博士論文

Testing of Earth-based Material Additive Manufacturing to create Temporary Low-cost Housing; Sudan as an Example

（ローコストな仮設住宅の製造に向けた土試料を用いた積層造形技術
に関する研究　スーダンを事例として）

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ABSTRACT

In this study, an earth- based mix consisting of soil, fly-ash, and an alkaline activator was developed for an extrusion- based additive manufacturing process (3D Potterbot 7 SUPER) to build low-cost, temporary housing for the urban poor in Khartoum the capital of Sudan. The architectural design was inspired by elements from local African vernacular architecture, more specifically the circular hut.

Artificial soil components were mixed to create a target soil found in Sudan resulting in an artificial soil with a Liquid limit (LL) of 55.7 %, a Plastic limit (PL) of 29.64%, and Plasticity index (PI) of 25.73% and is classified as inorganic clay of high plasticity, or fat clay(CH). The soil was then mixed with fly-ash class JIS-I and a mixture of Calcium Hydroxide $Ca(OH)_2$ and water. The fly- ash content was maintained at 20%, while the liquid content (water + $Ca(OH)_2$) was tested using the AM system at 30% and 40% of dry content weight. The $Ca(OH)_2$ was tested initially at 1.5 g/l and increased later to 5 g/l to improve structural behavior.

Workability and extrudability tests reviled that the optimum liquid content was at 37%, the optimum nozzle height was @ 5 mm for the 6 mm diameter nozzle, buildability is estimated @ 35 layers, and the average height of layer @ 3 mm. The Unconfined Compression Strength test showed that the increase in strength was not consistent with maximum strength gain of 0.70 kN/ m^2 after curing for 28 days. The specimens also showed linear cracking during testing and a brittle breakage behavior and generally displayed poor structural strength.

Evaluation of 3D printed units of same scale and layer number demonstrated that the cost of the printed unit cannot be based solely on the design complexity. Additionally, calculating the cost of an AM construction is very different as there are multiple factors that need to be considered such as the minimized need for formwork and labor, reductions in time and material usage, and the high degree of accuracy of the constructed part. Printing speed is directly related to nozzle size; a larger diameter or size results in a faster printing time and when a low- cost process is the target, speed has more precedent over the detail resolution.

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I would like to dedicate this work to my amazing husband and family for their love and support. Without them, this research wouldn't have been possible.

Finally, to my baby boy Kareem, I dedicate this work to you. You have been a shining light throughout this whole process showering me with love and joy.

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LIST OF TERMINOLOGY

Additive Manufacturing: "a process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies" (ASTM: F2792 – 12a, 2012)

Buildabilty: is the ability of the material to hold its shape under the pressure generated by the weight of the consecutively printed layers.

Extrudability: is the ability of the cementation material to pass or be pumped through a small pipe or extruder and then be deposited evenly and continuously in its fresh state.

Inter-layer adhesion: is defined as the capacity of the adjacent layers to create a strong bond and yield a structurally sound cohesive unit.

Open-time: Is the consistency of the above mentioned properties within the accepted tolerance of the 3D printing system.

Printability: the capacity of the material to be deposited through the deposition system.

Pumpabaility: The movability of the material through the delivery system.

Soil stabilization: is a process by which soil is mixed with chemical or physical components in order to enhance its engineering properties. These encasements include improved compression strength, porosity, density, water retention, durability, and firmness

Workability: is a property of freshly mixed cementitious materials and is used to describe its rheological behavior.

LIST OF SYMBOLS

2-D = Two- Dimensional

3-D = Three- Dimensional

AM = Additive Manufacturing

ASTM = The American Society for Testing and Materials

BIM = Building Information Modeling

B&C = Building and Construction

CAD = Computer-Aided Design

CAM = Computer- Aided Manufacturing

CDLP = Continues DLP

CEB = Adobe or Compressed Earth Bricks

CSH = calcium silicate hydrate gel

CASH = calcium aluminate silicate hydrate gel

CSIRO = Commonwealth Scientific and Industrial Research Organization

CJP = ColorJet Printing

CNC = Computer Numerical Control

DED = Directed Energy Deposition

DLP =Direct Light Processing

DMD = Direct Metal Deposition; Digital Mirror Device

DMLS = Direct Metal Laser Sintering

EBAM = Electron Beam Additive Manufacturing

EBM = Electron Beam Melting

DOD = Drop On Demand

EAM = Extrusion Based Additive Manufacturing

FDM = Fused Deposition Modeling

GPS = Global Positioning System

HQ = High Quality

HR = High Resolution

HS = High speed

ISO = International Standards Organization

GIS = Geographic Information System

IDPs =Internally Displaced Person

LAN =Local Area Network

LL =Liquid Limit

LENS = Laser Engineered Net Shape

LOM = Laminated Object Manufacturing

MEM = Melted Extrusion Manufacturing

MJM = Multi-Jet Modelling System

MJP = Multi-Jet Printing

MRI = Magnetic Resonance Imaging

NPJ = Nano Particle Jetting

NASA = National Aeronautical and Space Administration

OMC = The Optimum Moisture Content

PMMA= Poly (Methyl Methacrylate)

PL = Plastic Limit (PI: LL- PL)

PI = Plasticity Index

PSDO = Partner Standards Development Organization

RP = Rapid Prototyping

PMMA = Poly (Methyl Methacrylate)

RP = Rapid Prototyping

SDL = Selective Deposition Lamination

SDM = Shaped Deposition Manufacturing

SFF = Solid Free-Form Fabrication

SFM =Solid Free-Form Manufacturing

SLA = Stereolithography Apparatus

SL = Stereolithography

SLM =Selective Laser Melting

SLS =Selective Laser Sintering

SMS =Selective Mask Sintering

SSM = Slicing Solid Manufacturing

STEP = Standard for the Exchange of Product

SOUP = Solid Object Ultraviolet- Laser Plotting

SGC = Solid Ground Curing

UCS =Unconfined Compression Test

USCS = Unified Soil Classification System

CHAPTER 01

INTRODUCTION

1. Introduction

As the unprecedented global population growth continues, fears over the availability of adequate shelter and services are rising. The UN HABITAT estimates that by the year 2030, around 40% of earth's population (around three billion people) will need shelter and basic services. Although this is a global problem, developing countries are affected the most. In these countries poverty and civil upheaval are wide- spread and millions of residents are living in slum conditions. Moreover, there is a great possibility that the governments of developing countries will not be able to secure the needed funds in order to address the projected housing needs (Malpass, 2005).

Sudan much like other developing countries in Africa, witnessed an explosive rate of urban growth especially in the last four decades (Pavanello, 2011). Between 1973 and 2005 its capital Khartoum grew by a factor of eight which the equivalent of a 6% annual rate of growth (Murillo et al., 2009). Currently, Khartoum has the highest population density and is home to around 26% of the country's population of 43,148,408 (HABITAT, 2012; World Population Review, 2019). Although there has been a lot of international attention and aid, it was, for the most part, directed towards the rural areas and hasn't addressed housing needs of the urban poor (Martin & Mosel, 2011)

It's apparent that the global housing crisis needs immediate attention, however, building more houses means using more energy, consuming more natural resources, and producing more waste. As we face a growing host of environmental concerns, it's imperative that the response to the housing demand is environmentally conscious. Many efforts are being put forth by environmental experts. Most recently, at the 'Architecture of Emergency' climate summit held in London, they urged the architecture industry to stop using concrete as means to fight climate change and instead to replace it with other environmentally friendly construction materials such as timber given that cement Production accounts for around 8% of the global emissions of Carbon Dioxide (Block, 2019.)

Consequently, a trend- shift is taking place in the architecture world as many architects attempt to design more sustainable, energy- efficient forms. For some designers vernacular architectural is a source of great inspiration; vernacular forms have proven their energy efficient and green qualities as they are a direct response to available resources, local geography, and climate, honed over millennia (as cited in Rashid & Ara, 2015,p. 47). Such is the case with African vernacular architecture, the subject of inspiration for this study. In addition to the geographical, climate, and material compatibility, African vernacular forms have a great cultural significance; the round plan is said to represent 'nature's rhythm', and the delicate mud mixtures used in construction are a direct response to the transient life of most Africans, more so that in some African cultures permanent buildings are a source of embarrassment (Denyer, 1982).

The fact remains however, that cost is the most important factor when addressing the current housing crisis especially when considering the developing world. As mentioned earlier, developing countries will have great difficulties acquiring the needed funds to deal with their housing needs. Most studies have shown that the most effective way to reduce construction cost is to reduce material cost. As such, designers are again looking for inspiration from the past, more specifically, the most ancient construction material know to man; earth. This resulted in greater interest and a large academic inventory focused on earth construction. For example, a study done by Adegun & Adedeji (2017) where 136 academic papers from 17 African countries were reviewed, showed that earthen buildings were considerably cheaper, cleaner and offer great thermal comfortability. However, the study also revealed the low-uptake of earthen construction perhaps over fears of low durability and strength. Another detractor is the association of mud building in African countries with low- socioeconomic standing. A psychological barrier further intensified by the extensive use of modern constriction materials such as concrete and steel (Adam & Agib 2001).

The fragility of earth as a building material has long been a great concern, and many studies, especially as renewed interest in earthen construction is gathering pace, are being conducted in soil stabilization as a way to improve the engineering properties of soil used for construction. Throughout history, soil was stabilized using local vegetable and animal derivative, but more recently, materials such as fly-ash are being studied due to their low cost and strong pozzolanic action (as cited in Nath, Molla, & Sarkar, 2017,p. 1). Fly-ash is a grey, fine powder that is a by-product of coal burning in coal-based, thermal electric power plants and is considered waste material (Nath, Molla, & Sarkar, 2017). Using Fly-ash for stabilization instead of cement, the most common modern stabilizer, lowers cost considerably while also protecting the environment form the ill effects of disposing and land-filling loose fly-ash. The effect of fly-ash on soil strength could be further improved by alkaline activation, a process by which a component such as calcium hydroxide is added creating a strong chemical reaction that results in solid, cement-like material called a geo-polymer (Fernández-Jiménez & Palomo, 2003; Hefni, Zaher, & Wahab, 2018). Geo-polymers are being studied as an eco-friendly substitute to Portland cement (Hadi, Al-Azzawi, & Yu, 2018).

In terms of technology, the turn of the millennium has brought 3D printing or Additive manufacturing to the forefront of digital design. Advances in the AM technology as well as the access to faster computers capable of storing incredible amounts of data, has made it a great tool favoured by many architects and designers (Carpo, 2017). Although its integration in construction has been a slow process (Pegna,1997), the field of construction additive manufacturing has made significant progress in recent years especially in concrete building. Aside from design freedom, AM offers many other advantages such decreasing cost, limiting the need for formwork, increasing safety in construction sites due and reducing material waste. More importantly, AM coupled with other tools such as advanced environmental simulation softwares, BIM softwares, 3D scanning,etc. creates a unique opportunity for a more informed and reactive design. Another unique feature of AM is that it provides an opportunity for mass customizing as working in a digital environment provides flexibility and changes could be easily made and manufactured.

1.1. Defining 'Temporariness'

Temporariness could offers a unique approach to housing, one that could be seen as better for the environment; making shelters easier to demolish lessens their impact on the environment. For example, in some African cultures having a permanent home could bring shame and embarrassment. It doesn't fit with their nomadic nature and the need for constant change. Also, certain cultural norms such as the need to show respect to a new leader, or acquiring a new wife or child, means that the size, number, and sometimes the rotation of houses need to be changed (Denyer, 1982).

As it pertains to this study, temporariness is seen as the availability of a suitable shelter until a permanent one could be found. Temporariness is also a response to the fragile nature of the used material; it will not last for a long time, but, it will provide shelter until the existent housing issue is resolved.

1.2. Problem Statement

Numerous researchers have studied the benefits of using earth as a construction material (Adam & Agib 2001; Al-Temeemi & Harris, 2004; Pacheco-Torgal & Jalali, 2012; Bahobail, 2012) especially in hot and humid climates. These benefits include availability, high thermal conductivity rate, low energy impact, fire- resistance, low environmental impact, reduced energy consumption, and most importantly, it could be cheaply acquired, especially if cultivated locally for the construction process.

Significant research has also been done in the field of construction additive manufacturing and the many advantages associated with the process (Lim et al., 2012; Kazemian, Yuan, Cochran, & Khoshnevis, 2017; Soltan & Li, 2018) such as speed, increased design freedom, easy customization, increased construction site safety, waste reduction and limiting the need for formwork. However, the majority of the research done in construction AM focused on the use of concrete and not much research is being done on other cheap, environmentally friendly alternatives.

Throughout the course of this study, Some research that used 'mud mixtures' in an AM process was found but was limited to experimental, small scale studies. Examples include the study done by (Perrot, Rangeard, & Courteille, 2018) where a fine soil used in the past for cob construction was mixed with a biopolymer alginate, and 'Pylos' a research project done at the Institute for Advanced Architecture of Catalonia (IAAC) in Barcelona (Giannakopoulos, 2015) where soil was mixed with natural materials (study didn't identify the material type). The most extensive research effort found by this study was the work of the World's Advanced Saving Project (WASP) founded in 2012 by mechanics and electronic Italian company Centro Sviluppo Progetti (CSP). the project focused on developing reliable and professional 3D printers that encourage sustainable development and in-house production. They developed WASP BigDelta 12, a 12m high and 7m wide 3D printer and experimented with several types of soil and long fiber mixtures using cement, lime, blown glass and clay. Experiments with the addition of hemp or hemp derivatives to the mud and straw mix were conducted. They also experimented with geo- polymers but no results were provided (WASP, 2016).

Do to the lack of existing research in the field of Earth-based additive manufacturing, there is much we don't know. For example, there is no specific methodology for testing an earth based AM process and most of the testing strategies are borrowed form concrete 3D printing (as cited in Perrot, Rangeard, & Courteille, 2018, p. 670). Additionally, there is no detailed results regarding the use of geo- polymers as most studies focus on the use of biopolymers. Finally, there are no testing that is conducted in African countries where this technology might have the greatest impact. Consequently, further testing of soil mixes and machines needs to be done in order to improve the overall process. Some of the key areas that need testing are mix fresh properties, printability, buildability, and strength of printed structures, (Lim et al., 2012; Ghaffar, Corker, & Fan, 2018; Ngo, Kashani, Imbalzano, Nguyen, & Hui, 2018; Marchment, Sanjayan, & Xia, 2019). This study will focus on those key factors.

1.3. Purpose Statement

The Purpose of this study is to examine the use of a soil, fly-ash, and alkaline activation viscous mix in a extrusion- based, additive manufacturing process to build low-cost, temporary housing for the urban poor in Khartoum the capital of Sudan. The architectural design is inspired by elements from local African vernacular architecture, Figure 1.1. contains important definitions of key- terms used in the study title.

1.4. Research Questions & Aims and Objectives

1.4.2. Research Questions

This study aims to investigate the use of earth based additive manufacturing to create low -cost/ temporary housing for Sudan, therefore the main question of the study is: RQuestion 1: is the use of an earth based additive manufacturing process suitable for creating low-cost housing for Sudan?

In order to answer the aforementioned question, more specific questions need to be answered by the research first:

A mixture mainly composed of soil and soil additives and has been designed and calibrated for a specfic additive manufacturing (3D printing) system.

The American Society for Testing and Materials (ASTM) defines Additive Manufacturing (AM) as follows: “a process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies” (ASTM: F2792 – 12a, 2012). Extrusion- Based Additive Manufacturing is the technology used in this research

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As it pertains to this study, temporariness is seen as the availability of a suitable shelter until a permanent one could be found. Temporariness is also a response to the fragile nature of the used material; it will not last for a long time, but, it will provide shelter until the housing issue is resolved.

The target end users for this system are low-income individuals in need of immedate shelter. The construction cost is minimized by minimizing the cost of the construction materilas

The target demographics are the urban poor in the slum areas of Khartoum the capital of Sudan. Design features are derived from vernacular African architecture mixed with the Afro- Arabian, Muslim heritage

Figure 1.1. Important Definitions

RQuestion 2: What would be the appropriate building (shape) ?
RQuestion 3: What is the best soil type, additives found in Sudan for the AM process?
RQuestion 4: How durable are the structures that result from the 3D printed process when soil is used as the main component?
RQuestion 5: Does it make economical sense to used 3D printing of earth mixture in place of the traditional mud building techniques in Sudan?
RQuestion 6: What are the steps needed to promote cultural acceptability of AM mud construction?

1.4.2. Aims and Objectives

The main aim of this research is to test the use of an earth-based material additive manufacturing process and its ability to produce low-cost, residential units for Sudan. Also to establish a 'framework' that will put forth the important measures that need to be taken to insure a productive earth based additive manufacturing process. The suggested frame work is meant to be a general guide that could be adapted to the different needs and the changing locations and mixes.

Below are the main objectives of this study:
- Determining the general shape of the units
- Determining the composition of the earth-based mixture (soil, fly-ash, alkaline activator).
- Assessing the printability of the earth-based mixture
- Assessing the strength of printed components created using the earth-based mixture
- Evaluating the use of the system to create low-cost housing for Sudan.
- Determining the main steps needed to achieve a successful printing process

1.5. Contributions and Significance of study

As discusses in the previous sections, there is great demand for fast, low-cost housing around the world due to the unprecedented population growth. This is especially true for developing countries who are already facing high levels of poverty and economical and political instability. In addition, as we face an environmental crisis it is important that the response to the housing issue is environmentally conscious and less taxing on its surroundings.

This study presents a system that uses 'earth', one of the oldest and most environmentally friendly building materials, with the state of the art technology of additive manufacturing. Studies of earth additive manufacturing are sparse and further investigations are needed to better develop the technology and the soil mixes. Furthermore, not a lot of testing of construction additive manufacturing is done in African countries. Specifically, at the time of this study, testing of construction additive manufacturing in Sudan has yet to take place and no relevant studies were found.

Thus, the significance of this study lies in the fact that it explores the use of earth AM in Sudan and investigates the unique geographical, economic and cultural factors at play . Other unique features are the use of local African vernacular architecture as a source of inspiration for the form generation process, in addition to the use of fly-ash and alkaline activation for improving the soil's engineering properties.

The implications are far reaching and go beyond Sudan to the rest of Africa and ,in a broader sense, the rest of the world as it also attempts to establish a framework that specifies the important steps needed for a successful outcome.

1.6. Long- term Objectives of Study

The ultimate goal of this study is to help develop a system capable of producing stable, low-cost green, and quick housing for those who are in need. The system is meant to be energy efficient, could be moved to the desired location and easily assembled or de assembled. The soil is cultivated locally and using the suggested framework, is tested and adjusted to be compatible with the chosen AM system. The system works smoothly and with minimum human intervention.

However, to get to this point, further testing and development of soil mixes is needed as well as testing in selected locations to further understand the main challenges and test the systems's performance.

The study also hopes to serve as a foundation for other researches as studies in the field of earth based AM are quite limited and its potential needs to be explored further.

1.7. Study Limitations

The main limitation of this study is that the proposed Earth based AM process is local/ machine specific. Every 3D printer is different and has different limitations and the soil mix needs to be adjusted as to be compatible with the machine. As such, the study focused on one group of soil that contains high amounts of clay as well as a high swelling and shrinkage rate. This type of soil is common in Sudan specially in the central areas, where the study will take place. Thus, using a different type of soil requires a new set of tests and evaluation.

Another challenge was the unavailability of a large- scale 3D printer, therefore, testing of true-scale structures wasn't possible. In fact, acquiring a 3D printer capable of printing dense, viscous material was extremely difficult, and the printer used in this study was purchased over seas from America.

The final limitation was that testing in Sudan wasn't possible as preparing for such a test will require lots of funds and planning. All of the tests had to be done in Japan using artificial soil that is mixed to be as close as possible to local soils found in Sudan. Consequently, the results might differ if native soil is used.

The research acknowledges all of these shortcoming but it's the author's hope that the process and results of this study could be useful to other researchers in the field and create a much needed excitement about the potentials of Earth based AM.

1.8. Study Overview

The general layout of the this study is shown in Figure 1.2. It consists of an introductory chapter followed by a background chapter, a research design/ methodology chapter, a result discussion chapter, and finally, a chapter with the overall conclusion of the study in addition to future recommendations.

The aim of the first two chapters is to introduce the reader to the issue being presented in this study and the related background information; the introduction discusses the context, problem overview, aims and objectives, main challenges, and the study's distinguishing features and long-term applications while the background chapter gives a systematic and in-depth review of related literature.

The background chapter starts with the history of mud building and its use in the African vernacular architecture. It explores the different used techniques, forms, and the intricate social, economical, geographical, and cultural factors. The chapter continues with an investigation of the specificities of using soil in construction , its advantages, disadvantages, the different additives that could be used to add strength and durability, and the most common physical and mechanical tests.

The chapter then delves into the world of additive manufacturing (AM), starting with the history of the technology, definition and most common used terms, and the different types and classifications with a special focus on extrusion-based additive manufacturing, the basis of the AM technology used in this research. The chapter then continues with the how AM technologies entered the construction industry and their general impact. The section concludes with examining the specific testing parameters related to the use of AM technologies in construction.

In the Following sections, the chapter introduces the reader to the study's location, Sudan, staring with general information such as the geographical location and climate conditions, followed by the current economical, and political atmosphere. The focus then shifts to the capital Khartoum and explores the specific cultural housing requirements as well as an overview of the current conditions of low-cost housing.

The final section in the background chapter contains an analysis and critique of current research in the field of construction additive manufacturing with a focus on mud mixtures. It then ends with the chapter's main concluding remarks.

The third chapter is dedicated to the research design and methodology. The chapter starts with defining the overall strategy and the background information used to inform the methodological approach, next, a review of the methodology steps is conducted in correspondence with research questions. The final sections contains information on samples, data collections, and analysis of each phase of the study.

Chapter four discusses the study results and findings, while chapter five, the final chapter, contains the study's conclusion, where a 'framework' of mud AM is introduced in addition to a proposed AM system inspired by the circular form of the typical African 'mud hut'. Chapter five ends with a section dedicated to future recommendation.

Chapter five is followed by the bibliography section and appendices. The formatting of the research's bibliography and citation follows the 6th edition of the American Psychological Association (APA) manual.

