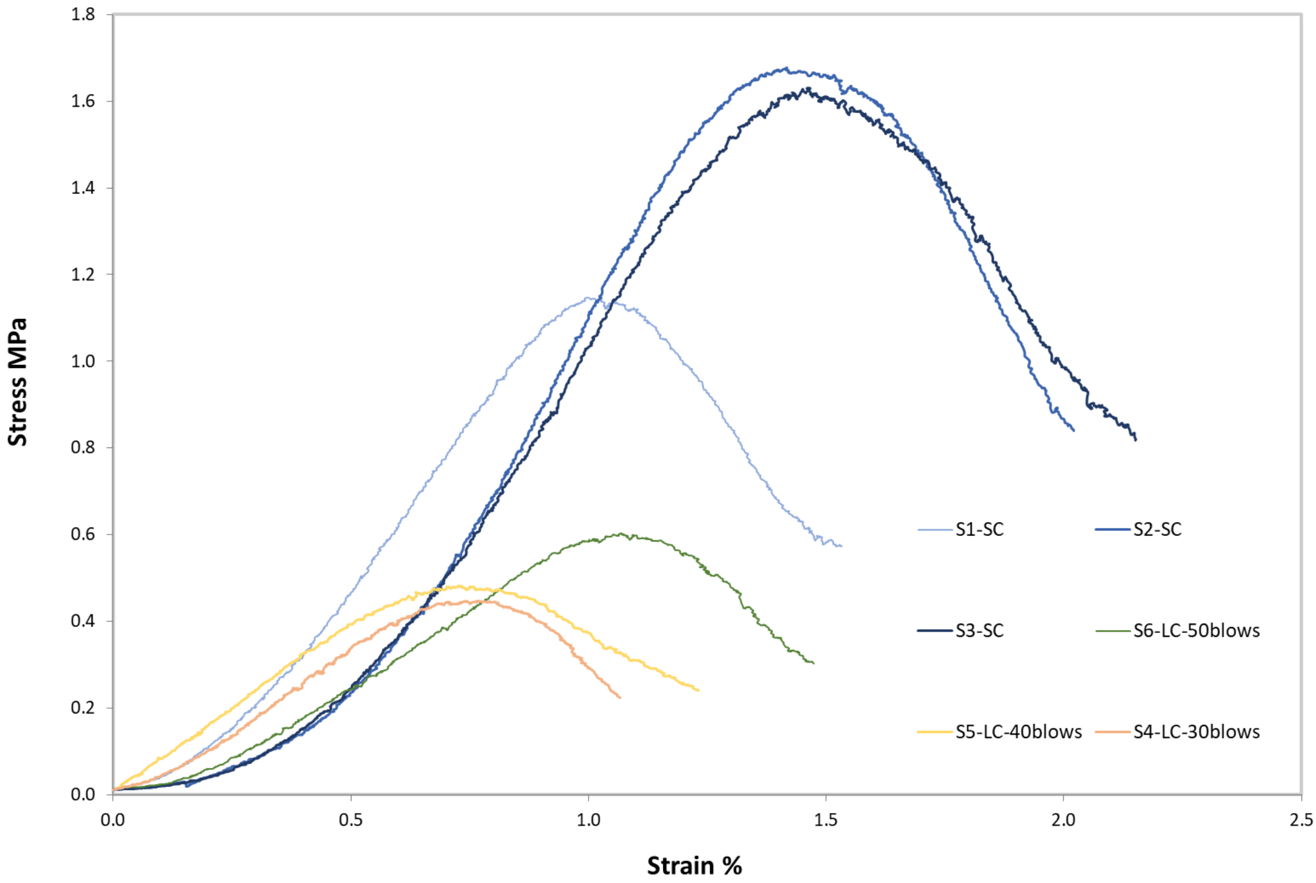

Figure 23 - Stress-Strain Behavior of Earth Cylinders Made Using Proctor Machine with varying blows vs. Pneumatic Tamper

The stress-strain curves clearly show the difference in strength but do not show signs of other major differences. In other words, the stress-strain curves of the rammed earth cylinders keep the same profile regardless of the compaction method, meaning the compaction method does not affect the way the cylinders fail but the load at which the cylinders fail and highlights the relationship between density and strength.

Additionally, the cracking patterns seen on the rammed earth cylinders, shown in ***Figure 24***, further emphasize the similar behavior of all samples that can be characterized as brittle.

Figure 24 - Brittle Failure Cracking Pattern on Rammed Earth Compressive Strength Test Cylinders

These findings indicate that current sampling methods available in the lab do not properly reproduce the construction process of rammed earth and thus do not provide reliable results with regards to compressive strength testing. A good alternative would be preparing the test cylinders with the same tools that will be used for construction. As such, future samples will not be made the Proctor Machine but using the pneumatic tamper, in order to replicate as much as possible the conditions in the field and provide viable results.

2. Effect of Mix Components and Additives on Strength

Since earth is a highly varying material, it is not always suitable for rammed earth construction. It could contain too much or too little clay and the clay might be too plastic or not plastic enough. Depending on the problem at hand, sand, or soil with different components and properties can be mixed together with the initial soil. Additives such as cement or lime can also be added to boost the properties of any mix.

As such it was important to understand how rammed earth's structural behavior changed when the soil properties changes and how additives such as cement and lime increased the strength of the material. Mr. Mostafa Mohamad, a fellow graduate student collaborating on the same research, was further co-investigating different material properties and their effect on the performance of a soil mix. several compressive strength tests were conducted on the six soil mixes discussed. The results obtained are tabulated in **Table *1Table 8***.