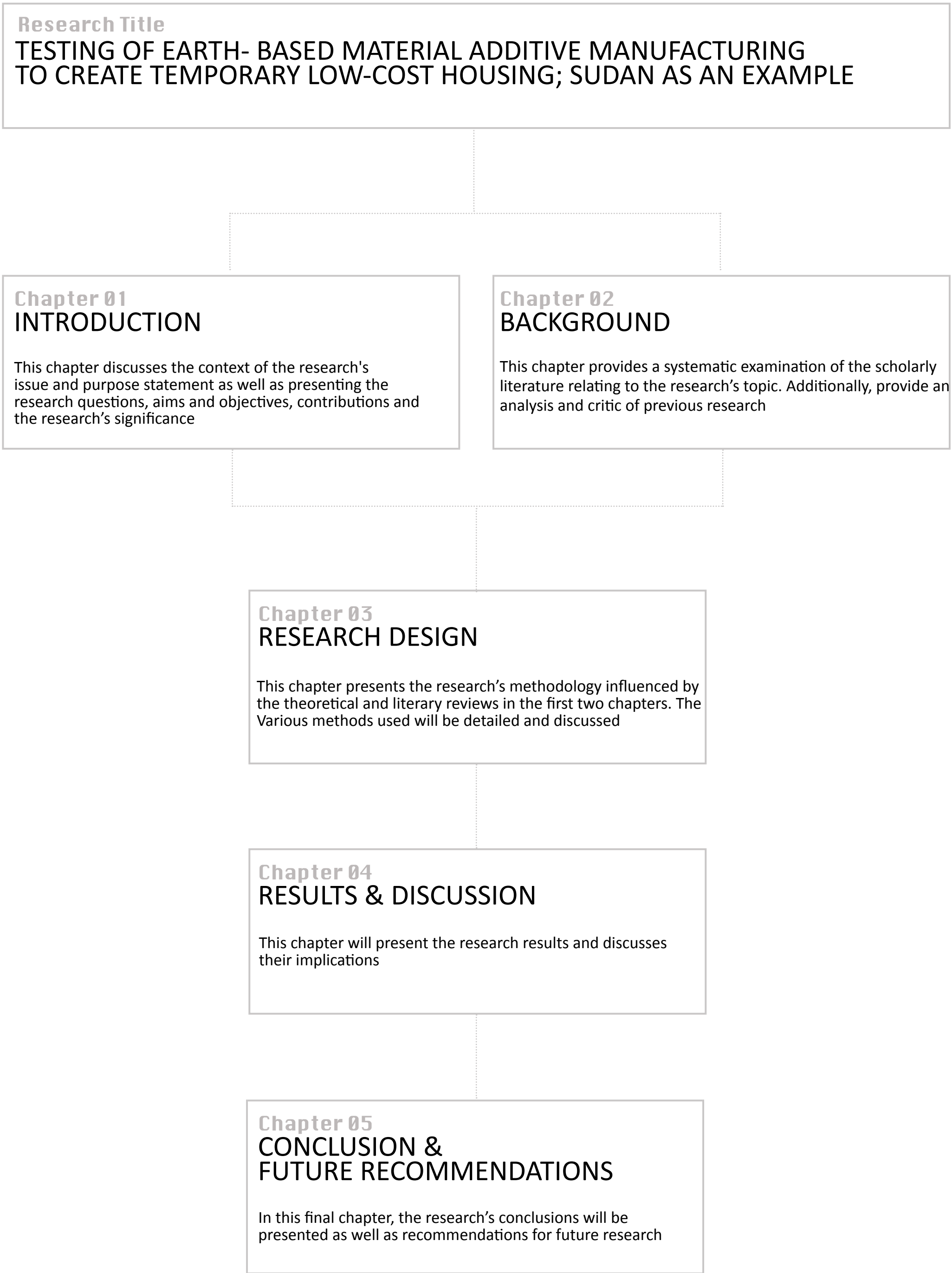

Figure 1.2. General Structure of Study

CHAPTER 02
BACKGROUND

2. Background

2.1. Introduction

The main goal of this chapter is to introduce the reader to the issues being presented in this study and the related background information.

The chapter starts with a brief history of mud building and its use in the African vernacular architecture. It explores the different used techniques, forms, and the intricate social, economical, geographical, and cultural factors. The chapter will then continue with an investigation of the specificities of using soil in construction , its advantages, disadvantages, the different additives that could be used to add strength and durability, and the most common physical and mechanical tests.

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The final section in this chapter will contain an analysis and critique of current research in the field of construction additive manufacturing with a focus on mud mixtures. It then ends with the chapter's main concluding remarks.

2.1. Earth Construction

2.1.1. History

It is very difficult to determine when man started using earth as a construction material. According to some researches (as cited in Pacheco-Torgal & Jalali, 2012,p. 513) the practice might have started over 9000 years ago based on the discovery of adobe block dwellings in Turkmenistan. Some other researchers (as cited in Pacheco-Torgal & Jalali, 2012,p. 513) think that earth construction dates to the period of El- Obeid in Mesopotamia around (5000- 4000 BC) based on the discovery of adobe blocks in the Tigris River basin that date back to 7500 BC. Although the exact date is hard to determine, it is safe to say that the beginning of earth construction could be linked to the formation of early agricultural societies around 12,000 to 7000 BC.

Many examples of earth structures still exist today. In central America Adobe buildings are very common. For example, in Peru, the remains of the city of Chanchan are considered amongst the most ancient earthen structures. Other examples of ancient earth construction are the village of Taos in New Mexico dating back to 1000- 1500 AC and the great wall of China where construction of the wall started 3000 years ago and large sections where built on rammed earth. (Pacheco-Torgal & Jalali, 2012). A famous example that illustrates the potential of earth building are the buildings of the city of Shibam in Yemen. These buildings stand up to 11 floors tall and were built around 100 years ago (UNESCO World Heritage Centre, 2015) Figure 2.1.

Recently, as earth population continues to grow, there is renewed interest in earth construction. Several countries started to experiment with earth building techniques as a more sustainable approach to building. Such dwelling can be found in Germany, France, and the UK where around 500,000 earth based residences can be found. They can also be seen rising in popularity in the USA, Brazil and Australia (Pacheco-Torgal & Jalali, 2012).

Old Walled City of Shibam (Gelbart, 2015)

Old Walled City of Shibam (Ribarska, 2015)

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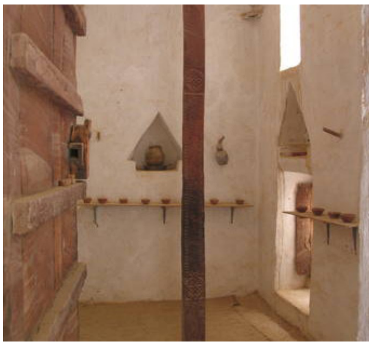


Old Walled City of Shibam (Ribarska, 2015)

Figure 2.1. Images of the Old Walled City of Shibam

2.1.2. Context in African Vernacular Architecture

In order to better understand the use of mud as a construction material in Sudan, it is important to investigate the African Vernacular Architecture. Looking at the broader picture will help provide insight into the historical, geographical, social, and cultural motivating factors.

Much of this exploration will focus heavily on mud construction and examples from different parts of Africa as well as specific examples from Sudan (North/ South) will be reviewed.

2.1.2.1. The Temporary VS. the Permanent

In her book 'African Traditional Architecture', Denyer (1982) starts the introduction by discussing the disparaging and detracting undertones present in the vocabulary used to describe African traditional architecture by referring to it as primitive "mud huts". She argues that the temporary nature of some African houses is not a reflection of an unstable, impoverished society, on the contrary, it is a prerequisite for some of the locals, in many cases, permanent houses were considered an embarrassment. For example, the transient life style of hunters and gatherers such as the Pygmies and bushmen, or the migrant shepherds such as the Fulani and Masai, or the farmers who had to rotate land and move every four of five years, temporary dwellings were essential. Other examples that had to do with social behavior include the high divorce rate amongst the Hausa which resulted in frequent child adoption and families changing in size and composition all the time so the dwellings needed to change to address their new needs. Or when one Tiv leader died and a new leader was designated, houses needed to reorient to face the new leader's house.

Broad generalizations cannot be made due to the different styles and materials that were used depending on location, climate,religion, and economics. However, a common thread is that most of the building was done without the aid of an architect; Houses were build in a specific physical style to reflect the communal needs of the people and the needed skills were passed down from one generation to another.

2.1.2.2. Layout

When looking at the layout of a family dwelling, it is usually composed of multiple buildings (rooms) (Figure 2.2.) each with it's own purpose; the man's bedroom, the woman's bedroom, kitchen, or a grain storage room. Figure 2.3. and Figure 2.6. show layouts of homesteads from different parts of Africa. A homestead with a single building was not common place, and if found It was usually rectangular in shape rather than circular and most common plan shape. It is also rare to see a room with multiple purposes, but some times small boys were made to sleep on top of granaries Figure 2.4., and the wife's bedroom might serve as the kitchen. In terms of physical appearance, the differences were minimal and all the rooms mostly looked alike from the outside. However, in the drier parts were the farming season was short, the granaries took prominence and became the largest buildings in the compound Figure 2.5.

In most parts of Africa the weather is warm year-round and during the dry periods many activities are done outside, as such, a designated open space is as crucial in a homestead as the rooms. In northern Ghana and northern Nigeria it is common for women to cook outside in an unroofed area surrounded by a low wall for wind protection (Denyer, 1982).

2.1.2.3. Royal and Religious Buildings

A chief's house in rural Africa is usually only distinguishable by its central position in the village and its size as chief's house was usually bigger and grander than a villager's house. However, it was mostly built from the same material. In some cases, and depending on the building material, the chief or a nobleman's house was higher and built with more courses. Additionally, the chief usually had more wives and his compound was usually more densely grouped than a commoner's. Some elaborate decoration was also present in the form of wood carvings on veranda posts or door frames Figure 2.7.

Although the chief's palace was built from the same material and manner of a typical village house, religious buildings such as churches and mosques retained some of their original, non African origins such as the tall minaret of a mosque or the basilica plan of a church (Denyer, 1982).

2.1.2.4. Materials

Building a house in rural Africa is a social occasion as both men and women participated in the building process with women usually doing the thatching. In some cultures a house needs to be

Figure 2.2. Mesakin, Nuba Mountain, Southern Sudan, 1955, mud houses on a mud platform (Denyer, 1982, p. 12)

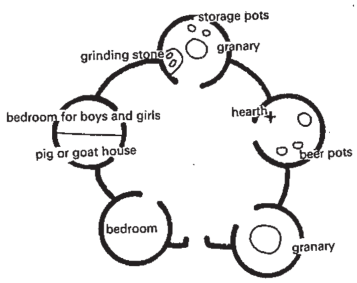


Figure 2.3. Heiban, Nuba Mountain, Southern Sudan, 1945, a typical plan of a Mesakin Home (Denyer, 1982, p. 12)

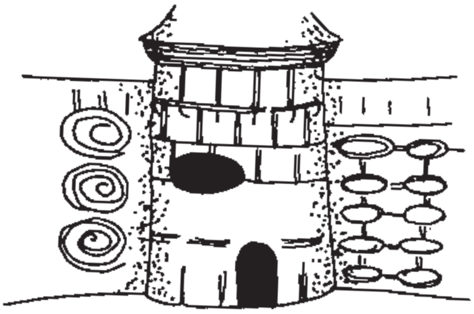


Figure 2.4. Mesakin, Nuba Mountain, Southern Sudan, 1938, the drawing shows the children's room atop of a barn (Denyer, 1982, p. 13)

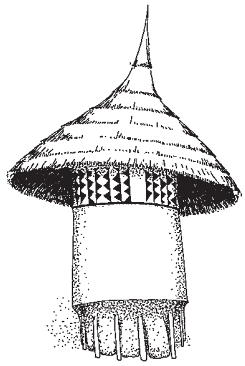


Figure 2.5. Heiban, Nuba Mountain, Southern Sudan, 1949, the drawing shows a granary (Denyer, 1982, p. 13)

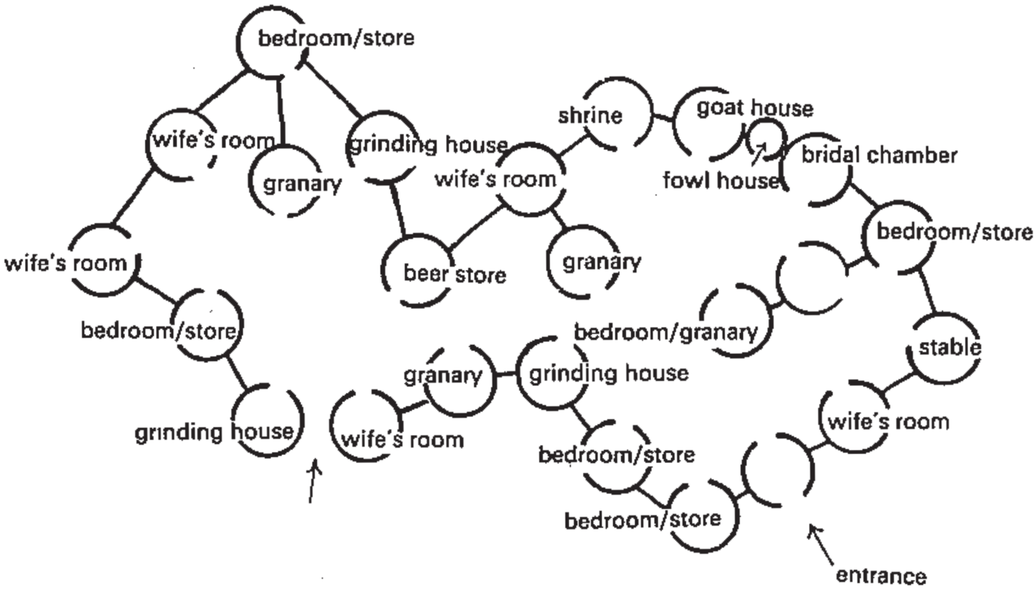


Figure 2.6. Plan of Birom Homesteads in northern Nigeria, 1949 (Denyer, 1982, p. 9)

Building a house in rural Africa is a social occasion as both men and women participated in the building process with women usually doing the thatching. In some cultures a house needs to be finished in a day due to superstition; it is believed that an unfinished house left overnight invites evil spirits.

Additionally, since only limited materials were available for construction, a great deal of skill was needed for the construction process. These skills were passed down from one generation to the next as most buildings wouldn't survive a single lifetime (Denyer, 1982).

Since the focus of this research is on earth-based materials, mud usage and African mud building techniques will be discussed at length while a short summery of the other popular construction materials will be presented.

2.1.2.5. African Mud Construction

The clayey nature of African soil makes it ideal for building as the extra clay provides stickiness. In effect, when the adequate content of sand and clay is present, mud becomes a strong and versatile construction material that could be used to build a multi-story building. Almost any basic shape can be expressed and a variety of roof shapes are attainable such as domes, vaults, shells, flat roofs, etc. However, the exterior surfaces must be routinely maintained to insure durability and prevent water from permeating and causing damage. This could help extend the building's life-span well beyond the life-span of its builder (Denyer, 1982).

In Africa many mud preparation and building techniques were used, for example, in parts of west Africa wooden frames were used to mold mud bricks that are then left to sun-dry. After drying the bricks are secured in place using a mud mortar. The mortar is also used on the exterior surfaces as plaster. A variation of this technique can be found in other African regions were pear-shaped bricks were made using a combination of mud and straw for reinforcement. They are then placed in horizontal rows with the point edge facing upwards and afterwards covered in mud plaster.

In forest areas a different technique referred to as ' swish puddling' was usually used. During the wet season, a pit is dug and the top soil is removed to expose the red clay underneath; this red clay is then taken and made into clumps; these clumps are exposed to the rain to dampen and are then 'puddled' by stamping. After this process is completed, the puddled red clay is made into a heap, covered with banana leaves and left to mature until the dry season when construction is due to start. During construction, the clay was constructed in courses each around 50 cm high, when a course is laid, it is left to dry for one day before the consecutive course was added. In some cases a mold using sticks and wattle work was made and after being filled-in it was covered with mud plaster. In special cases, such as when building a chief palace, Palm oil was used for the puddling process instead of water (Denyer, 1982).

Different types of mud plaster were used to protect the exterior surfaces of mud buildings and this plastering process had to be renewed on a regular basis. The plaster was applied by hand and in some cases decorations were using fingers. The simplest form of plaster is made from a mixture of mud and straw, but in some parts of Africa an addition of potash from die pits or an extract from locust-bean pods is some times practiced. The wealthy could afford more expensive alternatives such as Egyptian mimosa (commonly known as gum arabic) (as cited in Denyer, 1982,p.93).

In the forest areas a shiny wall finish was done by rubbing the new wall with a broken coconut shell and then washing it with a rich mixture of red earth that is applied using rotten banana leaves, or alternatively, rubbed with a mixture of crushed oil-seed leaves, or the extract of the locust bean. The women were usually tasked with polishing the walls, but in the case of palace walls, slaves were used instead (Denyer, 1982).

Special plaster mixtures were also developed for the interior walls. For example, the interior walls of the sleeping quarters were usually plastered using a mixture of mud and cow dung due to its repelling capabilities specially for repelling against pests. Another example is rubbing graphite on the interior walls of the shower buildings. This technique was developed by the Nuba of Sudan and is used mainly as a water repellent and is still use today by them.

Floors were also made out of mud and special care was taken to make them as strong and as smooth as possible. To achieve this, the mud floor is usually beaten by a wooden tool while it was setting. Sometimes additives were added to the mud such charcoal or small aggregates like

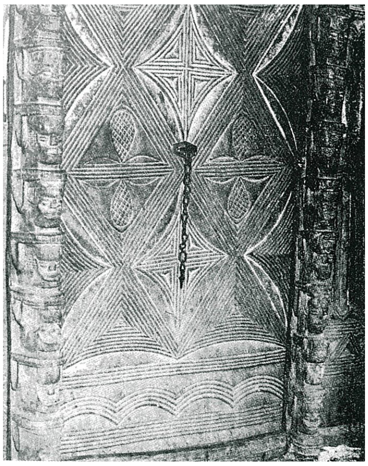


Figure 2.7. Awka, eastern Nigeria, 1959, a carved Ibo door (Denyer, 1982, p. 61)

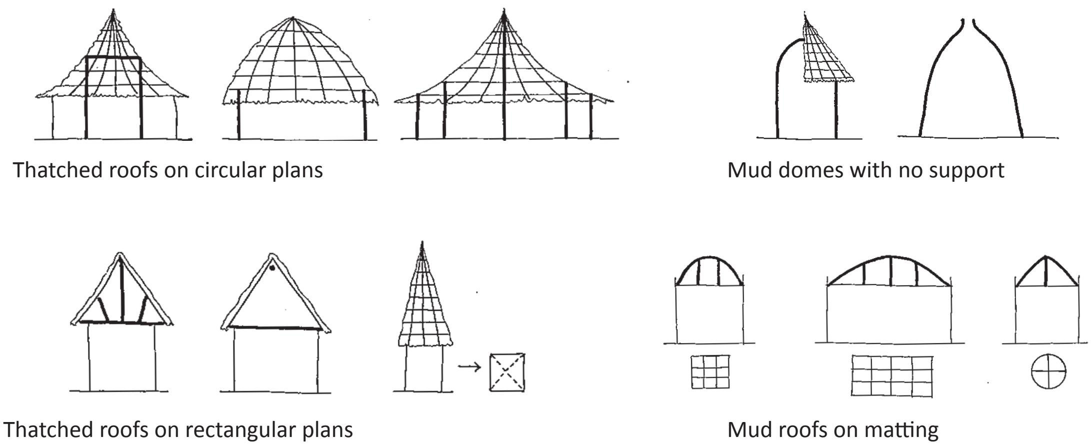


Figure 2.8. Examples of different roof construction techniques (Denyer, 1982, pp. 102-103)

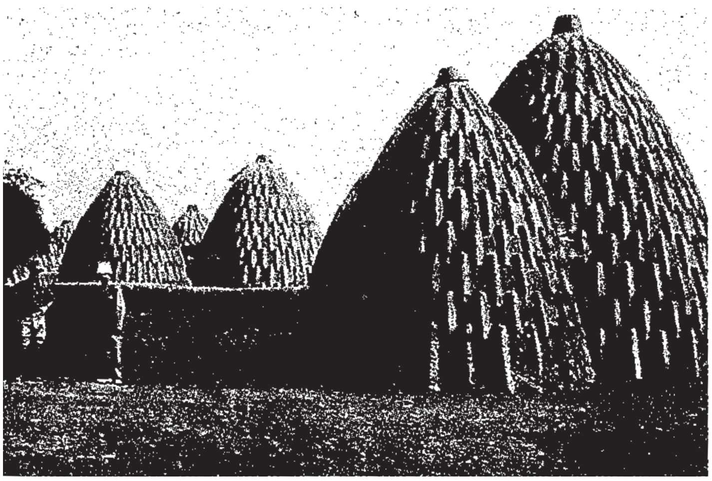


Figure 2.9. Northern Cameron, 1912, Mousgoum 'shell' buildings (Denyer, 1982, p. 131)

in the case of the Zulu houses, or using mud from low ant-hills that produced a bluish, water proof cement like in the case of the Raik Dinka in Sudan.

When constructing roofs, mud was usually reinforced with timber. Roof shapes changed from African region to another, in Mauritania and the Upper Niger region roofs were flat. In other parts vault roofs could be found, they resembled the shape of camel's back on rectangular buildings and a semi-dome shape on circle and square buildings. In same cases a domed mud ceiling under a thatched roof was built such as the case in some parts of Nigeria Figure 2.8.

An interesting example that illustrates the great potential of mud building are the Mousgoum 'shell' buildings. These bell-shaped Shells were constructed using layer of mud mixed with straw. The most striking feature of these buildings is the heavy embossing on the exterior. There is no specific information on the function of these decoration but it seems that they are perhaps used for climbing or for rain water drainage Figure 2.9.

Burnt mud bricks could was found in a specific region between the Upper Niger, Bornu, to Darfur in western Sudan and the nile region. Burnt bricks were enabled the walls to be load-bearing and the house plan was usually rectangular in shape with a flat roof supported by a brick column in the center.

Other materials that were used for construction aside from mud include, plants, stone, and as the changes in social, economic, and political factors, occurred, new materials emerged such as corrugated iron (Denyer, 1982).

2.1.2.6. A Taxonomy of Mud House Forms

Denyer (1982,p.133) defines style "as not only the form of individual buildings but also the way they are arranged." Styles vary pending on the tribe and material, and in some cases, multiple styles exist in one culture.

Due to the limited scope of this research, this section will focus mainly on the forms of mud buildings. Examples from different parts of Africa will be presented. Building arraignments will be disregarded. As a result, the following categories can be identified (Denyer, 1982) (Figure2.10):

a- Round-plan; diameter is less than height, the roof is usually thatched and conical or trumpet in shape. This form is found in parts of Sudan.
b- Round- plan; the diameter is equal or more than the height. The roofs are thatched and conical in shape (convex or concave).

c- Round-plan with a flat roof

d- Round-plan shell structure. The profile is slightly convex with heavy decoration on the outside. Mousgoum buildings from northern Cameroon are a prime example of this type.

e- Oval-plan with an asymmetrical thatched roof peaked to one side

f- Oval-plan with a saddle-back thatched roof. Some times the building is raised on stilts.

g- Round-plan; the building is made of multiple stories, sometimes up to three stories high. Roof is usually flat or conical.

h- Crown- plan, (concentric circles) with a thatched saddle-back roof. This type of building is usually sued a central court.

i- Square- plan with a conical thatched roof.

j- Rectangular- plan with thatched saddle-back roof

k- Rectangular- plan with flat or vaulted mud roofs. The walls are made from mud bricks and sometimes two stories.

l- Rectangular- plan units built on top of each other with flat mud roofs reinforced with timber or palm fronds.

m- Rectangular- plan with hipped thatched roofs. Sometimes wood carvings can be found on doors and are sometimes raised on stilts

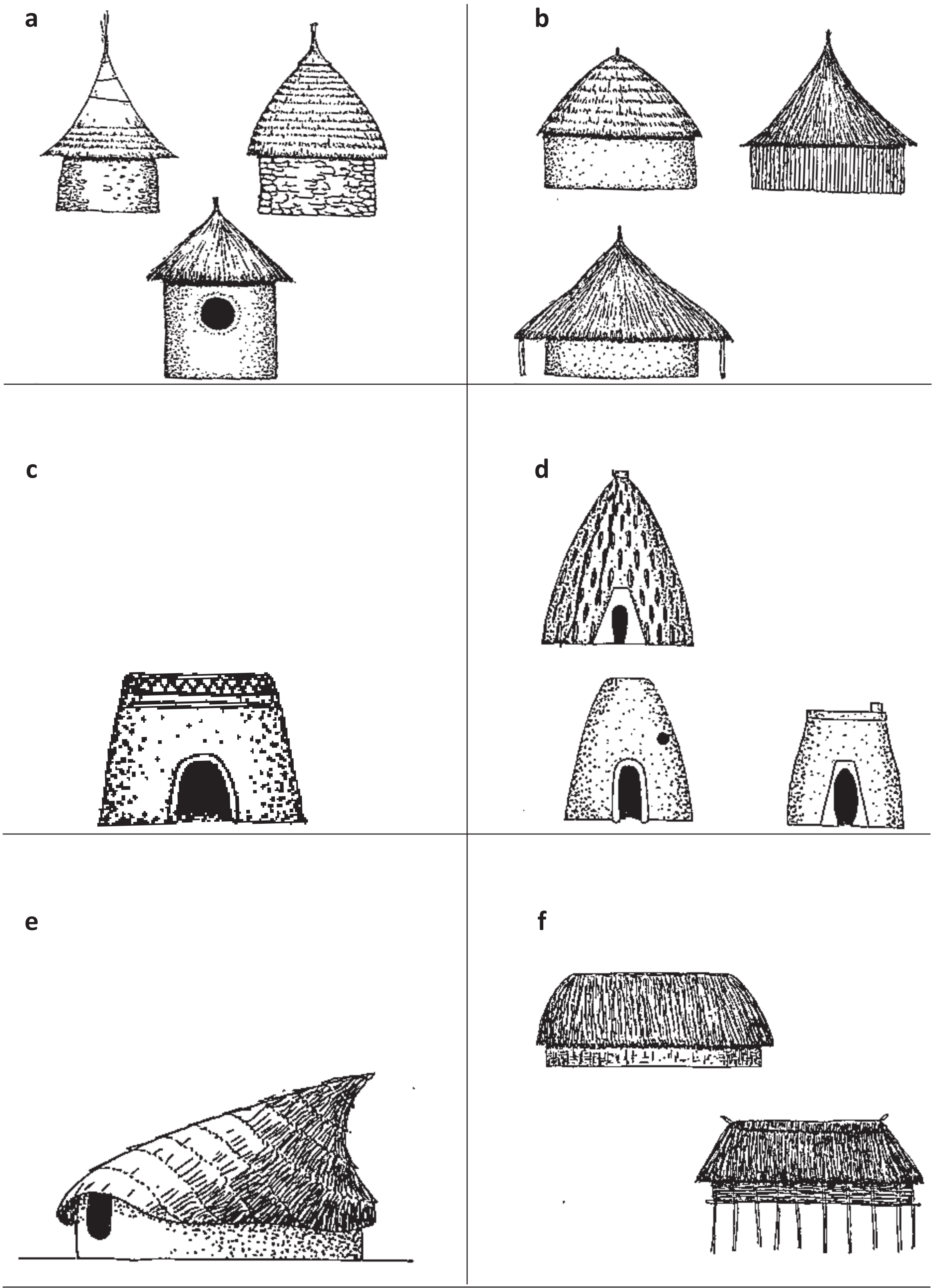
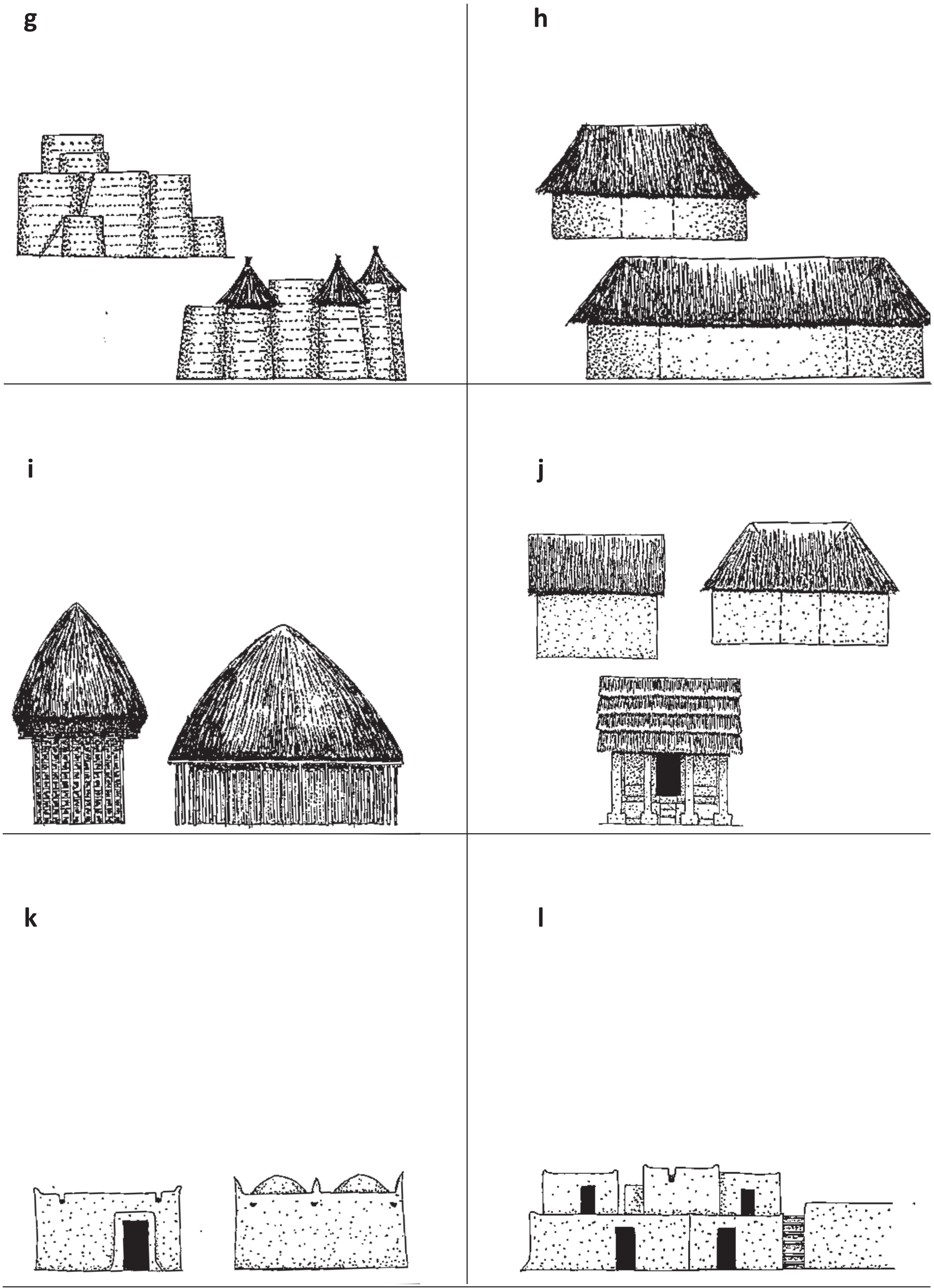


Figure 2.10. Taxonomy of Mud House Forms (Denyer, 1982, pp. 133-137)


g
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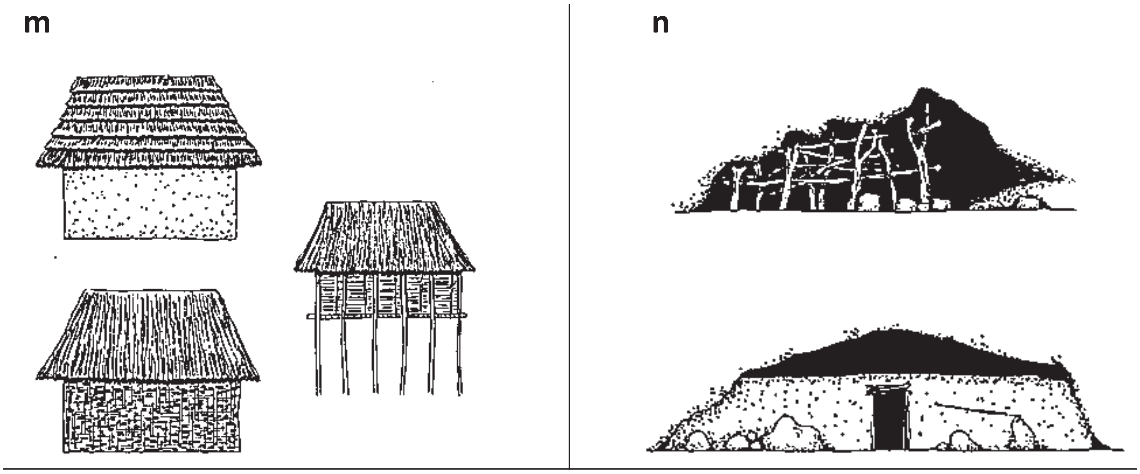


n- Cave-houses; the cave is enlarged by building a surrounding wall from mud of wood. In some cases the moth of the cave is covered with a mud wall. This type is usually found in Sudan.

2.1.2.7. Architectural Style Theories

It has been suggested that the circular plan might be “a sign of nature’s rhythm” (as cited in Denyer, 1982,p. 159). However, the African architectural style is of complex origin and is a result of a multitude of factors most importantly the local conditions; in some cases, a singly style might be a result of different ideas developed over generations. Another factor is migrations of one culture to another were shared ideas were fused together and resulted in a certain style. It is important to note however, that in some areas building styles remained the same for millennia.

Some styles were influenced by external factors like the introduction of religions such as Islam, this was the case with the ‘courtyard’. The rectangular-courtyard plan provides privacy specially for women in accordance to Islamic teachings. Nevertheless, there are multiple evidence that suggest that the rectangular-plan existed pre-Islam in different parts of the African continent.

Some of the important styles of African Architecture put forth by researches include:

The Sudanese Style (a style mainly influenced by Islam), the Impluvial Style, The Hill Style, and the Beehive Style (Denyer, 1982).

2.1.3. Traditional Earth Construction Techniques

Rogers & Smalley (1995) traces back the origins of the word 'adobe', a word that has become synonyms with ancient earth/ mud building, to its Arabic source the word (At-tub) meaning mud brick. The word was then integrated into the Spanish language and later the English language. According to some researches, this seems to suggest a north African origin of mud building before its existence in other parts of the world.

Through its long history, many techniques of earth building were developed such as the techniques discussed in the previous chapter, however, earth building techniques could be grouped into four main categories (Nair & Sajan, n.d.):
Cob: is the simplest type of mud construction. Mud is mixed with water and after achieving the desired consistency, it's then formed into spheres. Each sphere is then shaped into a cylinder and placed perpendicularly to the direction of the wall (along the width). These cylinders are known as "cobs". The cobs in the top layer are offset to sit between the cobs in the layer below to minimize gaps. The top layer should always be placed after insuring the dryness' of the bottom layer so it won't flatten.

Adobe Construction: mud is shaped and then packed into rectangular molds usually made from wood to produce mud bricks. The sizes of the bricks depend on the type of construction. The bricks are dried in the shade to prevent rapid drying that leads to the formation of cracks. A mud plaster can be used for finishing. It's normally used in load- bearing walls.

Daub and Wattle: a woven lattice of wood stripes "wattle" is "daubed" with a mud mixture. Thinner walls can be achieved using this method.

Rammed earth: soil is rammed and compressed in a well-braced mold shaped into the desired wall width. Ramming is done by a ramming rod or by mechanical means. Ramming improves soil strength and durability and can be used in a multi-story construction up to five stories in height. Adobe or Compressed Earth Bricks (CEB) are a form of rammed earth.

Hybrid systems exist where several techniques are combined to produce a building. In some cases plant fibers or other additives are used for reinforcement (Pacheco-Torgal & Jalali, 2012).

2.1.4. Additives/ Stabilizers

Soil stabilization is a process by which soil is mixed with chemical or physical components in order to enhance its engineering properties. These enhancements include improved compression strength, porosity, density, water retention, durability, and firmness. The type and amount of additive depends on soil condition and type of additive. Knowledge is derived through observation, testing, and trial and error. Laboratory tests provide guidance for field tests (Bahobail, 2012).

There are three main types of additives: organic additives (plant or animal based), Synthetic (industrial additives), and Mineral additives (Bahobail, 2012).

Due to the limited scope of this study this section will focus on mineral additives specifically fly-ash since it is the main additive in the earth mix being tested. Other additive types will be reviewed in short.

2.1.4.1. Additive Types

Organic additives:
Plant-based:
Examples include: fibers, vegetable oils and fats, tannins; a polyphenol substance that exists in seeds, grape stems, some tree barks, and tea leaves, gum Arabic, copal; it is resin that is obtained from some tropical trees such as manila copal, Sap and Latexes, and molasses.
Animal-based:
Examples include: animal fibers, blood, casein (whey), animal glues (protein colloid glues), oils and Fats, urine, and excrements.

Synthetic Additives:
Examples include: portland Cement, hydraulic lime (calcium carbonate), hydrate lime (calcium hydroxide), gypsum (calcium sulfate dehydrate), magnesium oxide, soap, and bitumen.

Mineral Additives:
Examples include:

Sand: consists of fine particles of rock and minerals. Is used when soil has too much clay to add uniformity and improve particle cohesion to reduce shrinkage/ swelling.

2.1.4.2. Fly- ash Stabilization

Fly-ash is a fine powder composed of mostly silica and results from burning finely crushed coal inside a boiler for electricity production. When mixed with soil, Fly-ash prompts a chemical reaction that results in a decrease of the soil's plasticity index and its shrinkage limit. Fly-ash is from a class of cementing admixtures favorable due to their low cost and strong pozzolanic action (as cited in Nath, Molla, & Sarkar, 2017,p. 1).

Disposing of fly-ash is a serious environmental problem, thus alternative uses must be found. Currently, fly-ash is used in geotechnical and geoenvironmental applications (Horpibulsuk, RACHAN, & RAKSACHON, 2009; Mir & Sridharan, 2013) such as stabilizing expansive soils like black cotton to improve there physical and engineering properties (Mir & Sridharan, 2013).

In Sudan, where there is an abundance of fly-ash, different applications are being investigated to reduce the significant environmental problems caused by low utilization and land filling of fly-ash. Many studies are being performed that focus on stabilizing clayey soils and replacing expensive stabilizers such as lime and cement. Those studies show that stabilizing clayey soils with different ratios of fly-ash improved their clay index and Atterberg limits as well as increased their bearing capacity (Ghais, 2014).

2.1.4.3. Pozzolanic Action

Tastan, Edil, Benson, & Aydilek (2011) explains that when a binder such as fly-ash is added to a mixture of soil and water, a series of chemical reactions occur resulting in the development of the pozzolanic gels calcium silicate hydrate gel (CSH) and calcium aluminate silicate hydrate gel (CASH), due to the release of lime (CaO):

$$\mathrm{CaO} + \mathrm{H_2O} \Rightarrow \mathrm{Ca(OH)_2}$$

$$\mathrm{Ca(OH)_2} \Rightarrow \mathrm{Ca^{2+}} + 2[\mathrm{OH}]^-$$

$$\mathrm{Ca^{2+}} + 2[\mathrm{OH}] + \mathrm{SiO_2} \Rightarrow \mathrm{CSH}$$

$$\mathrm{Ca^{2+}} + 2[\mathrm{OH}]^- + \mathrm{Al_2O_3} \Rightarrow \mathrm{CASH}$$

These reactions are referred to as pozzolanic/ cementitious reactions.

Pozzolanas increase soil strength in two ways:

1- reduction of soil plasticity due to the “exchange of calcium ions in the pore water with monovalent cations on clay surfaces and by compression of the adsorbed layer because of the elevated ionic strength of the pore water” (as cited in Tastan, Edil, Benson, & Aydilek, 2011,p.2)

2- an increase in soil matrix strength due the binding of soil particles together by the CSH or CASH gels formed by cementitious and pozzolanic reactions (as cited in Tastan, Edil, Benson, & Aydilek, 2011,p.2).

The effectiveness of a given type of fly-ash depends on the content of Silicon dioxide or silica SiO2 and Calcium oxide or lime CaO (Tastan, Edil, Benson, & Aydilek, 2011) and the CaO/SiO2 ratio which stands for the “relative abundance of CaO and SiO”is used to judge a binder’s potential pozzolanic reaction, the larger the mount the greater the effectiveness of a binder (as cited in Tastan, Edil, Benson, & Aydilek, 2011,p.2)

2.1.4.4. Fly-ash Classifications

Many classifications of Fly-ash exists around the world and it’s usually based on differences in chemical properties. In this section, the Japan Industrial Standard (JIS) of “Fly Ash for Use in Concrete”, JIS A 6201 will be discussed due to its utilization in this study.

Throughout its history, the JIS A 6201 has be amended several times including a major revision in 1999 in order to expand the uses of fly-ash after which four grades of fly-ash were established instead of one grade in the past, these four grades are: type I, type II, type III, and type IV (Ishikawa, 2007).

The main differences in these types are shown in Table 1.1.

Item	JIS Type I	JIS Type II	JIS Type III	JIS Type IV
Ignition loss (%)	3.0 or less	5.0 or less	8.0 or less	5.0 or less
Residue on 45µm sieve (mesh sieving method: %)	10 or less	40 or less	40 or less	70 or less
Specific surface area (cm^2/g) (Blaine method)	5000 or over	2500 or over	2500 or over	1500 or over
Flow value ratio (%)	105 or over	95 or over	85 or over	75 or over
Activity index (%) Material age 28 days	90 or over	80 or over	80 or over	60 or over
Activity index (%) Material age 91 days	100 or over	90 or over	90 or over	70 or over
Density (g/cm^3)(specific gravity)	1.95 or over	1.95 or over	1.95 or over	1.95 or over
Silicon dioxide: SiO_2(%)	45.0 or over	45.0 or over	45.0 or over	45.0 or over
Hygroscopic moister(%)	1.0 or less	1.0 or less	1.0 or less	1.0 or less
Homogeneity in quality, Blaine method (cm2/g)	±450 or over	±450 or over	±450 or over	±450 or over
Homogeneity in quality, Mesh sieving method (cm2/g)	±5 or over	±5 or over	±5 or over	±5 or over

Table 1.1. The JIS A 6201 Fly-ash 1999 Classifications, recreated from (Ishikawa, 2007, p.6)

In this study, JIS fly-ash type I would be used in testing due to its fineness and higher activity index.

2.1.4.5. Alkaline Activation

When fly-ash is mixed with calcium hydroxide it reacts strongly creating a solid, cement-like material, this process is called Alkali activation of fly ash (AAFA) and the resultant material is called a geo-polymer (Fernández-Jiménez & Palomo, 2003; Hefni, Zaher, & Wahab, 2018). Geo-polymers are being studied as an eco-friendly substitute to Portland cement (Hadi, Al-Azzawi, & Yu, 2018).

There are multiple factors that effect the geopolymerization (chemical reaction) process, these factors include the properties of the fly-ash and the type of the alkaline activator being used (as cited in Hadi, Al-Azzawi, & Yu, 2018, p. 41).

The reactivity depends on the quantity of the reactive SiO_2 and Al_2O_3 (Fernández-Jiménez et al., 2006) . The Fineness of the fly-ash also has an effect on the alkali-activation process; Fly-ash with a greater percentage of fines is considered favorable (Fernández-Jiménez & Palomo, 2003).

2.1.5. Earth Construction Standards

In a study by Jiménez Delgado & Guerrero (2007), an international survey was conducted in order to acquire information on the most modern earth construction standards used around the world. The study focused on un-stabilized earth and three main construction techniques used worldwide; adobe, rammed earth, and compressed earth blocks (CEB). Un-stabilized earth was chosen due to the difficulty of acquiring additives such as cement and lime in some third world countries as well as for its low embodied energy which makes it an environmentally friendly option. The study found that in many countries, there are no regulations for earth building. Also, it noted that some of the information was not clear and repetitive and a need for further research is clear.

The aforementioned study mentions countries that have issued standards for earth building, Examples include Australia, which is considered as one of the first countries to produce specific regulation for earth construction. They were published in 1952 by the Commonwealth Scientific and Industrial Research Organization (CSIRO) under the title ''Bulletin 5''. It was revised several times the last being in 1992, but it was replaced with the Australian Earth Building handbook in 2002. Another country was Germany were codes were introduced back in 1944, but were only put to practice in 1951 wit the DIN 18951. However, In 1998, the German Foundation for the Environment issued documents with technical recommendation titled the e ''Lehm- bau Regeln'' that was later revised in 2008. These recommendations were adopted by most German states throughout the years with the exception of Hamburg and Lower- Saxony. . Spain's Ministry of Transport and public works published the " Bases for design and construction with rammed earth" in 1992. However, studies have shown that mud building in Spain is still not regulated. In the US, there are no specific regulations for earth construction, but seismic design guidelines must be considered. Although, New Mexico state created its own regulations regarding earth building using rammed earth and adobe in 1992. New Zealand has the most advanced standards in regards to earth construction. In Zimbabwe a "Code of Practice for Rammed Earth Structures" was adopted in 2001.

2.1.5.1. Main Guidelines

When considering earth construction it is important to select the appropriate soil as not soils are suitable for earth building. In the study by Jiménez Delgado & Guerrero (2007) 20 standard documents were evaluated and analyzed. Soil classification is based on soil classification tables such as Unified Soil Classification System (USCS).

Although in this study stabilizers are used in the soil mix, it is important to consider international guidelines and get a better understanding of the of the over all process from soil selection to the adequate needed strength. This is made more crucial due to the lack of standards for earth construction in Sudan. Lastly, this review will focus on the guidelines for adobe building and will disregard guidelines for both rammed earth and compressed earth blocks (CEB) as adobe shows more similarities with the additive manufacturing process discussed in this study.

The study identifies the following main characteristics (Jiménez Delgado & Guerrero, 2007):

Texture:

Texture is the most frequently mentioned property. Knowing the particle size distribution is an important tool to understand texture. This is done through wet sieving and sedimentation tests. Some other suitable tests include visual examination, touch, hand washing, shine test, and thread test and dry strength test.