Table 8 - Compressive Strength Results for the Different Mixes

Mix	**Pure Soil**			**Soil +Sand**														
				Soil +Sand			**1%Lime+1%Cement**			**4%Lime+4%Cement**			**5%Lime**			**5%Cement**		
Sample	**S1**	**S2**	**S3**	**S10**	**S11**	**S12**	**S19**	**S20**	**S21**	**S16**	**S17**	**S18**	**S7**	**S8**	**S9**	**S13**	**S14**	**S15**
W% at preparation	11	11	10.7	9.1	9.2	9.5	9.5	11.8	11.9	9	9.2	8.9	12.2	10.4	12.4	9.5	7.6	8.7
W% at testing	4.87	4.46	4.13	2.27	2.84	3.49	2.29	3.49	3.43	2.64	4.27	3.65	3.99	2.22	3.54	3.79	2.27	3.33
Density at preparation (kg/m^3)	1925	1995	2049	2058	2082	2083	2114	2108	2092	2047	2000	2014	2111	2114	2115	2048	2020	2017
Density at testing (kg/m^3)	1807	1864	1914	1916	1951	1958	1963	1932	1914	1916	1903	1907	1938	1940	1928	1932	1912	1908
F'_c(Mpa)	1.15	1.68	1.63	1.96	1.84	2.03	2.07	1.73	1.39	3.42	2.39	2.27	1.28	1.29	1.06	1.93	2.21	1.64
Max F'_c	**1.68**			**2.03**			**2.07**			**3.42**			**1.29**			**2.21**		
Average F'_c	**1.49**			**1.94**			**1.73**			**2.69**			**1.21**			**1.93**		

Comparing test results in this case was not straightforward, some mixes had the results of their samples spread out significantly more than others. This can indicate the requirement of a larger sample pool or errors in the samples' preparation. To circumvent this issue, the maximum strength developed by any one of the three samples tested was also looked at. The data is summarized in ***Table 9***.

Table 9 - Compressive Strength Data Summary

Mix	Pure Soil	Soil +Sand				
		Soil + Sand	1% Lime + 1% Cement	4% Lime + 4% Cement	5% Lime	5% Cement
Max F'_c	1.68	2.03	2.07	3.42	1.29	2.21
Average F'_c	1.49	1.94	1.73	2.69	1.21	1.93

Firstly, and most importantly, is the noticeable effect of adding sand to the mix, which increased compressive strength by 30% in terms of average f'_c and confirms the positive effect of reducing a mix's plasticity and clay content to more acceptable norms. These findings align with the work of Burroughs, and are the result of reducing shrinkage cracks developed when a mix containing a large amount of clay dries and shrinks. Sand solves this problem by reducing the mix's clay content and spreading the clay within the soil matrix, allowing it to act as a binder to other soil particles but not concentrated enough to form major cracks.

Secondly, the addition of 4% lime and 4% cement to the soil-sand mix increased its strength by almost 40% compared to the soil-sand mix alone (in terms of average f'_c) and even doubled the strength developed by the original soil only mix, when considering the maximum f'_c.

The three other mixes containing additives could not achieve increased performance with regards to strength. In theory, the addition of additives should enhance the properties of the soil mix, however, it did not do so reliably in this context.

It should be noted that compressive strength decreased, in the case of the mix with 5% lime, even when density increased, meaning that factors other than density were at work and need to be further investigated.

C. Formwork

Formwork is a delicate part of the rammed earth construction process; it provides the walls with the required surface finish and geometry. A careful balance between functionality and weight is crucial for ease of handling and assembly. Weak formwork will result in deformed walls or could fail completely during construction by breaking, requiring repair or replacement for construction to continue. However, if the formwork is strengthened too much, it will become too heavy, reducing productivity and can even become prohibitive in case there is not enough manpower on site.

In essence, formwork for rammed earth is similar to the one used for concrete. They differ however due to the inherent differences between their respective material's construction processes. Rammed earth is placed as a loose and granular material and is compacted inside the formwork to form the wall. Compacting rammed earth places huge, repetitive loads on the formwork that must be accounted for when designing them. This is done by bracing the formwork with lateral elements, spaced at 30 cm from each other, providing good structural integrity to the form and a comfortable footing in case workers use them to climb the wall. By trial and error, and as construction carried on, the design became more and more developed. Formwork drawings were made using AutoCAD and were cut and assembled in AUB's carpentry shops.

Figure 25 below shows the form and its bracing.

Figure 25 - Formwork for Rammed Earth

In early construction trials, the plywood formwork deformed, cracked and burst under the ramming loads, shown in **Figure *26***, and construction had to be stopped until the formwork was repaired or replaced. It must be noted that the formwork broke in stages. At first, loud cracks were heard on site during the break hour after compaction was stopped, this meant that the walls accumulated pressure during construction and were still actively pressing against the formwork even when compaction had stopped. The broken bracing beams were made of 15 cm wide plywood that proved not to be strong enough to withstand the compaction effort for sustained periods of time.

Figure 26 - Cracked Formwork and Deformation (shown in the red ellipse)

To continue construction, an improvised bracing system shown in **Figure *27***, was used and the formwork was replaced for the following wall

Figure 27 - Improvised Formwork Bracing System

As such, the team started bracing the formwork panels with 5x15 cm wooden beams, rather than the initially used plywood beams, also spaced at 30 cm intervals and later on with 20x10 cm beams at the same intervals. Both choices provided sufficient bracing, but the 20x10 cm were much more durable and lasted the whole construction process of the 6 walls, while some of the 15x5 cm beams significantly deteriorated during construction. Additionally, the 15x5 cm beams required a wooden joint under them to lock onto the main panels, as they are not thick enough to allow the placing of more than one row of screws, rendering them weak against out of plane forces such as a worker using them to climb on the wall. However, the 20x10 cm beams could be placed directly onto the panels with two rows of screws, meaning they did not require an extra wooden joint and where sturdy enough to carry the weight of the workers. Both formwork variations are shown in ***Figure 28***.

Figure 28 - Variation in Bracing Elements' Dimensions

Two sets of 60 cm high panels proved to be sufficient for the job since the forms used to cast rammed earth walls were removed when compaction reached 15 cm below the edge of the formwork. This means that after building up the wall two lifts of formwork high (or about 100 to 110 centimeters), the lower set could be removed and reassembled on top of the upper panel, creating a new lift to continue construction. The

60 cm height was chosen due to the consideration of bracing spacing and weight and proved to be adequate in all regards.

The final formwork design plan used is shown in ***Figure 29***.