Some documents stress the need for a minimum clay content to insure natural cohesion. Generally, natural soils with more than 10% clay are considered suitable for adobe albeit some studies recommend a maximum clay content of 29%. Classes of soil usually considered as good for earth construction are sandy- clay or clayey- sand (as cited in Jiménez Delgado & Guerrero, 2007, p. 241). Effects of clay lumps in compaction are also very important; their presence creates weakness because they inhibit uniform compression. The NMAC 14.7.4 (The state of New Mexico, 2016) gives two values for the maximum size of clay lumps in earth mix 5 and 25 mm.

Plasticity:

Atterberg limits are the commonly used plasticity indicators. The most used are the liquid limit (LL) , the plastic limit (PL), and the plasticity index (PI(PI: LL- PL)). Some documents add the shrinkage age, and adhesion limit to these indicators.

Plasticity is defines as the ability to deform without breaking, it depends on the water content (from dry to plastic and finally fluid state) (Jiménez Delgado & Guerrero, 2007). for adobe construction, minimum values for the Liquid limit and plastic limit have higher values which means favoring more plastic soils. A recommended soil for earth building will be with a PI of 16- 28 and a LL of 32- 46.

Salts:

The presence of salts in soil makes it not suitable for construction, the presence of Na, Mg, and Ca sulfates make the soil fragile due to crystallization, thus, damaging to the soil (as cited in Jiménez Delgado & Guerrero, 2007, p. 247). The content of salt is determined through chemical lab tests. In some publications, such as NMAC 14.7.14 (The state of New Mexico, 2016) the maximum content was determined to be 2%.

Organic Content:

Organic matter needs to be removed in order for soil to be adequate for construction. The decomposition of organic matter will interfere with the structure's integrity, and might cause structural failure.

Organic matter usually is found in the 'topsoil', therefore, most publications recommends using 'subsoil' which is the under the vegetation layer.

Organic materials can be identified by Lab tests or by the smell test as recommended by some documents. The thread test is mentioned as another alternative by some researchers.

Binding force:

Binding force is the tensile strength of soil in a humid state, and it depends on the water content, clay content, and clay type. The best test to determine such quality is the "cigar test" also known as the "ribbon test", the "roll test" or the "sausage test". The comparable lab test is known as the "eight test".

The cigar test is very simple and practical. It consists of molding damp soil into a shape of a sausage, and allowing one end to hang free until it breaks. Then, the length of the broken piece is measured to determine the cohesion force. The recommend length of the broken piece should be between 60- 120 mm for adobe and CEB in accordance with HB 195 (Birkeland & Burroughs, 2019).

Shrinkage and Cracks:
Following recommendations, Soils that dry with plenty of fine surface cracks are not suitable for construction. The shrinkage box test or Alcock's test is used to determine the linear shrinkage of soil. The reviewed documents show that there is no need for a linear shrinkage limit for adobe and CEB.

Compact-ability:
Is identified as "the capability of soils to reduce its volume, decreasing the pores size and increasing the density, by application of a compaction effort." (Jiménez Delgado & Guerrero, 2007,p. 248). The optimum moisture content OMC determines the maximum compaction and the compaction proctor test is used to determine this property. The recommended Maximum densities for adobe is (1800 kg/ m3).

Compaction will not be used in this study, thus, compactions testing will be neglected.

2.1.5.2. Mechanical Tests

There are several types of mechanical tests that can be performed on soil in order to asses the soil's mechanical behavior. However, regarding this study, only one type of mechanical research will be used to asses the compressive stress of the soil mix. This test is called Unconfined Compression Test of Soils (UCS).

The UCS test will be performed as per the Japanese Geotechnical Society Standard (JGS 0511-2009) (The Japanese Geotechnical Society (JGS) , 2018).

2.2. Additive Manufacturing

2.2.1 History

In 1987,stereolithography (SL) by 3D Systems emerged as the first commercial AM technology. stereolithography is a process by which a solid is crated when a photopolymer solidifies after being exposed to a laser. Consequently, The SLA-1 (beta) retailed as the first AM system in the world (Wohlers Associate, 2015).

The development of AM systems was a turning point in the world of technology and had a great impact on designers and engineers around the world. This popularity prompted the development and commercialisation of other systems such as Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM) in 1991, followed by Selective Laser Sintering (SLS) in 1992. (Chua & Leong, 2014).

The continues development of AM systems was paralleled by developments in relevant materials and technologies which resulted in more refined, accurate, and faster AM systems, thus establishing the technology as a feasible alternative for tooling production. More systems kept developing such as a paper lamination system introduced by Kira Corp. in 1994, a Material Jetting technology in 1996, Laser Engineered Net Shaping (LENS) by Optomec in 1998, and Selective Laser Melting (SLM) by the German company Fockele & Shwarze in 1999. The Bioengineering industry realizing the potential of the AM technology, also begun developing AM systems that use bio-compatible materials such as the Bioplotter by EnvisionTEC GmbH in 2002 (Chua & Leong, 2014).

AM technology emerged first as a "visualization" tool and then a tool used for rapid prototyping and afterwards for tooling production, however, the development of AM systems capable of producing fully dense metal parts resulted in further refinement of the technology and prompted the creation of international standards. This paved the way for AM systems to be used for direct part manufacturing. Subsequently, the Expiration of older patents facilitated the large-scale production of low-cost personal 3D printers such as MakerBot and RepRap and the rise of open-source online 3D printing communities that share files and ideas regarding the various types of AM systems (Chua & Leong, 2014).

2.2.2. Definition & Terminology

The American Society for Testing and Materials (ASTM) defines Additive Manufacturing (AM) as follows: "a process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies" (ASTM: F2792 – 12a, 2012). Since the inception of the technology, many terms have been used to describe it. This could be attributed to the technology's versatility as well as the lack of standardization (Reddy & Dufera, 2019). one of the earliest terms used was Rapid prototyping (RP) however, this term became obsolete when the technology moved beyond prototyping. Another term that was popular in the public domain in the 90s was 3D printing, but this term was also limited because it was used to describe printers that employed nozzles only. Eventually the more encompassing term Additive Manufacturing (AM)emerged and has now become the industry's standard (Chua & Leong, 2014; Reddy & Dufera, 2019).

Lesser know terms include Direct CAD Manufacturing, Desktop Manufacturing, Instant Manufacturing, CAD Oriented Manufacturing, Layer Manufacturing, Material Deposit Manufacturing, Material Addition Manufacturing , Material Incress Manufacturing, Solid Freeform Manufacturing, and Solid Freeform Fabrication (Chua & Leong, 2014).

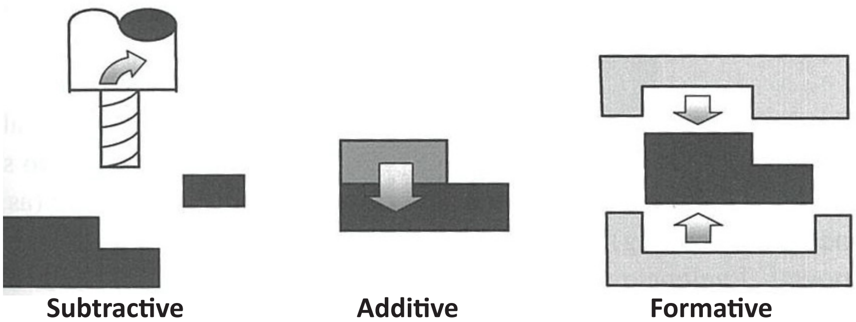


Figure 2.11. Three Types of Fundamental Fabrication Processes (Chua & Leong, 2014, p. 19)

2.2.3. Additive Manufacturing System Classification & Standards

Due to the constant evolving nature of AM technologies, multiple ways of classification were used. Chua & Leong (2014) describe a popular way of classification based on the material used to build the parts. This results in three main categories:

1- Liquid- based

2- Solid- based

3- Powder based

However, in an effort to standardize the industry, ATSM international collaborated with International Standards Organization (ISO) in 2011 and signed a Partner Standards Development Organization(PSDO) cooperative agreement (as cited in Chua & Leong, 2014, p. 14). In 2015 one of the results of that collaboration was the ISO/ASTM52900-15 classification (ASTM International, 2015) by which AM processes were classified into the following Seven categories:

1- Powder Bed Fusion

2- Directed Energy Deposition

3- Material Extrusion

4- Vat Photo polymerization

5- Binder Jetting

6- Material Jetting

7- Sheet Lamination

Figure 2.12. shows the seven different categories and includes a short description of each category as well as technology and material examples.

Additionally, ISO has proposed a new file format for AM known as Standard for the Exchange of Product (STEP) data (Chua & Leong, 2014).

2.2.4. Extrusion- Based Additive Manufacturing

2.2.4.1. Process

In a process visually similar to cake icing, elements are formed through extrusion; the material is placed in a container and through the application of force is deposited via a nozzle. Deposited/ extruded material is commonly referred to as “roads”. The application of constant pressure is crucial for a constant flow rate and a constant cross-section.

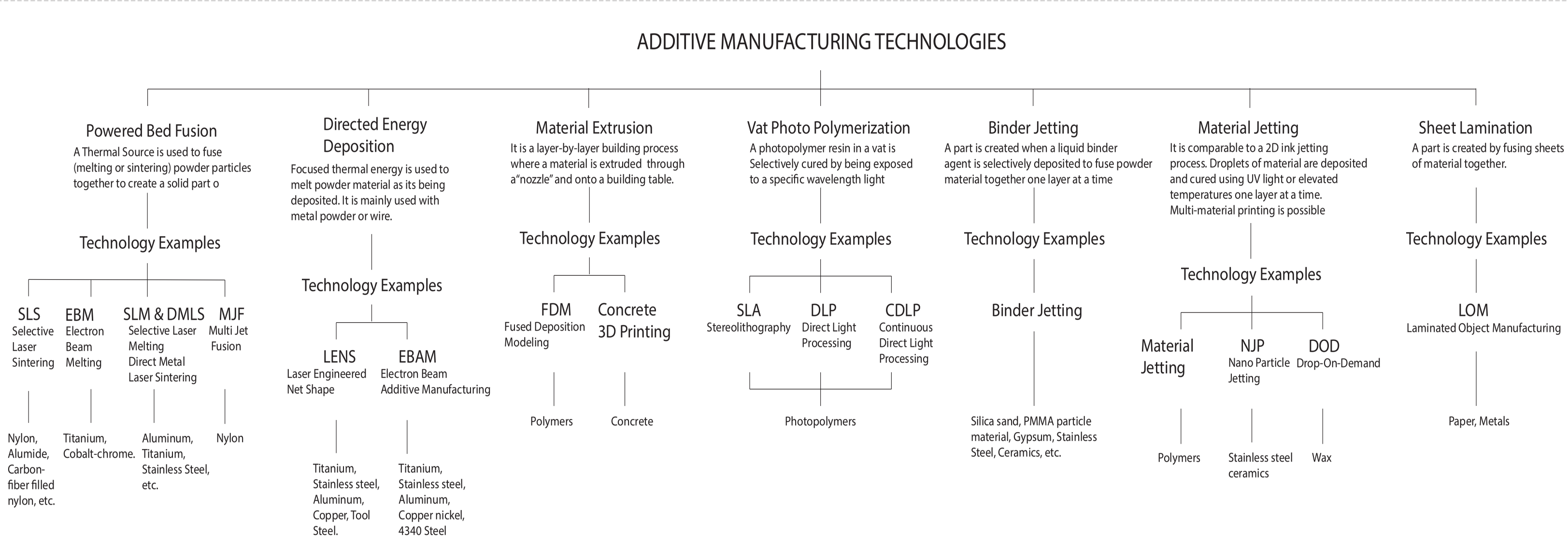


Figure 2. 12. ISO/ASTM52900-15 classification (ASTM International, 2015)

To further insure that the cross-section of the “roads” remains constant, the traveling speed should remain constant as well. The travel speed corresponds to the flow rate. Additionally, the deposited material must be in a semi-sold state to be extruded and it should harden fully in the same extruded shape. Bonding between the layers of the material is important to create a structurally sound component (Chua & Leong, 2015)

2.2.4.2. Types

There are two main approaches in extrusion-based AM systems:
1- Temperature manipulation: where different temperatures are used to manipulate the material state
2- Chemical changes: where a chemical reaction accrues and solidifies the deposited material. These chemical changes include the presence of a bonding agent, a residual solvent, a reaction to air when exposed or simply through a curing process (Chua & Leong, 2015).

2.2.4.3. Influencing Factors

Chua & Leong (2015) discuss the following important features in extrusion based additive Manufacturing:

Material loading:

In the extrusion process , the presence of a chamber were the material is kept is essential. In the chamber, the material is either pre-loaded or constantly fed through the use of a pump. The chamber is usually were the liquidation process takes place if the used material is in powder or pellet form. The material could be fed to the chamber using three methods:
Gravity (with the aid of a plunger or compressed gas), screw feeding, or a continues filament.

Material Liquefaction:

The material inside the chamber must be in liquid state in order for it to be pushed through the nozzle or die. It is either a solution that will quickly harden once deposited or is a liquid that results from a constant heating process in which coils are wrapped around the reservoir to generate heat. The applied heat should be adjusted carefully depending on the used material.

Extrusion:

The shape and size of the extruded material depends on the shape and size of the nozzle or die;

a larger nozzle will allow for faster material flow but will result in lower resolution. Additionally, the size of the nozzle determines the minimum size of the printed element. Normally, the desired structures should be large relative to the diameter of the nozzle in order to print elements with sufficient strength. For example, the ideal wall thickness should be twice the nominal size of the nozzle used for the extrusion.

Solidification:

Many factors affect the solidification process of the deposited material such as gravity, surface tension, and the cooling process (in the cased of molten material) resulting in changes in shape and size. Also, depending on the type of the material, shrinkage and increased porosity might occur upon drying.

Positional Control:

Extrusion- based systems print layers in the vertical direction (z axis). The printing head usually moves in the horizontal plane (x,y axis). Problems might occur if the plotting and the extrusion rate are not coordinated correctly thus resulting in non-consist deposition. Every time the printer head changes direction changes in speed must occur and the extrusion rate must adjust to compensate for the changing speed otherwise too much or too little material might be extruded.

Bonding:

After being extruded, the deposited material must solidify and adhere to the adjacent material layer. This bonding process is crucial o to form a satisfactory, structurally sound element.

Support Generation:

When a free-standing or disconnect feature is present in the printed part, supports might be need to keep those features in place during the fabrication process.

There are two types of supports:

- Supports made from the same material
- Supports made from a different martial

When the extrusion- based system only has one extruder head, the supports must be generated using the same material and care must be taken when designing and placing the supports in order to ensure a successful removal process in the end. If the supports are generated using a different material, a secondary extruding head is usually present and the support material has different properties such as a different visual appearance, different chemical properties, or different engineering properties. These different properties makes the removal process easier once the fabrication process is done.

2.2.4.4. Technologies

The most famous and most common extrusion-based AM technology is Fused Deposition Modeling (FDM) by Stratasys. A process by which a filament is fed to a heating chamber via a tractor wheel that also creates the pressure needed for the extrusion. Different types of polymers are used with this technology.

Another technology that is more related to this study is Contour Crafting developed by a team lead by Prof. B. Khoshnevis at the university of Southern California (as cited in Chua & Leong, 2015). In addition to the general principles of extrusion- based manufacturing, the team devised a scraping- tool that smooths the outer wall surface during the printing process. The main material used in this process is concrete (Chua & Leong, 2015).

More information regarding construction AM technologies will be discussed in the The "Use of Additive Manufacturing in Construction" section.

2.2.5. Additive Manufacturing Process Chain

Most AM technologies utilize the same five-step process chain (Chua & Leong, 2015):

1- 3D modelling:

Usually the most time- consuming part of the process. The most important thing to consider is making sure that the 3D model consists of closed volumes. Other things to consider are the orientation of the deigned part, the design and location of the supports if needed, and the presence of features that are difficult to print such as thin walls, voids, and overhangs.

2- Data Conversion and Transmission

After the 3D model design is finished, it is then converted to a file format knows as STL. The STL format triangulates the surfaces of the 3D model and depending on the presence of curves, the STL files might become very large as a result. Most CAD- CAM systems include a CAD- STL interface. Afterwards, the STL file is transmitted to the 3D printer via a thumb-drive, Local Area Network (LAN) network, email, etc.

3- Checking and Preparing:

In this step, the STL file is checked for errors such as the presence of shell- punctures (holes, cracks,etc.). These issues must be fixed in order to prevent failures in the fabrication process. There are software application that could be used to fix and optimize STL files, otherwise, the geometry will need to be fixed manually.

Once the STL file is deemed to be error-free, the model is sliced into cross-sections by the AM system's software for the fabrication process. Preparing the file for fabrication is a tedious task due to the different parameters that need to be considered such as geometry orientation, arrangement with other parts, slicing parameters, the need for support structures, and machine related parameters such as laser power, cure depth, etc. However, this task is made easier by the presence and continues development of user-friendly operating software that contain default values that could be altered easily. Moreover, these values could be retrieved to create specific profiles that can be used for other models.

4- Building:

Generally, this step is fully automated and depending on the size and number of the required parts, it might take several hours to finish a particular printing job. Another consideration is the constraints of the AM machine it self such as the building volume. Many modern machines are capable of remote communication which facilities monitoring and identifying issues.

5- Postprocessing:

This step occurs after the part is fully built, and might require some manual operations. Care must be taken due to the possibility of damaging the part. Some examples includes removing excess material, removing supports, using solvents for cleaning, sanding, or painting in order to improve the surface finish, and machining processes such as drilling and milling to add additional features. Figure 2.13. illustrates the aforementioned five-step process chain.

3D Modeling

The most important thing to consider when modeiling an object is making sure that the 3D model consists of closed volumes.

Data Conversion and Transmission

the file is thenconverted to an STL file format. The STL format triangulates the surfaces of the 3D model.

Checking and Preparing:

In this step, the STL file is checked for errors. Once the STL file is deemed to be error-free, the model is sliced into cross-sections for the fabrication process

Building:

This step is fully automated and depending on the size and number of the required parts, it might take several hours to finish a particular printing job

Image source:
3D Potter. (n.d.). 3D PotterBot 7. Retrieved June 30, 2018, from http://www.3dpotter.com/.

Postprocessing:

This is the final step. Some manual operations might be required. Examples includes removing excess material, removing supports, painting, drillin,etc.

Figure 2.13. AM technologies five-step process chain

2.2.6. Applications

Chua & Leong (2014) list a variety of applications, below are some of the important AM systems applications:

Applications in Design:

CAD Model Verification, Visualizing Objects, Proof of Concept, Marketing and Commercial Applications.

Applications in Engineering, Analysis and Planning:

Scaling, Form and Fit, Flow Analysis, Stress Analysis, Mock-Up Parts, Pre-Production Parts, Diagnostic and Surgical Operation Planning, Design and Fabrication of Custom Prostheses and Implants.

Industries:

Aerospace Industry, Automotive Industry, Jewelry Industry, Coin Industry, Tableware Industry, Geographic Information System (GIS) Applications, Arts and Architecture, Construction, Fashion and Textile, Weapons, Musical Instruments, Food, Movies.

2.2.7. The Use of Additive Manufacturing in Construction

2.2.7.1. History

The first attempt at construction additive manufacturing could be traced back to the work of Pegna (1997) where alternating thin layers of silica (matrix material) and Portland cement (reactive material) were used to build a small masonry structure. Water vapor was used to activate the cement. This early attempt has signaled a paradigm shift in construction manufacturing; parts could be built from Small and precise incremental additions rather than carving for example as has been done for centuries.

The construction industry has always been notoriously slow in implementing new technologies, this is perhaps due to the prototypic nature of construction and its wasteful use of material. Additionally, most previous automation efforts in construction has focused on replicating human labor and didn't seek to question the integrity of the process itself (Pegna,1997).
However, recent advances in construction- scale additive manufacturing has led to greater inter-

est in construction automation. This is further facilitated by with the development of BIM (Building Information Modeling) and its extensive use of digital information (Lim et al., 2012).

2.2.7.2. Large-scale AM systems Developed for Construction

Lim et al. (2012) discusses the three most prominent AM processes suitable for construction and architecture:

1- Contour Crafting 2- D-Shape (Monolite) 3- Concrete Printing

All technologies were used successfully to produce large- scale components and can be used on-site or off-site. The deposition head can be frame, robot or crane mounted. Figure 2.14. shows Examples of full scale builds from each process.

Contour crafting is a crane mounted system that can be used both on, and off site. Both D-Shape and Concrete printing are gantry- based systems and designed to be used off site. These processes use different materials and were developed for particular applications. The differences are mainly in speed, resolution, smallest possible details, finishing and post processing, and hardening times and properties. Both Contour Crafting and Concrete Printing are wet processes that extrude a Cementitious mortar while D-Shape is mainly a dry process that uses a powder deposition system.

The unique feature in Contour Crafting is the presence of a trowel that smooths the outer surfaces that are created through the layer extrusion process. In addition to creating a smoother surface finish, the system addresses the issues associated with high-speed automated construction. Concrete Printing also follows the same principle, consecutive layer deposition of a cement mortar, the difference however is that smaller resolution which allows for more detailing and more freedom of design. D-shape's main drawback is the considerable amount of powder material that needs to be deposited and then removed at the end to expose the built structure.

2.2.7.3. Materials

A high-performance cement-based mortar has been developed for Concrete Printing. Generally, the extrusion process is influenced by mix design, mix particle size, and the stability produced by the bonding capacity of the material after deposition. The larger the diameter, the faster the printing. Hardening of the material might be affected by the chosen system. Finally, when reinforcement is needed, mesh can be added for extra support (Lim et al., 2012).

A B

C

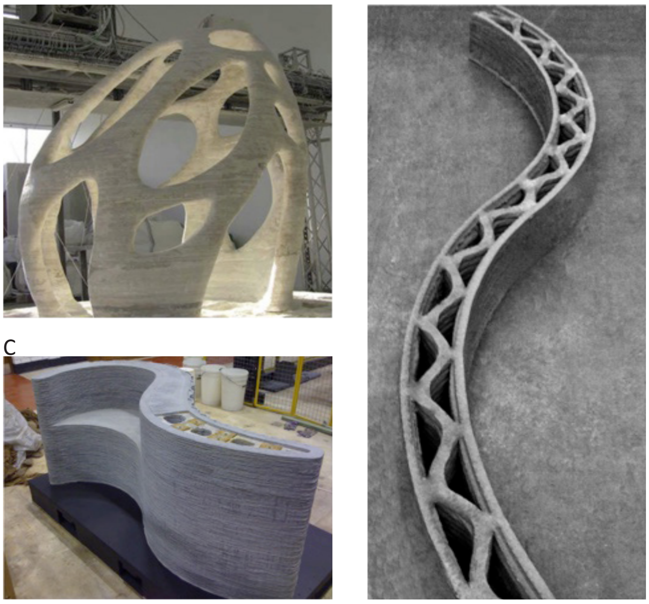


Figure 2.14. Examples of full scale builds from each process, (A) D-Shape, (B) Contour Crafting, and (C) Concrete Printing (Lim et al., 2012, p.263)

2.2.7.4. Advantages & Disadvantageous

The use of AM systems in construction creates great opportunities to save cost such as limiting the need for formwork, more safety in construction sites due to the reduction of worker numbers ,and by way of design optimization, reducing material waste and construction time leading to cost reduction. Also, working in a digital environment offers designers greater design freedom and flexibility and the presence of the texture could give a sense of "materiality" and could inform the design of the object. However, there are disadvantages to using AM systems in construction, the main disadvantage is related to the scale difference as the large, industrial- grade 3D printers needed for construction generally require higher energy levels to process printing. Other disadvantages include occurrence of technical issues such as too much martial deposition due to material flow interruption, too little material deposition, and material sensitivity to exterior conditions (Lim et al., 2012). In the end it is important to remember that It is still an emerging technology and further development and research is needed.

2.2.8. AM System Testing Parameters

Since the most popular application of construction AM systems is concrete 3D printing, most advances have been made to the machines as well as relevant concrete mixes to improve the printing process (Soltan & Li, 2018). As such, this study will employ the same methods and tests developed to test the earth- based mixture being presented and will treat it as a "cementitious" material.

The study done by Lim et al. (2012) stresses that the wet properties of cementitious materials are a crucial factor that has a great effect on the success of the manufacturing process and identifies Four key wet- material characteristics:
Pumpability: The movability of the material through the delivery system.
Printability: The capacity of the material to be deposited through the deposition system.
Buildability: The ability of the material to resist deformation under the load of the consecutively printed layers.
Open-time: Is the consistency of the above mentioned properties within the accepted tolerance of the 3D printing system.

2.2.8.1. Printability Evaluation

Generally, Printability depends highly on workability which is defined as a property of freshly mixed cementitious materials and is used to describe its rheological behavior. Several deterministic tests exist such as a tilt table test. These tests are done at regular time intervals after initial mixing and generate data that shows the stiffness of the material overtime (Soltan & Li, 2018).

Once a material is deemed as having proper workability, several factors, in addition to the factors mentioned above, need to be balanced in order to achieve proper printability, these factors are (Soltan & Li, 2018):
Extrudability: which is the ability of the cementation material to pass or be pumped through a small pipe or extruder and then be deposited evenly and continuously in its fresh state.
Inter-layer adhesion: which is defined as the capacity of the adjacent layers to create a strong bond and yield a structurally sound cohesive unit.

In basic terms, the ideal material should behave in following manner; it should be workable before printing, extrudable and buildable during printing, and hardens rapidly after printing in order to produce a part with structural integrity.

However, in order to achieve adequate balance, the competing nature of some of the factors need to be considered. Such is the case with Extrudability and buildability; the more workable the material the more extrudable it is, but the less workable the material the more buildable it is. Furthermore, low workability has a negative effect on inter-layer adhesion and increased followability could cause material segregation or the failure of the cementitious material to maintain a consistently heterogeneous state throughout the 3D printing process (Soltan & Li, 2018).

Extrudability It is influenced by mix design, mix particle size, and the stability produced by the bonding capacity of the material after deposition. In order to evaluate extrudability, usually a visual test is conducted where several tracks of the same length and diameter from different mixes are printed, mixes that produce minimum fracture and blockage are chosen (Le et al., 2012).

Buswell (2018), explains that due to the absence of formwork and the hydrostatic pressure caused by the increase of the built height and the number of layers, the bottom layers tend to compress under self-weight and this could cause buckling and eventually a complete collapse of the structure. The speed of printing, shape of filament, inter-layer adhesion, and early mechanical behavior are some of the factors affecting buildability. Buildability is usually evaluated visually by monitoring the number of layers that could be deposited without causing deformation to the shape of the bottom layers (Le et al., 2012).

Open-time has a strong relationship with setting time or the loss of slump in concrete. It also related to the volume of the printed component, the size of the work area which also determines the length of the printed filaments per layer, as well as the prepared batch volume (Buswell, 2018). One way to determine open-time is to assess the mix's workability at different intervals.

2.2.8.2. Mechanical performance evaluation

In order to assess the compressive strength of a chosen mix, a Unconfined Compression Test (UCS) is usually done. Specimens that are both printed using an AM system and those that are not printed (control specimens) are tested. They are left to dry in room temperature and left to cure for 28 days.

Based on previous research such as a study done by (Lim et al., 2012) where concrete was used the compressive strength of the 3D printed specimens is usually between 80% to 100% of the standard cast equivalent. There is no significant difference in flexural strength between in-situ extruded specimens and traditionally cast specimens, however, this depends on the direction of the printing orientation; testing has shown that the part is usually weaker when the loading axis is parallel to the direction of deposition .

2.2.9. AM System Used for this Study (3D Potterbot 7 SUPER)

The printer used in this study is a medium size, ceramics, heavy duty 3D printer manufactured by 3D Potter, Inc. located in Florida, U.S.A. Figure 2.15. shows the 3D Potterbot 7 SUPER appearances and general specifications (3D Potter, n.d.).

In this study the mixture used will be earth-based and since the material behavior depends on the used AM system, it is important to note that the testing results generated by this study only corresponds to this printer. However, some general points could be deduces and applied to other similar systems and materials.

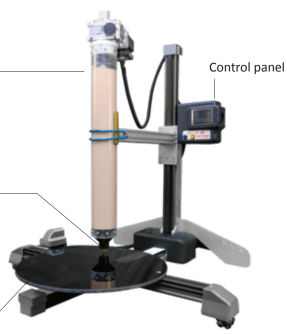


Image source:
3D Potter. (n.d.). 3D PotterBot 7. Retrieved June 30, 2018, from http://www.3dpotter.com/.

Name:	3D Potterbot 7 SUPER
Company:	3D Potter, Inc.
Type:	extrusion based, ceramic and paste 3D printer
Capacity:	3600 ml direct nozzle extruder
Nozzle:	Maximum nozzle diameter is 6mm
Printing Envelope:	X (432 mm), Y (356 mm), Z (483 mm)
Print Table Size:	diameter is 349mm
Speed:	average printing speed is 55 mm/s
Power consumption:	24 volts +/- 2 amps
Arm processor Cortex:	M3 100 - 120 Mhz

Figure 2.15. 3D Potterbot 7 SUPER Specifications

2.3. Context in Sudan

The importance of this section lies in the fact that the earth additive manufacturing process is a location- sensitive one, and relies heavily in its design on the local materials, and the local geographical and climate conditions. The design process also takes into consideration the local culture and the common design features , then uses that information to generate forms that are familiar but also appealing to the consumer.

2.3.1. General Information

Sudan used to be the name of the lands locates south of the African Greater Desert in the west all the way to the Red sea and the Indian Ocean in the east. However, the modern country Sudan is located south of Egypt and the center of the Nile basin.

Sudan has an area of 1.886 million km^2 making it the second largest African country and the third largest Arab speaking country. It is located in the northeastern part of Africa between the 22.4 latitude northern equator and 38.22 longitude and is neighbored by Egypt and Libya to the north, Chad and Central Africa to the west, Ethiopia, Eritrea, and the Red Sea to the east, and South Sudan to the south.

The main religion is Islam although there are a minority of Christians and other local beliefs. The main language is Arabic in addition to local dialects (Sudan Ministry of Foreign Affairs, 2016).

Sudan much like other developing countries in Africa, witnessed an explosive rate of urban growth especially in the last four decades (Pavanello, 2011). Between 1973 and 2005 its capital Khartoum grew by a factor of eight which the equivalent of a 6% annual rate of growth (Murillo et al., 2009). Currently, Khartoum has the highest population density and is home to around 26% of the country's population of 43,148,408 (HABITAT, 2012; World Population Review, 2019)

Figures 2.16. Shows Sudan's location within the African continent. Figure 2.17. shows the typography while Figure 2.18. provides climate information.

Figure 2.16. States and Major Cities of Sudan

Figure 2.17. Sudan Satellite Image showing Topography (source: Google Earth

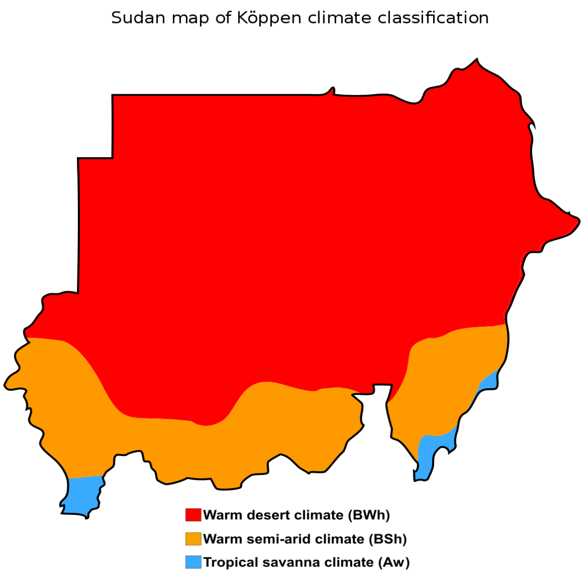


Figure 2.18. Sudan Map of Koppen Classification By (Ali Zifan, n.d.) (Enhanced, modified, and vectorized). - Derived from World Köppen Classification (with authors).svg., CC BY-SA 4.0

2.3.2. Soil Types of Sudan

30% of Sudan is covered in expansive soils such as black cotton. These soils are problematic due to the presence of the mineral montmorillonite which causes high swelling and shrinkage rates. In order for these soils to be safely used in construction applications, they need to be stabilized. It doesn't help that these soils are found where most of the country's major towns and cities are located (Zumrawi & Mohammed H., 2016).

Adam(2001) describes three main types of soil in Sudan (Figure 2.19.):

1- Black cotton soils (Badobe):

Is dark in color and was originally used to grow cotton and has a high clay content. Its plasticity makes it difficult to handle after it is mixed with water, but it is the most popular building material in Sudan because It is found in large areas in central Sudan where almost two-thirds of the Sudanese population resides. Buildings made using this type of soil have a short life span (around 15 years) and require constant repair. Due to its abundance, more research need to be done to improve soil quality.

Some important property information:

- Color ranges from dark grey to dark brown,
- Extreme expansion and shrinkage properties upon wetting and drying
- High Clay content around (35%) (clay is defined as soil fraction containing particle sizes less than 0.002mm)
- Atterberg limits : liquid limit (LL) is between (47% - 93%), plastic limit (PL) is between (26% - 50%) the plasticity index (PI) is between (13% - 58%) the linear shrinkage (IS) between (8% - 18%)

2- Red sand ironstone soils (Goz):

Formed from the breakdown of the Nubian sandstone rocks found in west Sudan. It's found in large areas approx. 7% of total area (before split)). Although property knowledge is limited, villages in the area built dwellings from this soil that show greater durability than dwelling built using black cotton soil. Perhaps due to it's low clay content which limits swelling and shrinkage and makes structure built using this type of soil more durable.

3- Laterite and lateritic soils:

Are red-iron rich soils that contain a variable and large amount of iron, aluminum dioxide, quartz, and other minerals. Usually found in tropical and sub-tropical climates.

The clay content is soil is the most important factor in determining the appropriate stabilizer. Clay provides adhesion. Clay is also important for insuring 'stickiness' providing good adhesion properties for the AM process.

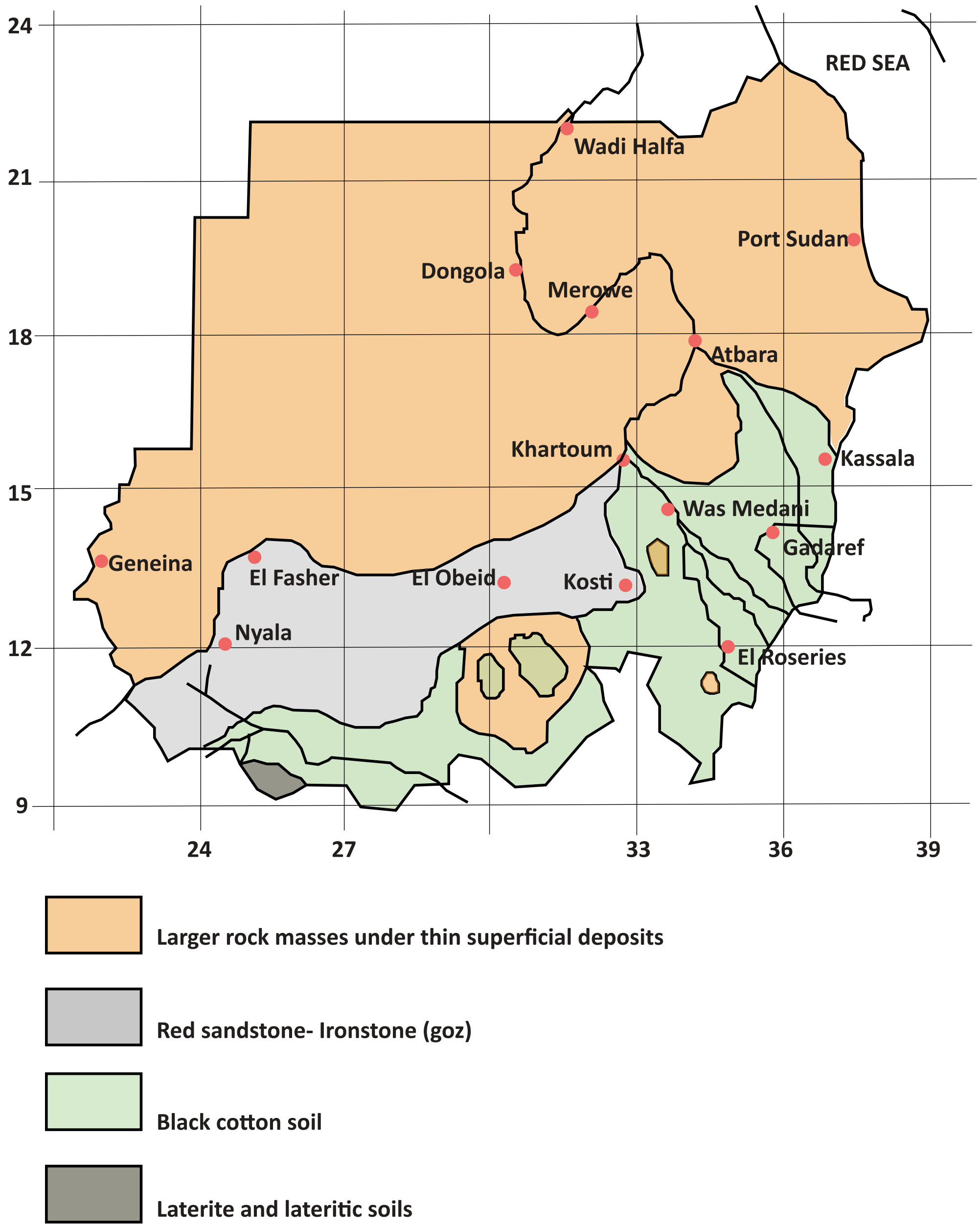


Figure 2.19. Distribution of main soil types across Sudan recreated from (Adam, 2001, p. 13)

2.3.3. The Impact of Urbanism and Internal Conflict

Khartoum is considered the hub of all political, economical, and educational activities (Omer, n.d.), it is divided to 3 main states: Omdurman, Khartoum and Khartoum North. Consequently, it is the main destination for all those who are moving from the other parts of the country. This is mainly the result of the centralization of power by the governments of Sudan (Elkhalifa & Shaddad, 2011).

Sudan has a long history of internal conflict the started since even before its independence in 1956 from the Anglo-Egyptian control. It started with the first civil war that lasted from 1955-1972 between the government of Sudan and the Sudanese People Liberation Army (SPLA). The second civil war was also between the government of Sudan and the Sudanese People Liberation Army (SPLA) between 1983-2005. The most famous and ongoing war is in the Darfur region that broke out in 2003 . This war is the fueled by the conflict between the Arab and African ethnic tribes on one hand and informal militias on the other hand. As a result, it is estimated that around 30% of the IDPs fleeing the conflict zones are resided in Khartoum (Omer, n.d.).

The Internal displacement crisis caused by the war reached its peak in 2005 at 6.1 million IDPs. Considered one of the worst in the world at that time. In recent years these numbers have decreased dramatically but as of the end of 2018 the number of IDPs was estimated at at least 2.1 million (IDMC), 2019).

The impact of this civil upheaval affected all facets of life in the country. For the construction industry this had a huge impact; the lack of security in these zones meant an almost complete halt of all construction projects due to the lack of funding, transportation, skilled labour, and the scarcity of construction materials and technologies (Elkhalifa & Shaddad, 2011).

In addition to the great influx of migrants trying to escape poverty or civil wars, other issues such as the rapid horizontal expansion accompanied by the low-density residential areas are exasperating the housing problem in the city of Khartoum (HABITAT, 2012). This meant that many live in slum-like conditions without adequate shelter and access to basic services.

2.3.4. Current Slum Conditions in the City of Khartoum

An article titled “Policy Reform, not Evictions! The Case of Slum Urbanisation in Khartoum, Sudan” by Khalafalla Omer (2018) asserts that as Khartoum’s population continues to increase, the problem of rapid “slum urbanisation” will continue to grow if no interventions by the government are made. It noted that this trend had been developing for the past 60 years; in 1960 only 5% lived in what are considered slum conditions, by 2010 this percentage had jumped to around 45%.

The article also estimated that currently around 50% of the city’s resident live in informal/ squatter settlements around the periphery of Khartoum. These household have no access to city services such as access to clean water, electricity, and swage disposal. Some are built haphazardly using card board, corrugated iron sheets, or basic mud techniques. Overcrowding is also a huge problem in these types of settlements. As a result, they are extremely venerable to external hazards such as extreme climate, spreading of disease, and crime.

When it comes to the government efforts the article describes them as lagging behind which further exasperates the problem. For example, when designing public housing, the general policy is to place the housing units far away from the city center rendering them inaccessible using public transport. These units also are very far from the important institutions located at the center of the city such as places of work, schools, and hospitals. Additionally, Instead of upgrading the current conditions in slum areas the government exercises forced evictions without notice or plans of relocation.

It is clear that the government efforts, and public housing polices are not sufficient enough to deal with the worsening slum conditions in the city of khartoum. As such, there is a great need for innovative solutions, especially ones that target the upgrading of the building structures in the slum settlements.

Figure 2.20. displays an image showing a slum area in the city of khartoum.

Figure 2.20. Abubaker-Abas, N. (2014). Slum Conditions in the City of Khartoum. Retrieved from https://atlascorps.org/khartoumcity-of-condradictions/

2.3.5. Residential Units Cultural Considerations

Sudan is a majorty muslim country which has a direct impact on the house design; females and males are usually sperated and have diffrent quarters. As such, detached houses are considered the most popular housing units. Bedrooms have multiple uses in a Sudanese house; as secondary living rooms.

Additionally, yard space is very important. Usually there are two yard spaces one for females and the other for the males and male guests,this yard is usually positioned at the front of the house.

In a survey done by (Mohammed & Kurosawa, 2005), the most popular layout was found to be the one showed in Figure 2.21.

Figure 2.21. The Most Popular House layout in Sudan Adobted from (Mohammed& Kurosawa, 2005, p. 16)

2.3.6. Issues facing the Construction Industry In Sudan

In a study done by Elkhalifa & Shaddad (2011), several factors affecting the construction industry **in Sudan starting with production of construction material:**

- Material production is lagging behind in the whole country but conflict areas are affected the worst.
- According to the UNCHS, Construction materials account to between 50%-80% of construction cost (as cited in Elkhalifa & Shaddad 2011,p. 99)
- According to Shaddad, In developing countries like Sudan construction materials and components can account up to 20 -30% of imported goods (as cited in Elkhalifa & Shaddad 2011, p. 101)
- Most modern construction techniques are used in the Capital Khartoum and other big cities.
- Most building materials are imported
- Some cement plants could be found in Khartoum and a few other cities, but there are no plants in the west, east, south of Sudan. Some simple building materials can be found in the local markets like sand and gravel, but most finishing, decorative, electrical, mechanical elements are imported from abroad.

Challenges facing the construction industry in Sudan:

- Low capabilities of the construction sector according to Du Plessis (as cited in Elkhalifa & Shaddad 2011,p. 106).
- Inadequacy or lack of regulatory organizations UNCHS (as cited in Elkhalifa & Shaddad 2011,p. 106).
- Inadequacy or lack of quality control, national standards, and clear specifications.
- Poor organization.
- Complex procedures and regulations.
- Lack of technical, supervisory, managerial skills, adequate finance, materials, equipment and skilled personnel UNCHS (as cited in Elkhalifa & Shaddad 2011,p. 107)
- Lack of planning.
- Fluctuating and inconsistent construction activities.
- Lack of economic wisdom specifically in design, construction, and the fabrication of building materials according to Wells (as cited in Elkhalifa & Shaddad 2011,p. 107).
- Finance deficiency, UNCH (as cited in Elkhalifa & Shaddad 2011,p. 107)
- Scarcity of dependable data, according to Du Plessis and Palalani (as cited in Elkhalifa & Shad-

dad 2011,p. 107)

- Lack of innovation, according to Milford (as cited in Elkhalifa & Shaddad 2011,p. 107)
- Lack of adequate well integrated academic research, according to Du Plessis and Ofori (as cited in Elkhalifa & Shaddad 2011,p. 107)
- High rates of risk taking and ambiguity, according to Du Plessis and Okema (as cited in Elkhalifa & Shaddad 2011,p. 107)
- Corruption.
- Absence of training programs and thus skilled labor.

Problems specific to building materials:

- Insufficiency
- High prices due to high transportation, manufacturing, and energy costs.
- Material scarcity specifically of locally produced materials according to wells (as cited in Elkhalifa & Shaddad 2011,p. 108)
- Dependency on important materials and reliance on certain conventional materials according to wells (as cited in Elkhalifa & Shaddad 2011,p. 108).

Political and Economic factors:

- Development is mostly centralized in the capital Khartoum and other big cities.
- In developing countries, the impact of the growth of the construction industry on the country's development is bigger than developed countries.
- Due to political instability and its impact on economic growth, Sudan has high rates of inflation thus instable exchange rates and low rate of investments.
- As in a lot of other developing countries, political corruption is rampant.
- The major reasons for political instability and civil wars in Sudan are political and economic marginalization felt by certain groups.
- Civil wars resulted in destruction, neglect, and a major halt in the development of infrastructure in war stricken areas in addition to displacement of locals.
- Civil wars are creating and economic strain resulting in the suspension of some development projects and stopping others indefinitely.
- The housing market was severely affected resulting in a huge gap between supply and demand.
- Investing in real state is considered risky resulting in the reluctance of the private sector to

invest in construction.

Social factors:

In the eyes of most Sudanese people, earth is considered an inferior building material and associated with low socio-economic status. Consequently, this social resistance in accepting soil as a building materials resulted in governmental institutions not developing the appropriate standards and codes (Adam & Agib, 2001).

2.4. Current Research in the Field of Earth Based Additive Manufacturing

Earth- based additive manufacturing is an emerging field and research studies are few and far between. But some research is being done and so far it is showing a lot of promise.