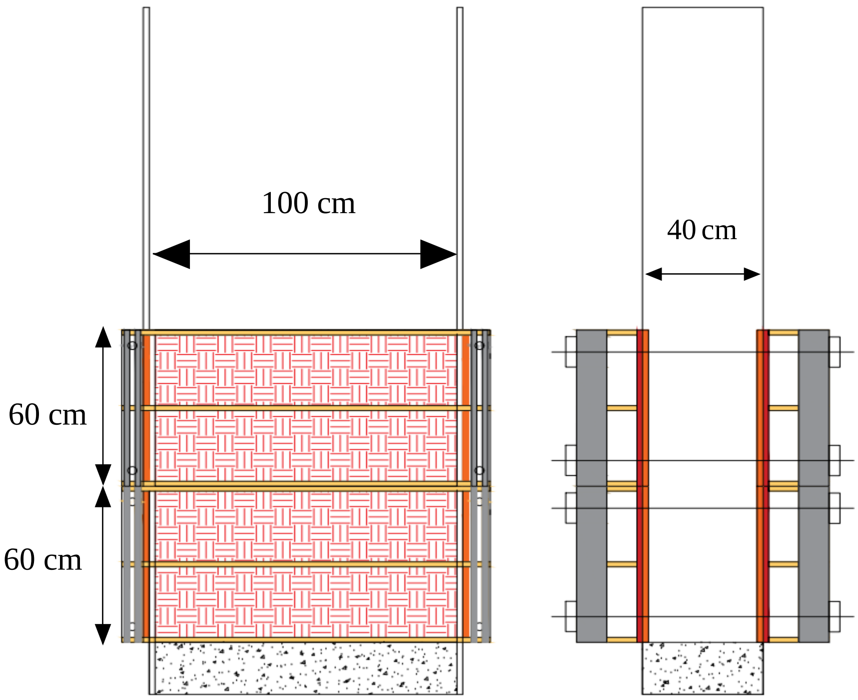

Figure 29 - Formwork Drawings (elevation and section)

The design is based on two fixed longitudinal panels placed on the sides of the wall and two sets of main panels that can be removed and reassembled to continue construction in lifts. The lateral panels carry triangular tubes that chamfer the corners of the walls to 45°, because 90° corners are weak spots on rammed earth structures that can be accidentally chipped off.

The main panels have horizontal bracing beams screwed into them and the bracing beams are themselves braced with two vertical beams on each side. The tie rods press against the vertical beam at the corner of the formwork panel encasing the whole wall.

D. Quality Control

1. Water Content

To achieve the optimum soil density when compacting, the mix needs to be at the optimum moisture content. The optimum moisture content is determined in the lab by the standard proctor test procedure. The water content of the soil can be measured by acquiring a sample of soil and weighing it before and after drying in an oven. However, since measuring the water content of the soil takes around one day to complete (to allow the sample to dry in the oven) and due to the unavailability of all necessary equipment on construction sites, the ball drop method, shown in the following figure, is commonly used to determine the adequacy of the water content. The test is relatively simple; a handful of the soil mix is packed into a ball with the soil as dry as possible, yet wet enough to be formed into a ball 4 cm in diameter. The formed ball is dropped from a height of 1.5 m onto a hard, flat surface (Minke, 2013) and depending on the soil's water content, the result should look like one of those shown in ***Figure 30***.

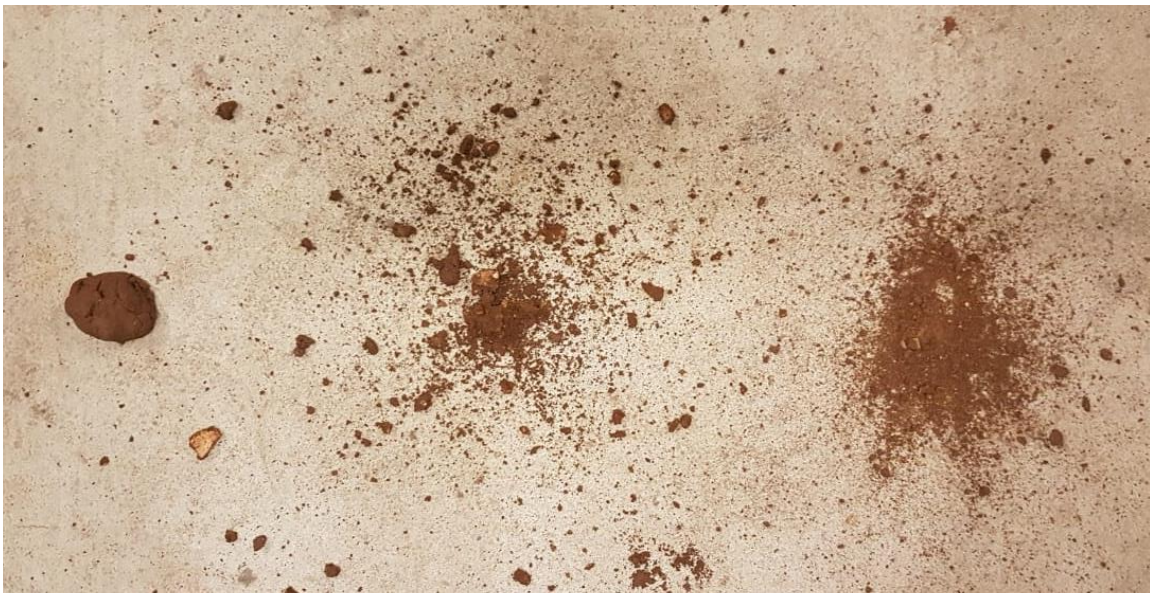

Figure 30 - Ball Drop Test Results with Decreasing Water Content from Left to Right

The ball on the left flattens on impact, but keeps a spherical shape, meaning its water content is too high and the clay in the sample is behaving like mud. A mix with such a water content will be very problematic during construction, it will stick to the tampers making compaction inefficient and the optimum density will not be reached due to the excess water and inadequate compaction. If a mix on site contains this much water, it must be spread to allow for more evaporation or dry soil must be added to reduce its water content.

The ball on the right breaks down and scatters completely, meaning its water content is too low and is not activating the binding force of the clay in the mix. A mix with such a water content is too dry and will not achieve its optimum density and hold itself together when compacted. If a mix on site contains this little water, simply spraying and mixing will solve the problem.

The ball in the middle displays the ideal result, it disintegrates on impact but a small core remains intact, meaning it has enough water content to activate the binding force of the clay in the mix but not enough for it to behave like mud. A mix with this water content on site is ready for compaction and should ideally be covered to avoid loss of moisture due to evaporation.

The ball drop test proves to be effective on construction sites worldwide but is subjective. It relies heavily on the user’s experience to be effective. This means that there is room for errors to occur and consequently a good chance of building lower quality walls.

2. Mixing

Mixing a rammed earth mix is not as straightforward as it might seem and major problems can arise if it is not well mixed. The main problems encountered were due to inappropriate addition of water to the mix or insufficient mixing.

If a large amount of water is added quickly or in a single point when mixing, the result will be the formation of clay pebbles that soak up the water and clump together. These pebbles will be too moist on the outside and too dry on the inside forming weak points in the rammed earth wall and decreasing the efficiency of compaction. Additional mixing will not necessarily solve the problem, as water does not travel easily through clay. As such, it is very important to sprinkle water gradually over the whole mix and continuously mix it to avoid clumping.

Mixing must be done thoroughly and must not stop until the whole mix is homogeneous. Workers must make sure that they are reaching the total volume of the mix, as it was found common that the part closer to the ground was the most likely to remain dry or heterogeneous during mixing.

As such, adopting good mixing practices proved to be the best solution to avoid problems. Good practices include the use of multiple types of tools (shovels, rakes, hoes) and moving the mix around making sure the bottom part of the soil is turned.

3. Worker Efficiency

Workmanship plays an important role in rammed earth construction. Worker productivity and effectiveness directly influence project cost, time and the final product's quality. Properly measuring and monitoring workmanship output will help better control construction quality and further develop construction practices and techniques. An example application of such findings would be figuring out the optimum volume of soil placed into the form per layer. Layer thickness is an important parameter to control due to its direct effect on the finished product's quality. On one hand, a layer too thick will make work go faster with fewer layers per wall, but might jeopardize the density of the layers and in turn the quality of the finished product. On the other hand, a layer too thin will increase the number of layers per wall and make compaction consume too much time, reducing productivity and risking the economic feasibility of the job.

a. Productivity

To measure productivity, the time required to compact one layer of rammed earth was measured. Compaction time starts when the earth buckets are placed and includes spreading the soil inside the form and ends when compaction is complete. Sample measurements of the time spent by unskilled labor were recorded and compared to those of skilled labor and shown in ***Table 10***.

Table 10 - Ramming Time of Skilled vs. Unskilled Labor

Labor	Unskilled	Skilled
Time per Layer (min)	8	7.5
	8.5	7
	12.5	8
	14	7.3
	8.3	7
Average	**10.3**	**7.3**

Inexperienced workers showed around 40 % slower compaction time on average, sometimes amounting to double the time required by an experienced one. This indicates the importance of skill in the construction process. It was noted however that the increased time did not jeopardize layer density as discussed in the following section.

b. <u>Effectiveness</u>

To measure the workers' compaction efficiency, a simple approach was taken. By measuring the weight and volume of the filled buckets used to place the soil, the weight and volume of soil before compaction could be determined.

After compaction, knowing the wall's cross-section, multiple height measurements were taken for each layer in order to find the average compacted layer thickness and determine the walls' density. Sample measurements are presented in ***Table 11***.

Table 11 - Sample Layer Height Measurements

Sample Layer	Thickness (cm)				Average (cm)
1	10	9	8.5	7	8.6
2	9	8	7.5	7	7.9
3	8	8.5	9	7.5	8.3
4	6.5	7.5	7.5	8	7.4
5	8	7.5	7	6.5	7.3
6	6.5	7.5	7.5	6.5	7.0
7	7.5	6.5	6.5	7	6.9
8	8	8	7	7	7.5
9	6.5	8.5	6	6.5	6.9
Average					**7.5**

The task was simplified by using paint spray, shown in ***Figure 31***, to mark every layer after its compaction. This technique facilitated thickness measurements while reducing the risk of errors.

Figure 31 – Paint Marked Layers

The buckets used could hold around 20 to 21 kilograms of soil. The measured layer heights are used to calculate the layer density (method detailed in chapter III section F) that are compared to the developed cylinder density in order to assess the quality of ramming.

The average layer height of 7.5 cm amounts to a density of 2000 Kg/m^3. Based on the sample cylinders made, the density achieved can be considered suitable.

E. Thermal Behavior

Rammed earth walls are characterized by their high thermal mass, meaning they have the ability to even out temperature variations between day and night. They do this by storing the heat provided by the sun during the day and radiating it out during the night (Ciancio and Beckett, 2015).

In order to measure the temperature fluctuations within the walls as a function of ambient external conditions, a sample of the material was tested for its thermal conductivity to be properly characterized.

The results of the test are presented in ***Table 12***.

Table 12 - Thermal Properties of the Rammed Earth Sample

Property	Value
Thickness (mm)	30
Density (kg/m^3)	2222.22
Thermal Resistance R (m.K/W)	0.025
Thermal Conductivity K (W/m.K)	1.663

These values are similar to the ones typically associated with rammed earth as found by Stone et al. (2013) and are shown in comparison to other construction materials in ***Figure 32***.