One such example is a study done by Perrot, Rangeard, & Courteille (2018). The main focus here was initial green strength. A Soil from Saint-Sulpice- la- Foret was chosen. The soil is defined as a fine soil with a Particle size distribution PSD of 60% of the particles finer than 10 micro millimeter. The plasticity index is 21, liquid limit is 48%, and plastic limit of 27%. The used water content is 45%. The soil was mixed with commercial alginate "is a family of seaweed biopolymers which are alginic salts obtained from the cell walls of brown seaweed" Perrot, Rangeard, & Courteille , 2018,p. 671) from Cimaprem (Redon, France)was used in this study. In comes in a form of white powder of alginic salt Cimalgin HS3.

The 3D printer was made up of a six-axis industrial robot designed by Staübli robotics with a load capacity of 195kg. It has a TP5 Giema electric pump designed specifically to handle render/ mortar. The maximum pump pressure is 20 bar, and maximum flow rate is 40 L/min.

In the study, early green strength, compressive strength and rheological behavior were measured as well as the mechanical performance of the printed samples.

The study concluded that the addition of alginate helped the soil gain sufficient strength more quickly which resulted in printed samples that have a compressive strength equivalent to the compressive strength generated by traditional cob mud construction. The study highlights the great potential of using earth-based AM and recommends combining the technology with topology, environment, and cost optimization tools. It also recommended the use of a rectangular cross section as it resulted in printed samples with improved compressive strength.

Another study named ‘Pylos’ was done by the Institute for Advanced Architecture of Catalonia (IAAC) in Barcelona (Giannakopoulos, 2015). It was conducted with the same approach of the previous study; mixing soil with an organic material to create a bio- polymer. No specific detail was given regarding the constitution of the used organic material, it only states that the first stage of the research yielded a material that is 95% soil and has 3 times tensile strength than industrially produced hard clay and that the project is motivated by “unbaked soil properties”.

The final example being reviewed in this section is the work done by the World’s Advanced Saving Project (WASP). It is a project that is focused on developing reliable and professional 3D printers that encourage sustainable development and in-house production and was founded in 2012 by mechanics and electronic Italian company Centro Sviluppo Progetti (CSP) (WASP, 2016).

WASP focused much of its attention on the low- cost aspect of earth- additive manufacturing. They designed a low-cost, easy to build 3D printers such as the ‘BigDelta 12’, a 12m high and 7m wide printer that could be assembled using 6m modular arms. The printer uses about 220 volts of electricity but is able to use as little as 60 volts with the integration of solar panels. They also experimented with a variety of additives ranging from cement to popcorn as well as fly-ash, and used long-fibers (organic and synthetic) to add tensile strength. They also emphasized the use of locally available materials with as little processing as possible.

The main takeaway from their results is the importance of lowering the cost of the 3D printing process by developing robust, modular printers that could be assembled on site, and lowering the amount of energy used by incorporating other energy sources such as solar energy.

However, no specific results regarding mix design and development were published as of the time of this study so it isn’t clear what the final results were.

2.4.1. 3D Printed Housing Example; Apis Cor

As there are no current examples of fully equipped housing built using an earth- based AM system, a housing example built using a concrete 3D printing process will be discussed instead.

a Russian company called Apis Cor, built a fully equipped house in one day using a mobile 3D printing system and a concrete mix in 24 hrs and claimed to have saved 25-40% in construction costs.

Apis Cor recently received a lot of attention when they 3D printed this whole house in just 24 hours. (2018). photograph. Retrieved from https://www.3dnatives.com/en/apis-cor-3d-printed-house-060320184/

Figure 2.22. A Concrete Housing Unit 3D printed by Apis Core in 24 hrs

A mobile construction 3D printer was used to build directly on site. The printer is light enough to be transported using a standard truck and the printing preparations on site took around 30 min. The printing mix consisted of a sand-cement mixture mixed with accelerants that increased setting strength as well as viscosity. The accelerant types were not disclosed. The total construction cost was reported to be $10,134 (3D Nativs, 2018).

Although this example is a lot expensive than the target housing units in this study due to the different target demographic. It illustrates the potential of construction additive manufacturing.

2.5. Conclusions

- Earth is the oldest building material known to man and the beginning of earth construction could be linked to the formation of early agricultural societies around 12,000 to 7000 BC.

- African vernacular architecture has a long history of building with mud. The temporariness of mud buildings served cultural and geographical needs.

- In African architecture there are no noticeable differences in the appearance of rich and noble residences. However, in agricultural cultures granaries gained prominence as they were built taller than other buildings.

- The integration process of 3D printing technologies into the construction industry is very slow but shows a lot of promise.

- Like all developing countries, there is a great need for low- cost housing in Sudan especially in the slums of Khartoum

- Building using mud is currently gaining traction, however, there is still a lot of resistance due to the association of mud building with low socioeconomic status and the lack of good and modern examples.

- As cost is the main issue when designing low- cost housing, careful selection of cost- effective material is paramount. The focus should be on locally available material and the reduction of 3D printer prices.

- Not a lot of research exists in the filed of earth- based additive manufacturing, mix design and machine development studies are greatly needed.

CHAPTER 03
RESEARCH DESIGN

3. Research Design

3.1. Introduction

The purpose of this chapter is to clarify the methodological framework and outline the various steps taken to plan, design, and execute this study.

The chapter starts with a research overview where the research questions and purpose are reiterated in order to align them with the chosen methodological approach. Then, a research strategy section will explain the reasons behind the selection of the research's strategy and how it was developed. Afterwards, an explanation of how the data was sourced, generated, and analyzed will follow. Finally, the chapter ends with a detailed explanation of the methods used in every step of this research.

3.2. Research Overview

As explained in chapter one, the main purpose of this study is to examine the use of a soil, fly-ash, and alkaline activation mix, in an additive manufacturing system to build low-cost, temporary housing for the urban poor in Khartoum the capital of Sudan. The architectural design is inspired by elements from local African vernacular architecture.

As such, the main question of this research is: **RQuestion 1: is the use of an earth based additive manufacturing process suitable for creating low-cost housing for Sudan?**

But, in order to effectively answer the main question, it's broken- up into smaller question that are then used to guide the methodological approach:

RQuestion 2: What would be the appropriate building (shape) ?
RQuestion 3: What is the best soil type, additives found in Sudan for the AM process?

RQuestion 4: How durable are the structures that result from the 3D printed process when soil is used as the main component?
RQuestion 5: Does it make economical sense to used 3D printing of earth mixture in place of the traditional mud building techniques in Sudan?
RQuestion 6: What are the steps needed to promote cultural acceptability of AM mud construction?
Figure 3.1. and 3.2 illustrate the research strategy and how each of the testing methods was aligned with the appropriate research's question.

3.3. Research Strategy

The approach for the study was developed based on the reviewed literature. As mentioned in the earlier chapters, the earth based additive manufacturing process is a novel one, and there is little research done on the appropriate methodology. Consequently, researchers had to borrow and adapt tools usually used in concrete 3D printing (as cited in Perrot, Rangeard, & Courteille, 2018, p. 670). Additionally, since this study deals with soil and soil mechanics, some standardized tests from the Geotechnical field were adapted as well. All of the standardized tests will follow the Japanese Geotechnical Society Standards (The Japanese Geotechnical Society (JGS) , 2018).

The goal of the first step in the methodological approach is to select a shape suitable for the low-cost housing units, this is done through reviewing the literature and identifying a common architectural language as well as important cultural and religious influences specific to the research location. This step is then followed by a soil selection process by which crucial information regarding the soil's plasticity index and composition is gathered. Then information regarding mix composition including the percentages of both the fly-ash and the alkaline-activator, as well as, the water content is also gathered. Once the initial mix composition is determined, a series of tests will take place using the 3D printer where printability and workability are assessed and that information is then used to further inform the mix design. The main goal of this step is to insure that the earth mix is compatible with the 3D printer and can result in a successful printing process. Afterwards, standardized tests will be performed on mix samples in order to asses its physical and mechanical properties. Finally, a mock-up test where a true to scale wall section will be printed in order to asses time and cost.

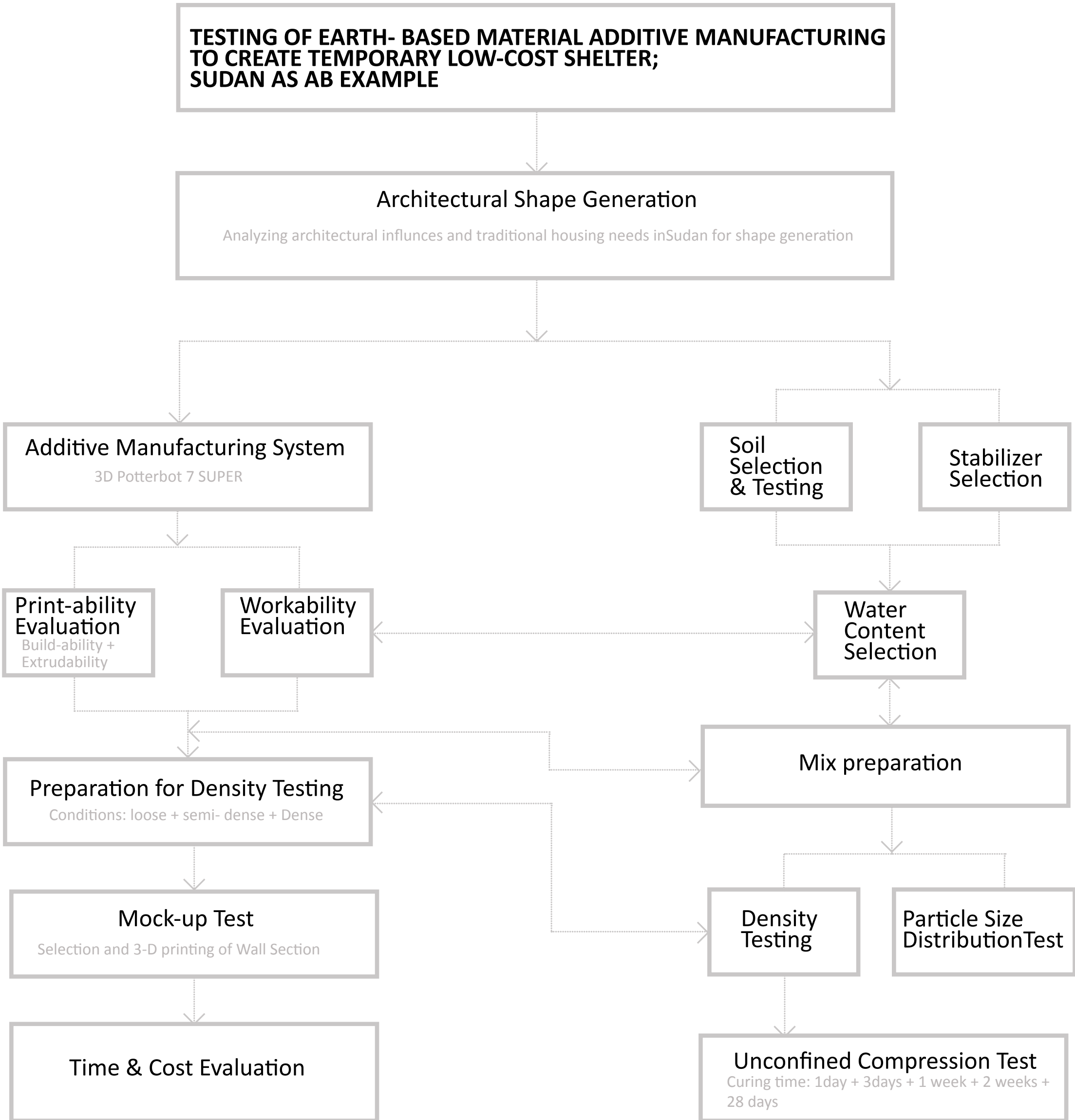


Figure 3.1. Research Framework

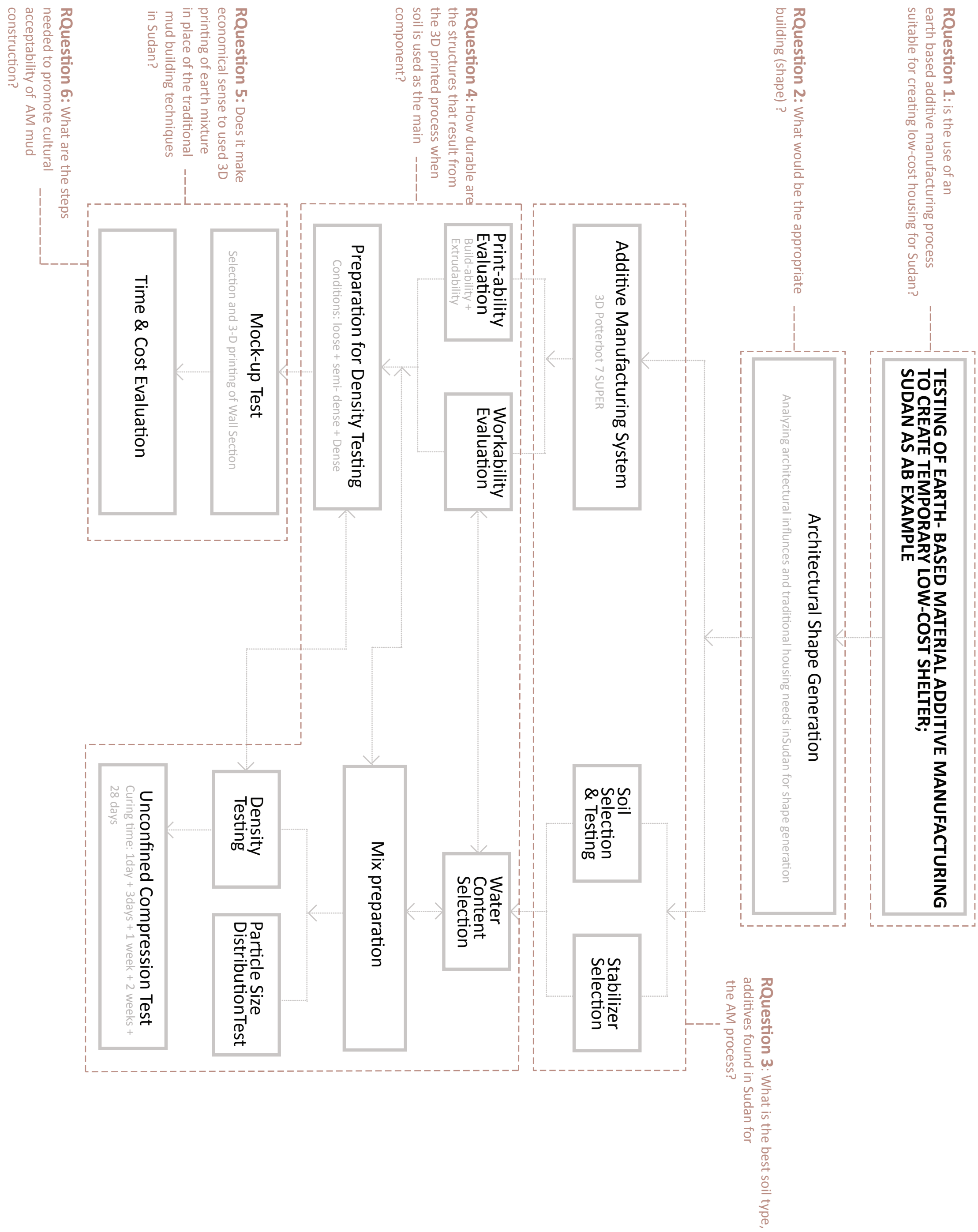


Figure 3.2. Research Questions aligned with Research Framework

However, It's important to mention that the collected data is only relative to the testing apparatus, since every 3D printer has different capabilities, new testing will have to be done to create a compatible mix. However, the testing methods used in this study can be generalized and used to asses different mixes and 3D printers as has been done in the referenced literature (Lim et al., 2012; Perrot, Rangeard, & Courteille, 2018; Soltan & Li, 2018).

3.4. Data Collection and analysis

Both primary and secondary data were collected for this study. The secondary data was organized from the literature and involved data pertaining to local vernacular architecture, soil types of Sudan, as well as information from previous testing of earth-based additive manufacturing processes. Another sources for secondary data was data that resulted from communications with World's Advanced Saving Project (WASP), where three soil data samples from different areas in Khartoum, Sudan collected from the literature were sent via e-mail and WASP technicians responded by choosing a favorable soil for the AM process. Secondary data was also collected from several meetings with experts in all of the relative fields to this research (geotechnical engineering, structural engineering, additive manufacturing).

Primary data was collected from the initial soil mixing process throughout the development of the soil/ additive mix. Another set of primary data was generated from the printability and workability tests performed on the 3D printer. Data was also collected by observing the speed, shape, and consistency of the 3D printed components. The standardized physical and mechanical testing of the mix samples yielded data that was used to asses the mechanical and physical properties of the developed soil mix. Finally, data regarding the projected time and cost assessment of the earth-based additive manufacturing process was collected from printing a full-scale wall section and calculating the amount of used materials and total time of printing.

The data analysis process was done using Microsoft Excel 2019 where the raw data was fed directly to Excel and various charts and plots were generated. The analyzed data was then used to draw conclusions relative to testing results.

Figure 3.3. shows the names of the various software used throughout the study and the specific tasks they were used for.

Rhino 3D is used for 3D modeling By Robert McNeel & Associates	Adobe Photoshop is used for photo editing and modification By Adobe Inc.
Used for slicing 3D model and generating Gcode for 3D printer By Simplify3D	Adobe Illustrator is used for line drawigns and color adjusments By Adobe Inc.
Microsoft Excel is used for all data analysis By Microsoft Corporation	

Figure 3.3. Software used in Study

3.5. Research Methods

3.5.1. Initial Investigation

It was clear from the beginning that this study will require a multi- disciplinary approach. As such, several meetings with experts from the civil engineering department, more specifically, from the concrete design and geotechnical engineering departments were conducted. Meetings with experts in the field of additive manufacturing were also conducted. In addition, to better understand the earth additive manufacturing process, contact with WASP a leader in the field was established.

As a result, crucial information regarding the best approach for this study were gathered. The first step was to understand the type of soil that this study will be using in the AM process. Since the location for this study was Khartoum, Sudan, a general understanding of the most prominent soil type was done.

Generally, there are three main soil types in Sudan: Black cotton soils (Badobe), Red sand iron-stone soils (Goz), Laterite and lateritic soils (Adam,2001). Black cotton is an expansive and problematic soil that covers around 30% of Sudan. The presence of the mineral montmorillonite causes high swelling and shrinkage rates. In order for these soils to be safely used in construction applications they need to be stabilized. Also, these soils are found where most of the country's major towns and cities are located (Zumrawi & Mohammed H., 2016). The capital Khartoum is located in the central area where it is mostly covered in black cotton soils. Through this initial investigation, it was found that soil samples cannot be imported outside of Japan due to governmental regulations. Instead, artificial soil will be mixed to mimic the properties of the chosen soil from Sudan.

Afterwards, a deep investigation of the literature was conducted and focused on vernacular African mud building, soil mechanics, earth construction, the Additive manufacturing processes, and the appropriate AM technology for this research. It was concluded that the best AM technology capable of extruding a dense viscous material was 'extrusion- based additive manufacturing' the same technology used in concrete 3D printing. After contacting several vendors, a medium size, ceramics, heavy duty 3D printer manufactured by 3D Potter, Inc. located in Florida, U.S.A. was chosen as the test apparatus.

When searching for additives the main focus was finding an additive that was capable of improving soil properties, can be locally found, and is low-cost. After consulting experts and the literature, fly-ash was chosen. Fly-ash is a fine powder composed of mostly silica and results from burning finely crushed coal inside a boiler for electricity production. When mixed with soil, Fly-ash prompts a chemical reaction that results in a decrease of the soil's plasticity index and its shrinkage limit. Fly-ash is from a class of cementing admixtures favorable due to their low cost and strong pozzolanic action (as cited in Nath, Molla, & Sarkar, 2017,p. 1). Disposing of fly-ash is a serious environmental problem, and currently, fly-ash is used in geotechnical and geoenvironmental applications (Horpibulsuk, RACHAN, & RAKSACHON, 2009; Mir & Sridharan, 2013) for the purpose of stabilizing expansive soils like black cotton to improve there physical and engineering properties (Mir & Sridharan, 2013).

In Sudan, where there is an abundance of fly-ash, different applications are being investigated to reduce the significant environmental problems caused by low utilization and land filling of fly-ash. Many studies are being performed that focus on stabilizing clayey soils and replacing expensive stabilizers such as lime and cement. Those studies show that stabilizing clayey soils with different ratios of fly-ash improved their clay index and Atterberg limits as well as increase their bearing capacity (Ghais, 2014). Since it is not possible to acquire fly-ash from Sudan, a fly-ash from Japan will be used. In this study, JIS fly-ash type I would be used in testing due to its fineness and higher activity index.

However, fly-ash is known to be slow and weak specially in the development of initial strength, therefor, to further improve its pozzolanic action, it was recommended that an alkaline activator be added. The process of Alkali activation of fly ash (AAFA) happens when fly-ash is mixed with calcium hydroxide creating a solid, cement-like material. The the resultant material is called a geo-polymer (Fernández-Jiménez & Palomo, 2003; Hefni, Zaher, & Wahab, 2018). Geo-polymers are being studied as an eco-friendly substitute to Portland cement (Hadi, Al-Azzawi, & Yu, 2018). In this study, a mixture of Calcium Hydroxide Ca(OH)2 and water will be used as the alkaline activator.

3.5.2. Unit Shape

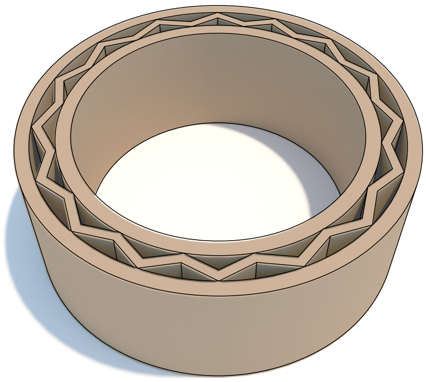
Throughout history the central plan has been the most common shape. Many early nomadic cultures lived in yurts, trulli, tepees, igloos, etc (Szczegielniak, 2019). In African vernacular architecture, the circular hut is the most prevalent, and according to some researchers, the circle represent the 'nature's rhythm' in African culture (Denyer, 1982). Circular huts could be found in many parts of Sudan.

Circular buildings have many advantages, they are more energy efficient, cost less to construct, and maximise exposure to day light (Szczegielniak, 2019). Additionally, due to the absence of angles, they have better aerodynamic behavior which allows to withstand strong winds better than square or irregular shaped buildings.

As a result, the circular shape has be chosen as the main shape for the units. A circular hut in addition to two variations will be 3D printed at the same scale and number of layers and evaluated in terms of ease of printing and printing time. Figure 3.4. shows the three chosen designs.