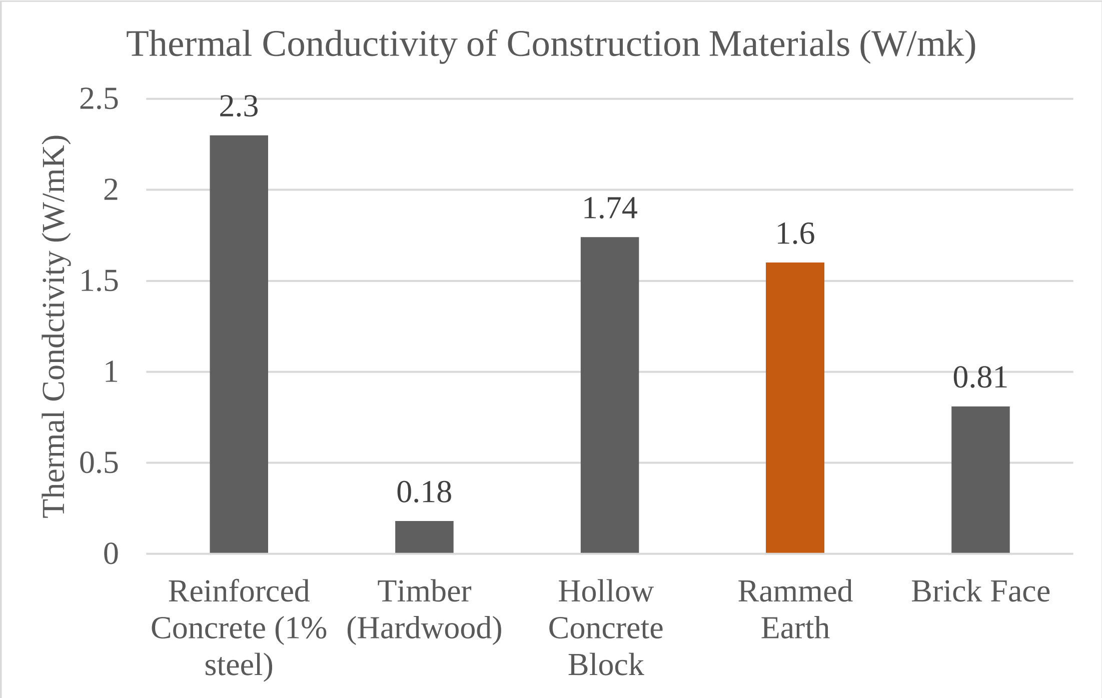

Figure 32 - Thermal Conductivity of Common Construction Materials (Mishra., 2017)

The temperature and humidity sensors were setup to gather data hourly over several months inside the walls, at both locations, AREC and AUB. All the walls are exposed from both sides, with the sensors positioned in their middle. This means that temperature and humidity are measured within the walls rather than at their surface and that the data gathered does not reflect the behavior of the walls in a regular building setting, but rather the effect of the of the climate on the temperature and humidity fluctuations.

Several technical issues and delays, including the disappearance of the logger at AREC, resulted in three months of usable data from the walls at AUB only. The data collected is presented in ***Figure 33, 34 and 35.***

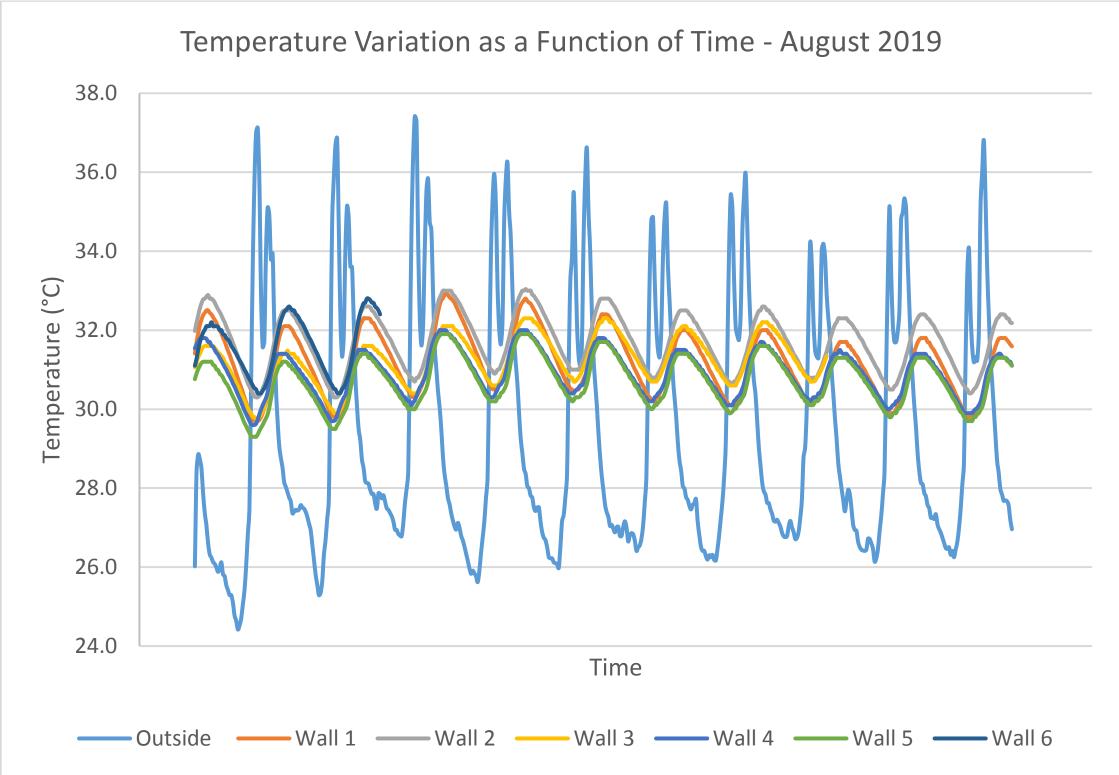

Figure 33 - Temperature Variation as a Function of Time, August 2019

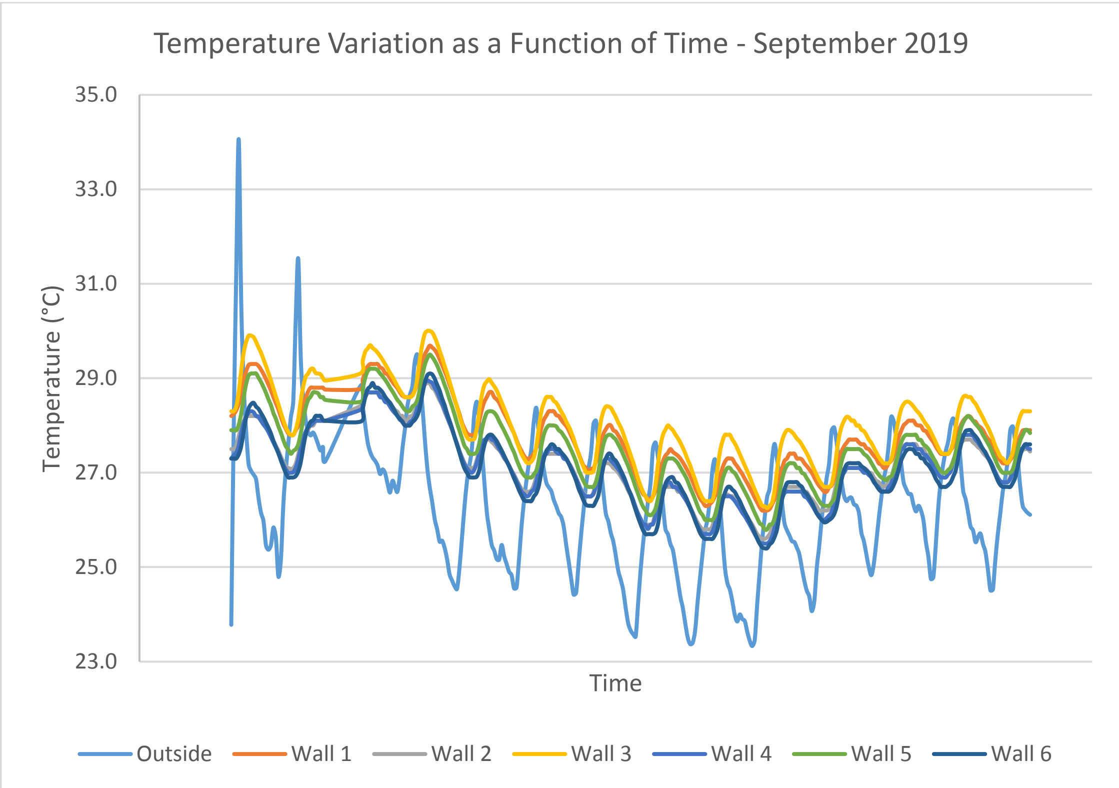

Figure 34 -Temperature Variation as a Function of Time, September 2019

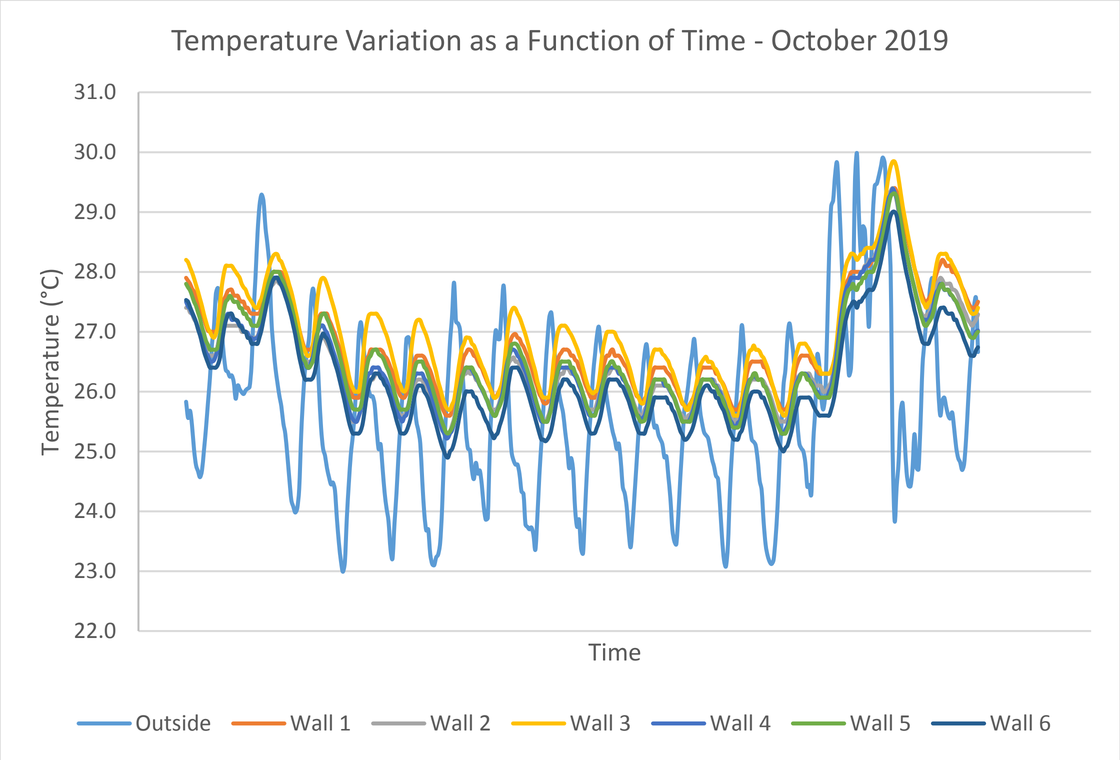

Figure 35 - Temperature Variation as a Function of Time, October 2019

Table 13 - Walls Composition

Wall	Composition
1	Soil Only
2	75% Soil + 25% Sand
3	75% Soil + 25% Sand + 1% Cement + 1% Lime
4	75% Soil + 25% Sand + 5% Cement
5	75% Soil + 25% Sand + 5% Lime
6	75% Soil + 25% Sand + 4% Cement + 4% Lime

The difference in temperature variations between the walls and the outside is apparent. It should be noted that during the month of August, the outside thermometer was exposed to sunlight and was later placed under the shade during the months of September and October, significantly reducing the peaks of outdoor temperature. Some values were also peculiar such as wall 3 reaching temperatures higher than the outside temperature during the month of October.

Additional data must be collected and sun exposure must be monitored to factor in the different variables affecting the walls. Their different placement with regards to the sun was due to the limited space available for construction, meaning sun exposure was not the same and could be the source of the different walls' temperature with regards to one another. These differences made comparison between the walls difficult and in order to simplify the analysis process, wall 1 alone was investigated and its decrement factors and time lags for the months of September and October were calculated. These months were selected due to their higher regularity, and the results are presented in ***Table 14 and 16*** and summarized in ***Table 16***.

Table 14 - Decrement Factor and Heat Flux Time Lag of Wall 1 for the Month of September 2019

	Wall 1			Outdoor		
	Max T°C	Time of Max	Min T°C	Max T°C	Time of Max	Min T°C
9/22/2019	28.3	10:00:00 PM	27.3	28.37	4:00:00 PM	24.55
Time Lag	6:00					
Decrement	0.262					
9/23/2019	28	9:30:00 PM	27	28.1	4:00:00 PM	24.42
Time Lag	5:30					
Decrement	0.272					
9/24/2019	27.5	10:00:00 PM	26.4	27.6	4:00:00 PM	23.5
Time Lag	6:00					
Decrement	0.268					
9/25/2019	27.3	10:00:00 PM	26.3	27.28	4:00:00 PM	23.37
Time Lag	6:00					
Decrement	0.256					
9/26/2019	27.4	10:30:00 PM	26.2	27.61	4:00:00 PM	23.33
Time Lag	6:30					
Decrement	0.280					
9/27/2019	27.7	10:30:00 PM	26.6	27.96	4:00:00 PM	24.07
Time Lag	6:30					
Decrement	0.283					
9/28/2019	28.1	10:00:00 PM	27.1	28.18	3:00:00 PM	24.83
Time Lag	7:00					
Decrement	0.299					
9/29/2019	28.2	10:00:00 PM	27.4	28.15	4:00:00 PM	24.75
Time Lag	6:00					
Decrement	0.235					
9/30/2019	27.9	9:30:00 PM	27.2	27.98	4:00:00 PM	24.51
Time Lag	5:30					
Decrement	0.202					