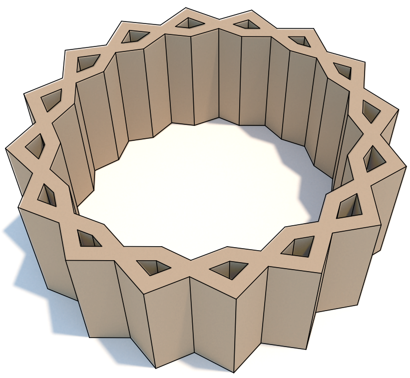
The circular units represent the `rooms`, as such, an example that shows how the circular rooms can be organized to form a `house` with multiple rooms will be 3D printed. The house setting follows the cultural requirements of a traditional Sudanese residential unit where men and women quarters are separated. Finally, a non- circular structure will be 3D printed that is made to address non-residential functions such as a commercial unit or a common gathering place. Figure 3.5. and Figure 3.6. show the suggested designs.

A



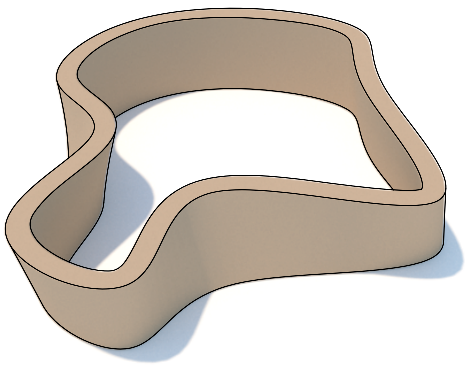
Circular Design with a smooth exterior and internal Support

B



Circular Design with an Angular Exterior

C



Free Form Design

Figure 3.4. Unit Shape

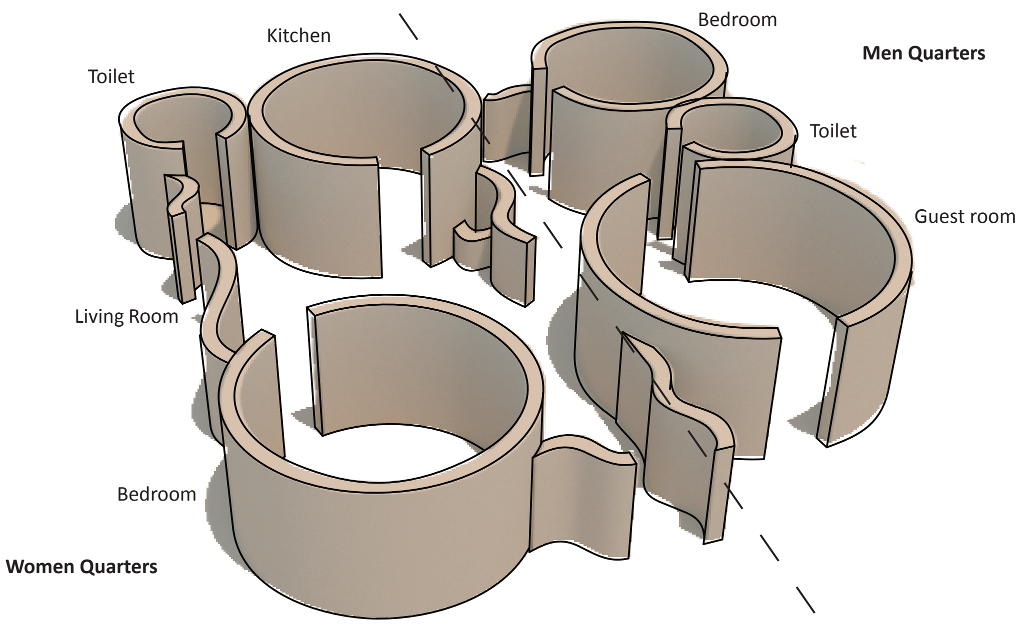


Figure 3.5. Residential Unit Shape

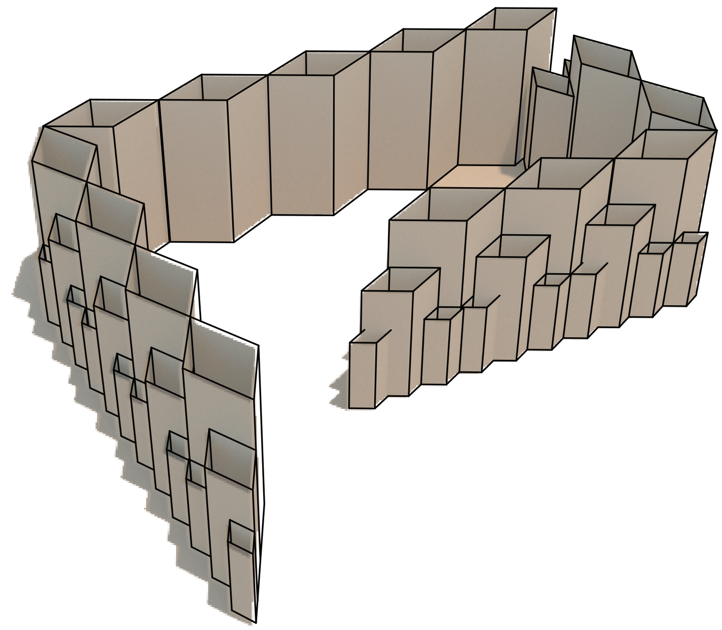


Figure 3.6. Commercial Unit

3.5.3. Soil Mix

Generally, when developing a mix for an additive manufacturing process, it needs to satisfy the following:

- It needs to be workable before printing
- Easily and consistently extrudable during printing and is able to hold its shape upon printing
- The printed layers are able to adhere to each other properly.
- After printing, the extruded material is able to harden quickly

However, to fulfil the PhD program time limitations, the study will focus on developing one mix and the development process will stop as soon as the aforementioned criteria is met. Figure 3.7. shows the important considerations when designing a mix for an additive manufacturing process.

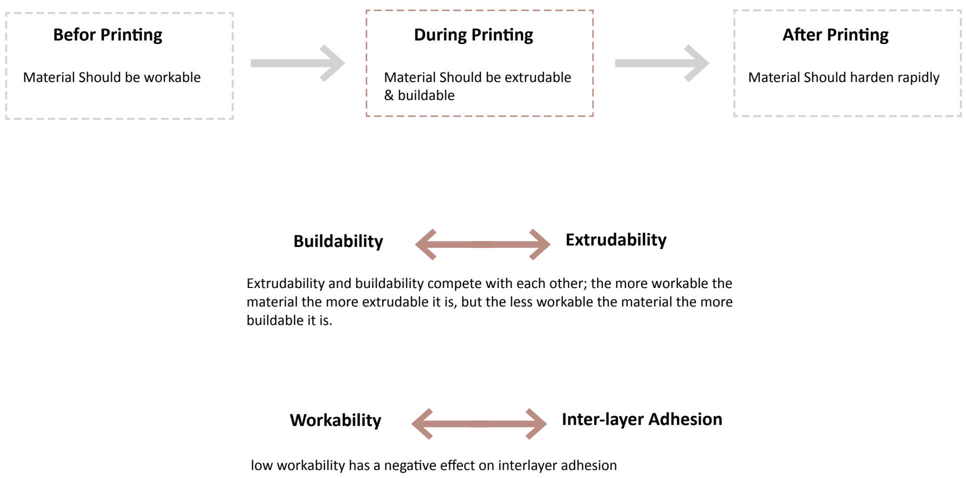


Figure 3.7. Important criteria of mix deign

3.5.3.1. Soil Selection

An artificial soil was used to create the mix. Initial target values were based on data from the literature review. For sand, Silica #8 was used, for silt, DL Clay was used, and for clay, A-A Kaolin was used. Appendix 1, Appendix 2, and Appendix 3 contain more information regarding the used material.

A plasticity index (PI) of 21 is chosen based on the work of (Perrot, Rangeard, & Courteille, 2018) where successful attempts of 3D printing soil mixed with a biopolymer were achieved using the selected PI of 21. Also, this PI falls within the range of the recommended plasticity index by international standards for earth construction (PI between 16- 28 LL between 32- 46) (Jiménez Delgado & Guerrero, 2007).

The plasticity index of 21, represents a highly plastic soil which is a very common soil type in Sudan. General values of Atterberg limits for black cotton soils in Sudan are:

- Liquid limit (LL) is between (47% - 93%),
- Plastic limit (PL) is between (26% - 50%)
- Plasticity index (PI) is between (13% - 58%)
- Linear shrinkage (IS) between (8% - 18%)

Additionally, after sending soil sample data form Khartoum that was analyzed based on the research of Adam & Jones (as cited in 1995,p. 247) (Table 3.1.) to WASP, their engineering team chose the soil sample from ‘El Hizam’ with a Liquid limit (LL) of 44%, a Plastic limit (PL) of 17%, and Plasticity index (PI) of 27%. Based on these values, the soil could be classified as clay with medium plasticity.

Information regarding the fines content and mixing ratio were selected from the work of (Papadopoulou & Tika, 2016) (Table 3.2.) .The closest fines plasticity index selected was 22%, the corresponding silt content was 6.9%, the corresponding clay content was 8.1%, and total fines content was 15%.

Atterberg limit is very important for the characterization of soil within a broad category. Thus, the standard test method for liquid limit and plastic limit of soils was used and it follows the

Soil Properties		Location		
		Fetehab	El Hizam	Deroshab
Engineering Properties	Gravel (%)	14.00	06.00	04.00
	Sand (%)	43.00	36.00	64.00
	Silt (%)	37.00	21.00	20.00
	Clay (%)	06.00	37.00	12.00
	Liquid limit (%)	52.00	44.00	30.00
	Plastic limit (%)	29.00	17.00	15.00
	Linear shrinkage (%)	12.00	11.00	08.00
	Specific gravity	02.71	02.87	02.81
	Natural water content (%)	20.00	21.00	27.00
	Dry density (kg/m') (max.)	1720	1750	1960
	O.M.C. (%)*	21.40	20.00	11.40
Chemical Analyses	Classification	SHP†	CMP‡	CLP§
	SiO_2	58.12	61.91	79.95
	AL_3O_2	09.50	19.80	14.49
	FeO	07.94	05.86	02.54
	CaO	06.67	06.40	06.57
	MgO	03.12	01.95	00.89
	P_2O_2	00.16	00.13	00.02
	SO_2	Nil	Nil	00.32
	K_2O	00.52	00.78	00.23
	Na_2O	00.06	00.68	00.51
	TiO_2	01.53	01.02	00.52
	Mn_2O_3	00.30	00.31	00.13
	Loss on ignition	10.52	08.90	05.43

* O.M.C.- optimummoisture content.
†SHP-siltwith high plasticity.
‡CMP- clay with medium plasticity.
§CLP- clay with low plasticity.

Table 3.1. Engineering properties and chemical analyses of the three soil samples from Sudan recreated from (Adam & Jones, 1995,p. 247)

Mixture	Fines content f_c (%)	Fines Plasticity Index PI (%)	Fines Liquid Limit LL (%)	Fines Plastic Limit PL (%)	Specific Gravity G_s	Max. Void ratio e_{max}	Min. Void ratio e_{min}	Mean Diameter D_{50} (mm)	Coefficient of Uniformity C_u	Fines composition (%)		Silt content 5μm < % < 75μm	Clay content % < 5μm
										Assyros Silt	Speswhite Kaolin		
SF15 (PI=22)	15	22	14	19	2.647	0.872	0.496	0.30	18. 8	6.9	8.1	6.9	8.1

Table 3.2. Physical properties of tested samples recreated from (Papadopoulou & Tika, 2016,p. 192)

Japanese Geotechnical Society Standards Liquid limit & Plastic limit tests (JGS 0141- 2009) (The Japanese Geotechnical Society (JGS) , 2018). Appendix 4 contains a complete explanation of the testing process per the guidelines of (The Japanese Geotechnical Society (JGS). Figure 3.7 show parts of the testing process. The main goal of this step was to create an artificial soil that falls within the range of the chosen soil properties.

3.5.3.2. Additive Selection

Fly-ash:

Fly-ash class JIS-I was chosen to be used in this research. It has the highest quality and fineness as well as the highest pozzolanic activity index; 28 days = 90%, 91 days= 100% (Nagataki, Tomosawa, Kanazu, & Yamamoto, 2001) see Table 3.3.

The fly-ash will was mixed at 20% of the dry weight of soil.

Alkaline Activator:

A mixture of Calcium Hydroxide $Ca(OH)_2$ and water was used as the alkaline activator (liquid content). The initial mixing proportion was 1.5 g for every liter of water, and was increased to 5g/ L and the mixing percentages was started at 30% and then increased to 40% of the dry weight of the mixture of soil and fly-ash.

Item	JIS Type I	JIS Type II	JIS Type III	JIS Type IV
Ignition loss (%)	3.0 or less	5.0 or less	8.0 or less	5.0 or less
Residue on 45µm sieve (mesh sieving method: %)	10 or less	40 or less	40 or less	70 or less
Specific surface area (cm^2/g) (Blaine method)	5000 or over	2500 or over	2500 or over	1500 or over
Flow value ratio (%)	105 or over	95 or over	85 or over	75 or over
Activity index (%) Material age 28 days	90 or over	80 or over	80 or over	60 or over
Activity index (%) Material age 91 days	100 or over	90 or over	90 or over	70 or over
Density (g/cm^3)(specific gravity)	1.95 or over	1.95 or over	1.95 or over	1.95 or over
Silicon dioxide: SiO_2(%)	45.0 or over	45.0 or over	45.0 or over	45.0 or over
Hygroscopic moister(%)	1.0 or less	1.0 or less	1.0 or less	1.0 or less
Homogeneity in quality, Blaine method (cm2/g)	±450 or over	±450 or over	±450 or over	±450 or over
Homogeneity in quality, Mesh sieving method (cm2/g)	±5 or over	±5 or over	±5 or over	±5 or over

Table 3.3. The JIS A 6201 Fly-ash 1999 Classifications, recreated from (Ishikawa, 2007, p.6)

Figure 3.7. Liquid limit & Plastic limit tests (JGS 0141- 2009)

3.5.3.3. Preparing the Earth Mixture (soil+ flay-ash+ alkaline activator)

The soil mixture was prepared by first mixing the dry material. The used mixer is an industrial ACM mixer (see Figure 3.8.). The dry material was mixed for about 5 min, then, the liquid was added gradually and the mixing continued for another 20 min on the highest setting to insure a uniform mixture.

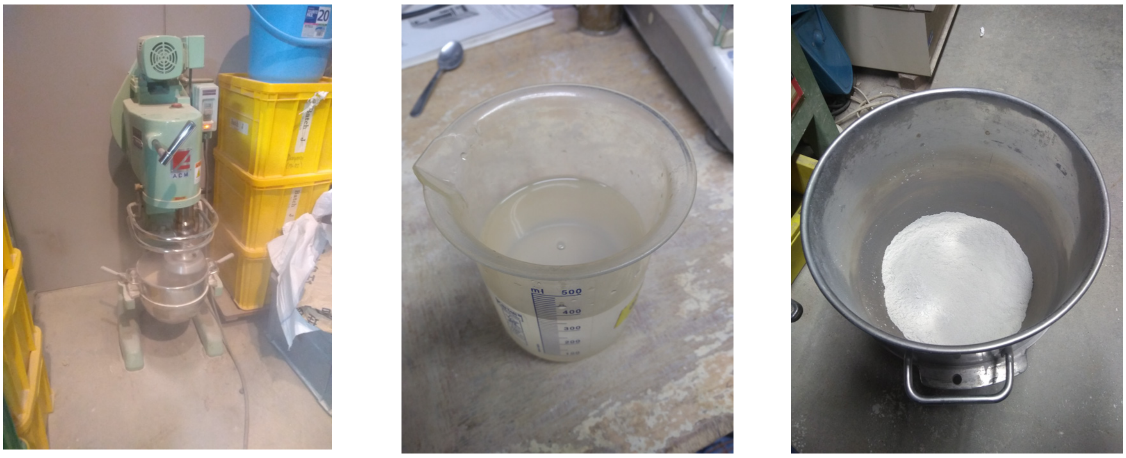


Figure 3.8. Soil Mixing

3.5.4. Workability and Printability Evaluation

After the earth mixture was prepared, it was then loaded into the 3D Potterbot 3600ml extruder.

Soil mass (1000 g) + fly-ash @ 20% (200 g) + Liquid @ 30% (360 ml ($Ca(OH)_2$ @ 1.5 g/L))

The material was loaded gradually into the extruder tube, and after loading was finished, both ends of the tube were sealed. After sealing the tube ends the mix was then agitated by shaking the tube in an up and down motion to force the air bubbles to the surfaces. The tube was then placed upwards and left for 24 hrs in order for the mix to settle overnight.

After 24 hrs the 3D printing process was started. First, the nozzle height was adjusted manually by placing a 5 mm cardboard piece on the bat (printing table) and placing the nozzle tip on the top of the cardboard piece after attaching the nozzle to the extruder tube, see Figure 3.9 . Usu-

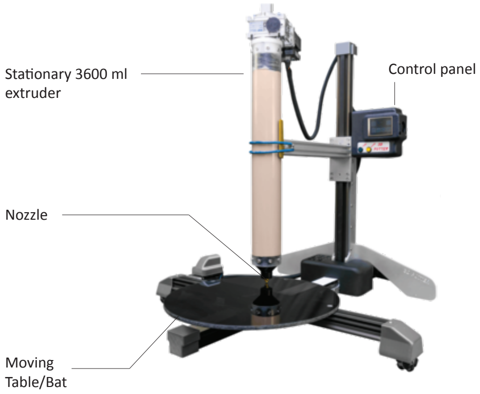


Image source:
3D Potter. (n.d.). 3D PotterBot 7. Retrieved June 30, 2018, from http://www.3dpotter.com/.

Name:	3D Potterbot 7 SUPER
Company:	3D Potter, Inc.
Type:	extrusion based, ceramic and paste 3D printer
Capacity:	3600 ml direct nozzle extruder
Nozzle:	Maximum nozzle diameter is 6mm
Printing Envelope:	X (432 mm), Y (356 mm), Z (483 mm)
Print Table Size:	diameter is 349mm
Speed:	average printing speed is 55 mm/s
Power consumption:	24 volts +/- 2 amps
Arm processor Cortex:	M3 100 - 120 Mhz

Figure 3.9. 3D Potterbot 7 SUPER Specifications

ally in 3D printing, the optimum height of layer (nozzle height from 0.00 on the Z axis) is adjusted to be around 50% of nozzle diameter (6 mm), however, due to the dense nature of the soil mix, the height of the layer was adjusted to 5mm. The 6 mm nozzle tip is used throughout the study as it was found to be the most consistent and provides the needed degree of printing resolution.

After securing the extruder to the main frame of the printer, the printer was then turned on. Per Manufacturer instructions, the first step is to activate the priming file on the display to pressurize the extruder and force all air out of the material reservoir. After the pressurization process was completed, an existing test file 'vase 2000' was printed to test the printing process. For this first test, the speed was set to the maximum 100% and the extrusion rate was set to 180%.

As mentioned in chapter 2, Printability depends highly on workability which is defined as a property of freshly mixed cementations materials and is used to describe its rheological behavior (Soltan & Li, 2018). Several deterministic tests exist but for the purpose of this study, workability will be controlled by adjusting the liquid content percentage based on the smoothness of the extrusion process. This decision was made because of the closed nature of the material reservoir.

This means that the material will not be exposed to air and there is no concern over stiffness. To evaluate printability, Four key wet- material characteristics need to be monitored based on previous research (Lim et al., 2012), these four characteristics are:

Pumpability: The movability of the material through the delivery system.
Extrudability: The capacity of the material to be deposited through the deposition system.
Buildability: The ability of the material to resist deformation under the load of the consecutively printed layers.
Open-time: Is the consistency of the above mentioned properties within the accepted tolerance of the 3D printing system.

However, two characteristics will be neglected in this study, 'Pumpability' and 'open- time'. Pumpability will be ignored because the used 3D printer doesn't use a pumping mechanism to move the material to the printing head, instead, it uses a screw -based compression system. Open- time is neglected due to the closed nature of the material reservoir and the limited exposure of the material to air. The manufacturer recommends de pressurizing the extruder when printing is finished and there is remaining material by activating the "retract" file and allowing to run for 60 sec. This insures that the material will keep its consistency for up to two weeks.

Extrudability is observed visually by printing several "roads " that are similar in length and monitoring the presence of voids or cracking in order to assess the consistency of the mix . Buildability is also visually monitored by observing deformation in the bottom layers when the top consecutive layers are printed and stopping at the point of failure in order to count the number of layers that could be printed without causing failure of the structure. After the test was done, the printed samples where left to cure for two days at room temperature in order to asses shrinkage and the presence of voids.

The same test was repeated again starting with the mixing process. However, this time the liquid content was increased to 40% and the $Ca(OH)_2$ concentration was increased to 5 g/L after consulting with a chemistry expert . The amount of material was also doubled for this test.

Soil mass (2000 g) + fly-ash @ 20% (400 g) + Liquid @ 40% (960 ml ($Ca(OH)_2$ @ 5 g/L))

3.5.5. Particle Size Distribution Test

After the workability and printability evaluation testing was completed, the Particle Size Distribution Test was done. This test was done to a the mixture of soil and fly-ash (all dry components).

In the pervious test and based on the evaluation of workability, printability (extrudability + buildability) a clear understanding of the earth mix was formed and the mix components were decided.

The initial test mass prepared for this test was:
Soil 1000 g (42% course content (Silica #8 (420 g) + 58% fine content (23.33% Silt (135 g) + 76.67% A-A Kaolin(445 g)) + fly-ash 200 g

All of the components were mixed for around 10 min using the industrial ACM mixer until a homogeneous mixture was achieved.

This test followed the Test Method for Particle Size Distribution of Soils 'Dry Method' (JGS 0131-2009) (The Japanese Geotechnical Society (JGS) , 2018). Refer to Appendix 5 for a full explanation of the testing process. Figure 3.10. shows parts of the testing process.

3.5.6. Density Testing

The main purpose of this test is to analyze the effect of the 3D printing process on the density of the soil mix, and consequently, the strength of the overall printed structure.

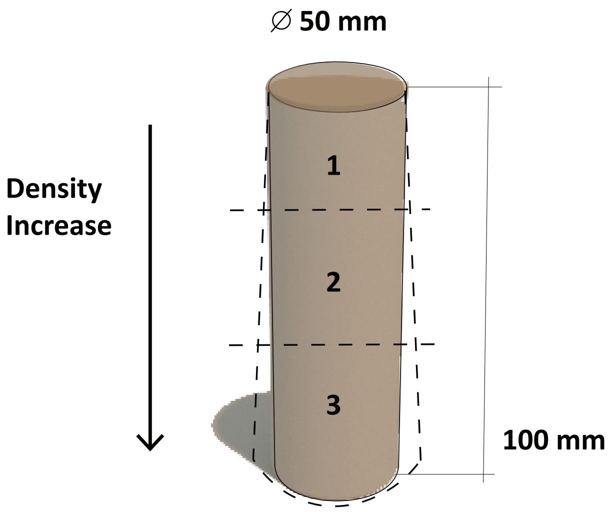
Under normal conditions, the bottom layers tend to flatten and lose height due to the weight of the top printed layers. Thus, the bottom is usually denser than the top. As a results, In this research, density will be calculated from samples collected from the top, mid, and bottom of the printed specimen.