Table 15 - Decrement Factor and Heat Flux Time Lag of Wall 1 for the Month of October 2019

	Wall 1			Outdoor		
	Max T°C	Time of Max	Min T°C	Max T°C	Time of Max	Min T°C
10/6/2020	26.7	10:30:00 PM	25.6	27.82	3:00:00 PM	23.1
Time Lag	7:30					
Decrement	0.233					
10/7/2020	26.95	9:30:00 PM	25.9	27.77	4:00:00 PM	23.9
Time Lag	5:30					
Decrement	0.269					
10/8/2020	26.65	10:00:00 PM	25.8	27.32	4:00:00 PM	23.4
Time Lag	6:00					
Decrement	0.215					
10/9/2020	26.7	11:00:00 PM	25.9	27.08	4:00:00 PM	23.3
Time Lag	7:00					
Decrement	0.212					
10/10/2020	26.6	10:00:00 PM	25.8	26.79	4:00:00 PM	23.4
Time Lag	6:00					
Decrement	0.236					
10/11/2020	26.4	11:00:00 PM	25.7	26.9	4:00:00 PM	23.5
Time Lag	7:00					
Decrement	0.204					
10/12/2020	26.5	11:00:00 PM	25.7	27.11	4:00:00 PM	23.1
Time Lag	7:00					
Decrement	0.199					
10/13/2020	26.6	11:30:00 PM	25.7	27.14	4:00:00 PM	23.1
Time Lag	7:30					
Decrement	0.224					
10/14/2020	27.99	10:30:00 PM	26.3	29.82	4:00:00 PM	24.3
Time Lag	6:30					
Decrement	0.305					

The decrement factors and heat flux time lags of the 40 cm thick rammed earth wall recorded are much better performance indicators than reported figures for a 10 cm thick prefabricated concrete wall tested in Egypt by El Gamal (2014) that proved to have a heat flux time lag of 2.8 hours and a decrement factor of 0.816. Additionally, by factoring in the fact that the calculated values for the rammed earth walls only represent temperature fluctuations happening in the middle of the wall (20 cm) rather that at the indoor surface, means that the thick rammed earth walls can significantly outperform regular reinforced concrete walls in terms of reducing indoor temperature disturbance and providing thermal comfort.

Table 16 – Summary of Decrement Factor and Heat Flux Time Lag of Wall 1 for the Months of September and October 2019

September			October		
Date	**Time Lag**	**Decrement**	**Date**	**Time Lag**	**Decrement**
9/22/2019	6:00	0.262	10/6/2019	7:30	0.233
9/23/2019	5:30	0.272	10/7/2019	5:30	0.269
9/24/2019	6:00	0.268	10/8/2019	6:00	0.215
9/25/2019	6:00	0.256	10/9/2019	7:00	0.212
9/26/2019	6:30	0.280	10/10/2019	6:00	0.236
9/27/2019	6:30	0.283	10/11/2019	7:00	0.204
9/28/2019	7:00	0.299	10/12/2019	7:00	0.199
9/29/2019	6:00	0.235	10/13/2019	7:30	0.224
9/30/2019	5:30	0.202	10/14/2019	6:30	0.305
Average	6:06	0.26	**Average**	6:40	0.23
Standard Deviation	0:27	0.027	**Standard Deviation**	0:40	0.032

From September to October, the average heat flux time lag increased 34 minutes, an increase of 10%, and the standard deviation increased by 13 minutes, an increase of 48%. The decrement factor decreased by 0.03, a 12% decrease, while the standard deviation increased by 0.005, a 5% decrease. These results indicate a correlation between the different ambient conditions and changes in the wall's performance parameters over the span of the dates investigated.

F. Humidity Dissipation

The granular property of rammed earth allows it to absorb and desorb humidity to some degree. As mentioned before the temperature and humidity sensors were placed within the walls that were exposed on both sides. The wall moisture content and the outdoor humidity for the month of October are presented in ***Figure 36*** and ***Figure 37*** respectively. The month of October alone is shown due to large gaps of data missing from malfunctions in the data collection apparatus.

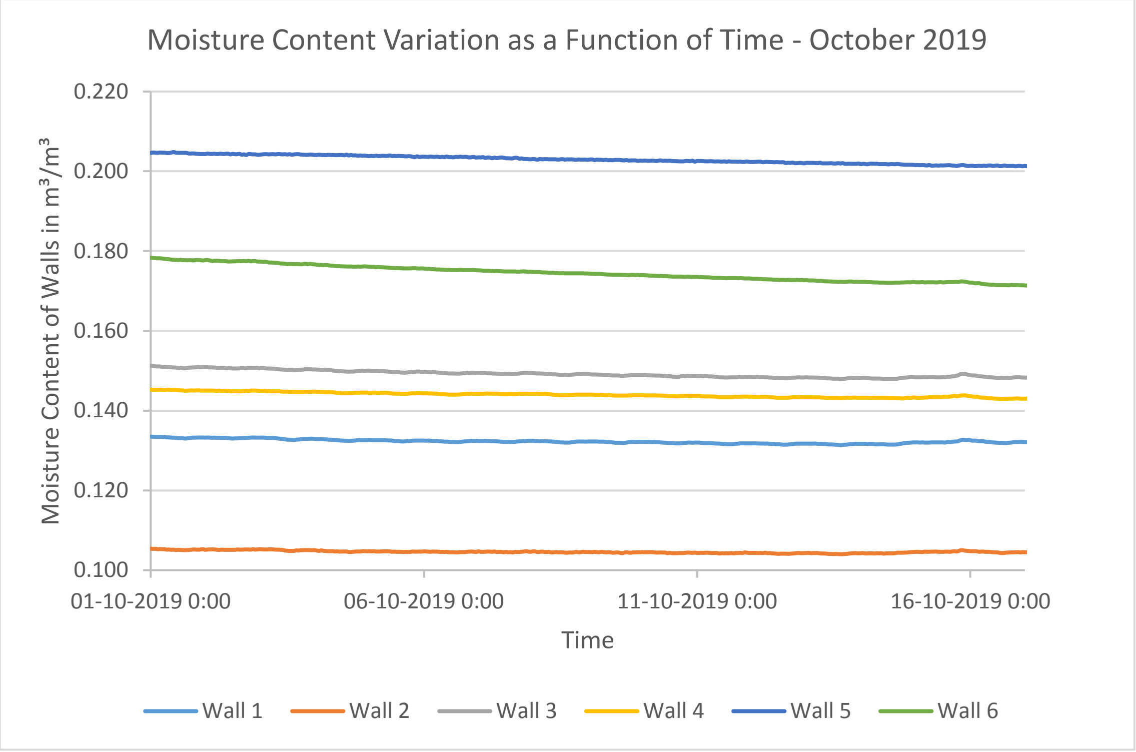

Figure 36 - Moisture Content Variation as a Function of Time - October 2019

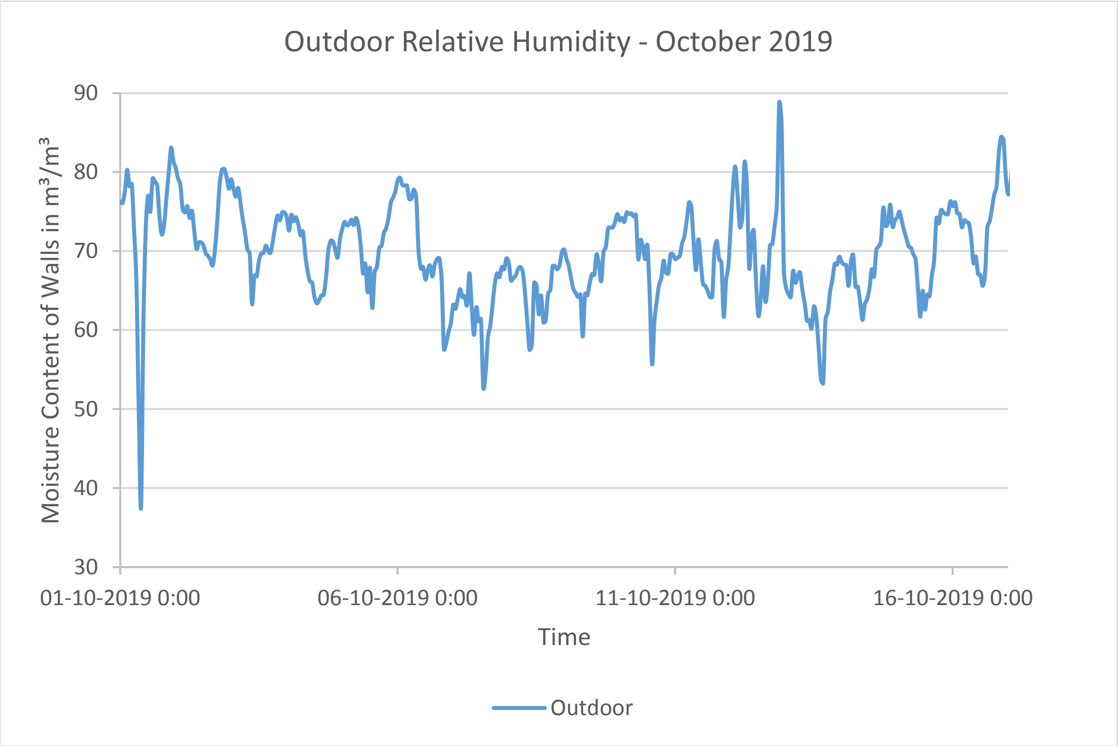

Figure 37 - Outdoor Relative Humidity **-** October 20194

Overall, the outdoor humidity levels seem to have no significant impact on the moisture content within the walls. The water content measured by the sensors in m^3/ m^3 is relatively stagnant for walls 1, 2 and 4, and is slightly decreasing for walls 3, 5 and 6. These findings suggest that the absorption and desorption processes happen mostly at the surface of the walls, whereas the sensors installed only recorded moisture values in the middle of the walls, that are not affected by external humidity variations. This is due to wall's high density and clay content that make it hard for water to travel through the wall's whole thickness.

CHAPTER IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary and Conclusion

Rammed earth construction is one of the many solutions needed to help mitigate climate change and reduce its reach. It provides an alternative solution to construction needs when high structural performance is not required, effectively cutting on CO_2 emissions. Together with reducing environmental harm, rammed earth provides a healthy and efficient living environment for its occupants and can be tailored to the needs of its builders. The recyclability and long life of the material coupled with the low energy input required for construction and upkeep make rammed earth buildings sustainable from cradle to cradle.

This study successfully develops a practical methodology to achieve its goals. It included the construction of six walls in two different locations with different climatic conditions, the aim of which is accentuating the effect of different environments on rammed earth's thermal properties. The soil used was tested for suitability in rammed earth construction and proposed mix adjustments and improvements, along with the original soil, were tested and used for construction. These tests provided clarifying results in the positive effects of reducing excess clay content and adding additives such as lime and cement. Additionally, the formwork used for construction was designed iteratively to make it more efficient and construction quality was measured in both time and achieved density through a new yet simple method. To quantify the varying thermal and humidity parameters, sensors were placed in the middle of the walls and the decrement factor and heat flux time lag of one wall were calculated over a two-month period.

B. Recommendations for Future Works

1. Full Scale Construction

The construction of a life size, fully functional room will shed light and help better understand possible complications. Detailing is still a problem to overcome from a practical point of view.

Additionally, monitoring the temperature and humidity inside the room will better reflect the behavior of the walls with regards to these parameters.

2. Standardization and Increase of Sample Pool Used for Compressive Tests

A large variation in the results obtained from compressive tests underline the inaccuracy of current methods. It is recommended to increase future sample numbers to account for the high variability and mitigate the associated risks. This step will help better understand and reduce the sources of variability in future research.

3. Mix Strength Optimization

Sand is shown to increase mix quality when the soil is considered high in clay content. Further investigation is required in order to better understand the interaction of soil with sand and identify key parameters such as percentage of replacement and sand gradation, which can lead to better mix optimization.

4. Modeling and Testing of Lateral Load Capacity

Rammed earth as a material does not handle tensile forces well, as such, evaluating the material in lateral loading cases is important to determine the limits of this construction technique and increase safety.

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