A specific cylinder specimen will be printed for this test in which the extrusion rate setting will be manipulated to produce extreme changes. The goal is to produce a specimen that is loose on the top, semi- dense in the middle, and dens at the bottom.

Figure 3.10. Test Method for Particle Size Distribution of Soils 'Dry Method' (JGS 0131- 2009)

After the cylinder was printed, samples from the specified sections were taken and measured in order to calculate their volume, they were then weighed to get their wet weight, the samples were then put into an oven to dry for 24 hrs. After the drying process was completed, the samples were weighed again in order to get the dry weight. The dry weight was then used to calculate mix density using the following formula: **(weight of sample/ volume of sample)**

Figure 3.11. illustrates the density calculation process.



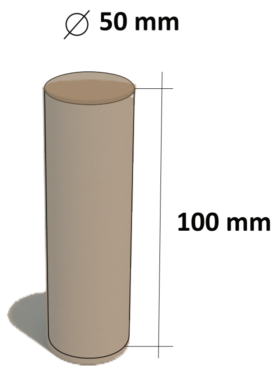
NUMBER OF SPECIMENS	**1 from each section**

Figure 3.11. Density Testing

3.5.8. Unconfined Compression Test

The loading test will be conducted on the printed samples after curing for 1 day, 3 days, 1 week, 2 weeks, and 28 days at room temperature. The samples will be a direct result of the additive manufacturing process and will be 3D printed to the standard dimensions needed for the mechanical testing, Ø50mm * 100mm. Figure 3.12. illustrates the standard dimensions of the standard testing cylinder and the number of samples needed for the test.

The Unconfined Compression Test will follow the (JGS 0511- 2009) standard testing method (The Japanese Geotechnical Society (JGS) , 2018). Refer to Appendix 6 for a full discretion of the testing process.



CURING TIME	NUMBER OF SPECIMENS
24 hr	3
3 days	3
1 week	3
2 week	3
28 days	3

Figure 3.12. The Loading Test

3.6. Evaluation of Time & Cost

A full scale wall section will be built using the 3D printing process. The cost calculations will be based on an assumed wall where the printed section will represent one unit of that wall. The test was designed to simplify the calculation process. Figure 3.13. illustrates the Assumed Wall Dimensions.

The wall section dimensions will be as follows: 300 mm * 250 mm * 100 mm

The Assumed wall dimensions will be as follows: 2000mm * 300 mm * 3000 mm

- The wall section represents 1/80 units form the assumed wall.

Information regarding the amount and cost of the materials used (soil (Silica #8+ DL caly+ A-A Kaolin), fly-ash, alkaline activator), number of layers, speed of printing, and amount of energy used in the process will be calculated and used to project the cost of printing a wall of the same size mentioned above.

The cost of building the same wall in Sudan using conventional building materials will be calculated and then compared to the cost of the 3D printed wall in order to economically evaluate

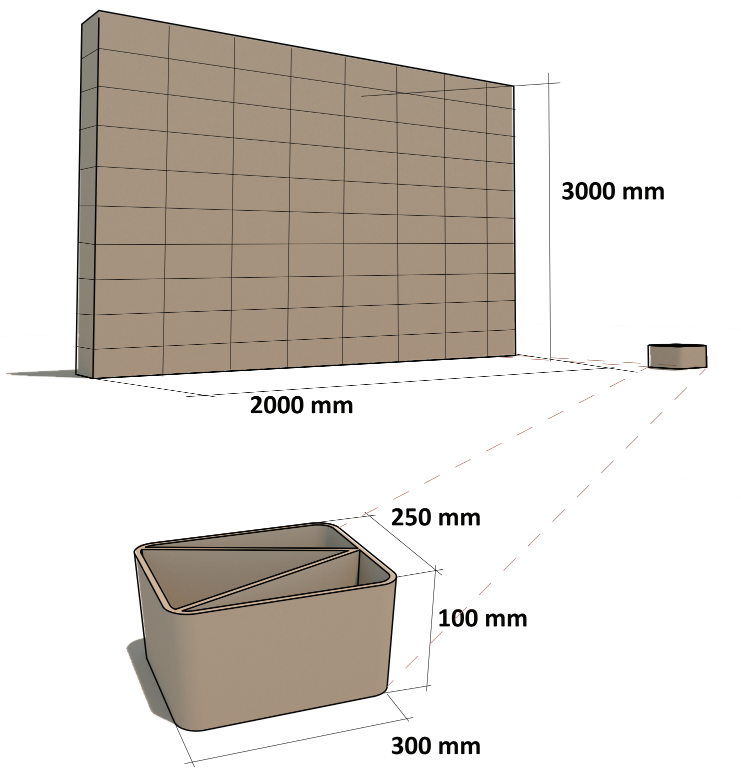


Figure 3.13. Assumed Wall Dimensions

CHAPTER 04

RESULTS & DISCUSSION

4. Results and Discussion

4.1. Introduction

The purpose of this chapter is to discuss the results of the various tests performed in this study.

The chapter starts with the results of the liquid limit and plastic test and the particle size distribution test (PSD), both illustrate the physical properties of the earth mix. Then, the results of the printability evaluation of the AM system will be discussed. Next, the results of the density testing and the loading test will be discussed in order to illustrate the mechanical properties of the soil mix. The chapter ends with a discussion of the shape design and the time and cost evaluation results. Both represent the real- life application of the system.

4.2. Test Results

4.2.1. Liquid limit & Plastic limit test

The Liquid limit and Plastic Limit tests were repeated several times until a soil with a relatively close physical properties to the chosen Sudanese soil sample data was reached. In chapter three the desired soil from 'El Hizam' had a Liquid limit (LL) of 44%, a Plastic limit (PL) of 17%, and Plasticity index (PI) of 27%, and was classified as a clay with medium plasticity.

The resulting artificial soil has a Liquid limit (LL) of 55.7 %, a Plastic limit (PL) of 29.64%, and Plasticity index (PI) of 25.73%. Figure 4.1. shows the test results. Based on the Unified Soil Classification System (USCS), the resulting soil is classified as CH, inorganic clay of high plasticity, fat clay. Refer to Appendix 7.

The resulting soil mix is stickier and has more clay content, however, during the 3D printing test, the extra stickiness resulted in better adhesion between the layers. However, it also resulted in the forming of cracks upon drying as well as brittle breaking behavior.

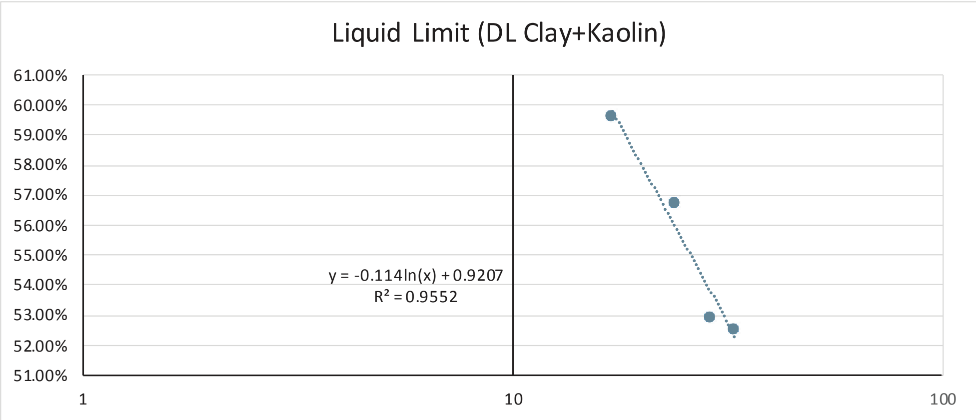


Figure 4.1. Liquid limit & Plastic limit tests (JGS 0141)

4.2.2. Particle Size Distribution Test

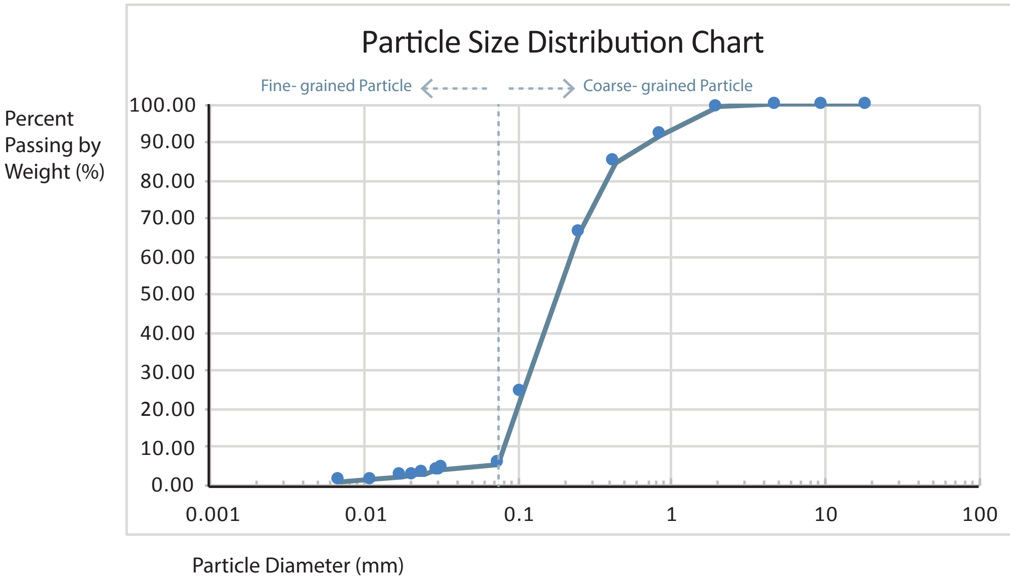


Figure 4.2. Particle Size Distribution Test (JGS 0131-2009)

The test mass prepared for was as follows:

Soil 1000 g (42% course content (Silica #8 (420 g) + 58% fine content (23.33% Silt (135 g) + 76.67% A-A Kaolin(445 g) + fly-ash 200 g

The Particle Size Distribution Test shows that around 7% of the mix is considered fine content and around 93% of the mix is considered course content. Although the graph doesn't reflect the finesse of the mix, the convention to a majority course content could be an affect of adding the fly-ash. Refer to Appendix 8 & 9.

4.2.3. Printability Evaluation

4.2.3.1. Workability Evaluation

As discussed in the previous chapter, two tests were performed to evaluate the workability and printability of the AM system. In the first test the test mass was prepared as follows:

Soil mass (1000 g) + fly-ash @ 20% (200 g) + Liquid @ 30% (360 ml ($Ca(OH)_2$ @ 1.5 g/L))

The speed was set to the maximum 100% and the extrusion rate was set at 180%. The number of printed layers was 43 and the printing process took about 20 min. The layers held their shape well and the extrusion process was smooth. However, the material was thick and more moister was needed. Upon drying, which took around 24 hrs for the structure to dry completely, the material was fragile and started to chip away. Also, the drying process resulted in the appearance of voids and cracking. Figure 4.3. shows the 3D printing first test result.

Figure 4.3. Workability Test

In the second try, the moister content was increased as well as the content of the alkaline activator, the hope was that increasing the moister content will help with the appearance of voids and make the mix more workable. The increase of the alkaline activator was done in order to increase the pozzolanic action and create better strength.
The second test the test mass was prepared as follows:

Soil mass (2000 g) + fly-ash @ 20% (400 g) + Liquid @ 40% (960 ml (($Ca(OH)_2$ @ 5 g/L))

The increase of the moister content to 40% helped with workability and the appearance of voids but resulted in a looser mix, after repeating the test a few more times, the best water content was found to be @ 37%. The increase in the alkaline activator from 1.5 g/L to 5 g/L didn't have a noticeable effect.

4.2.3.2. Nozzle Height Calibration

Although the recommendation by the 3D printing guidelines suggests adjusting the height of the nozzle (layer height) at around 50% of nozzle diameter, testing showed that the best nozzle height for the used nozzle diameter of 6 mm is @5 mm (around 83.33% of nozzle diameter). This is due to the thick composition of the mixture.

Nozzle Height at 5 mm Nozzle Height at 3 mm Nozzle Height at 10 mm

Figure 4.4. Nozzle height Calibration

4.2.3.3. Simplify 3D Settings

Simplify 3D is the slicing software used to slice the digital models and generate the G-code necessary for the 3D printing process. The settings were provided by the manufacturer of the 3D printer (3D Potterbot 7 SUPER) in the form of downloadable files for the different nozzle sizes. In this research the 3.5 profile was used as it correlate to the used nozzle size (6 mm). Most setting weren't changed, however the (Extrusion Multiplier) setting needed calibration and its value was lowered to 1.30 from the original setting of 4.00 as it resulted in over extrusion of material.

The infill setting was also manipulated in accordance with the printing behavior of the soil mix. For example, in order to make an object a solid, such as the cylinders for the loading test,
a setting of 73% infill was used This setting was determined by a trial and error process after it was observed that using a setting of 100% will results in over extrusion of material. Conversely, when printing an outline only an infill of 0% was used. Figure 4.5. shows some of the important Simplify 3D settings used in this study.

4.2.3.4. Extrdudability Evaluation

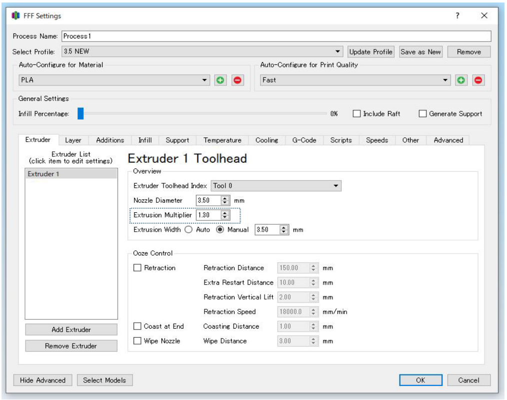
Both mixtures (water content 30%, water content 40%) produced satisfactory results. However, the higher water content (40%) resulted in a much more workable mix (Figure 4.5). The breakage in some of the roads is due to the presence of air pockets in the mixture, in order to minimize the presence of the air pockets, the process of shaking the material revisor before printing was made longer.

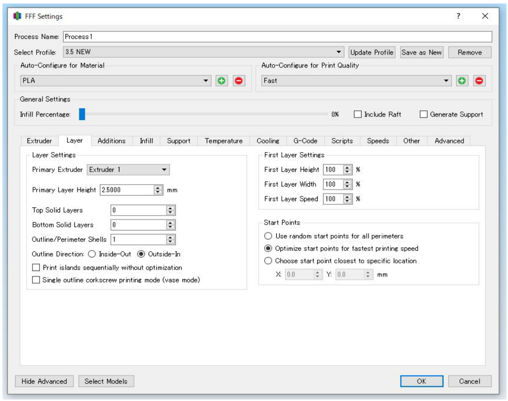
4.2.3.5. Buildability Evaluation

The average layer height is around 3 mm. Layers hold shape up to 35 layers afterwards failure tends to occur (buckling of wall). Understanding buildability helps with deciding when to stop printing and wait for the structure to dry before continuing.

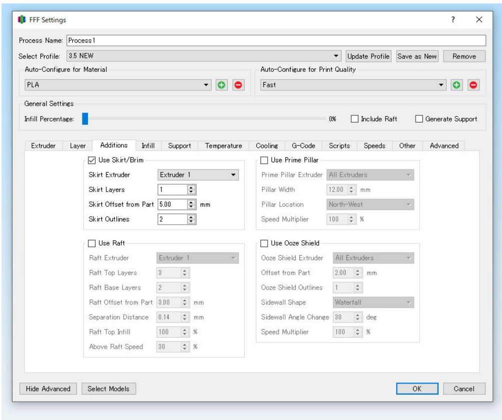
4.2.4. Density Testing

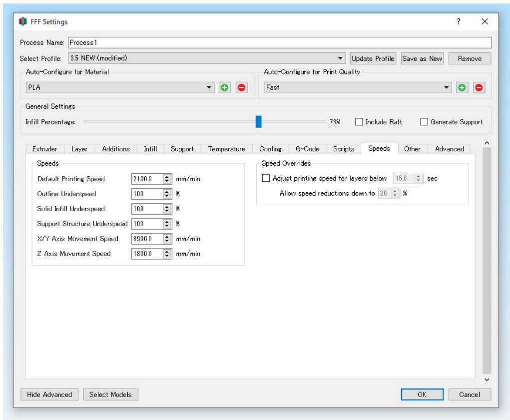
The results of the density testing are shown in figure 4.6. Based on the calculations, the density in the loosest part of the specimen is 1.317 g/cm3, the semi-dense middle area is 1.757 g/cm3, and the densest area at the bottom is 1.766 g/cm3. The difference in density between the top

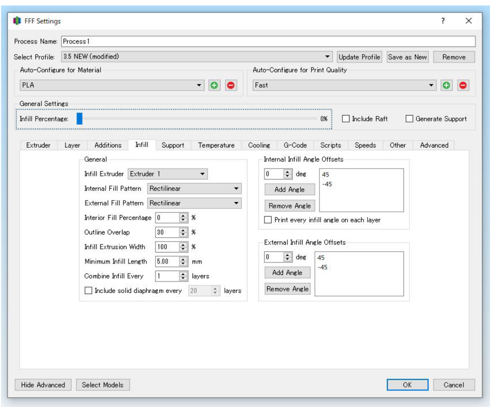


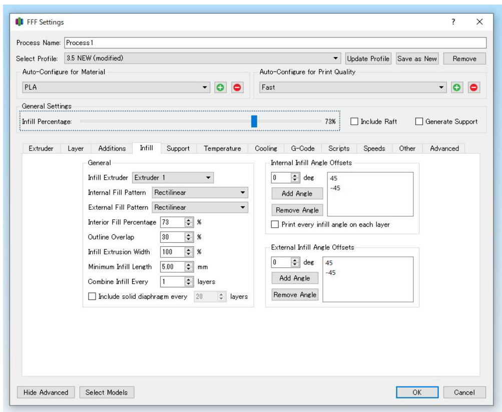


These images show the 3D printing settings used in this research. The settings were provided by the manufacturer of the 3D printer (3D Potterbot 7 SUPER) for different nozzle sizes. In this research the 3.5 profile was used as it correlate to the used nozzle size.
The only setting that needed calibration was the (Extrusion Multiplier) it was lowered to 1.30 from the original setting 4.00 as it resulted in over extrusion of material.









These above images show two different settings of (Infill), When infill was needed to make the printing object a solid such as the cylinders for the loading test, a setting of 70- 73% (right image) infill was used. This setting was determined by a trial and error process after it was observed that using a setting of 100% will results in over extrusion of material. Conversely, when printing an outline only an infill of 0% (left image) was used.

Figure 4.5. Simplify 3D Settings

and bottom is 0.449 g/cm3 which is a considerable difference. This is due to the pressure on the bottom layers caused by printing the top layers of the specimen. Although in this case the printing process was manipulated (slow extrusion rate in the beginning and fast extrusion rate at the end) to produce extreme differences between the top and bottom of the specimen, it is clear that the density of the top part of any 3D printed object will be lower than the density of the bottom part.

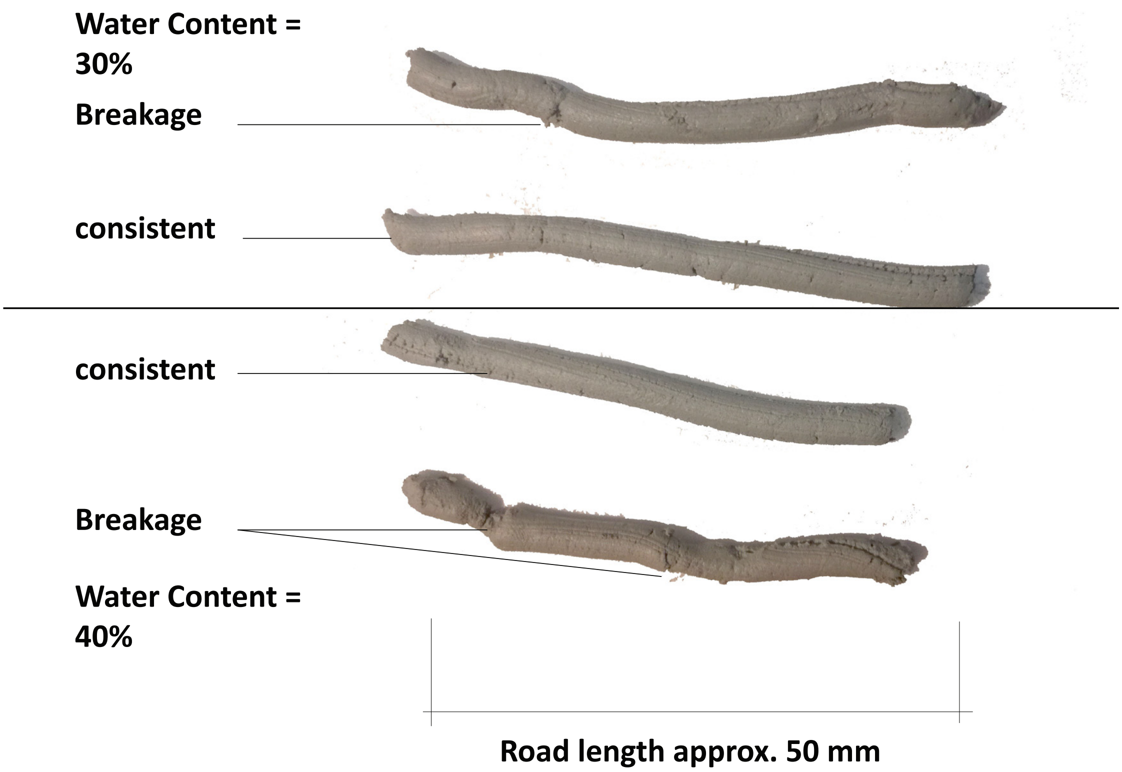
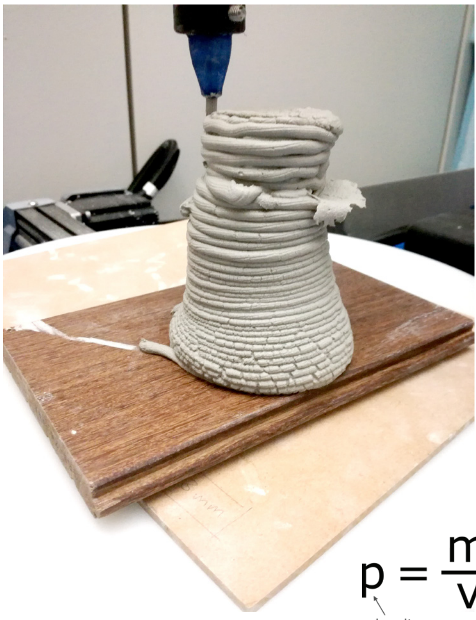
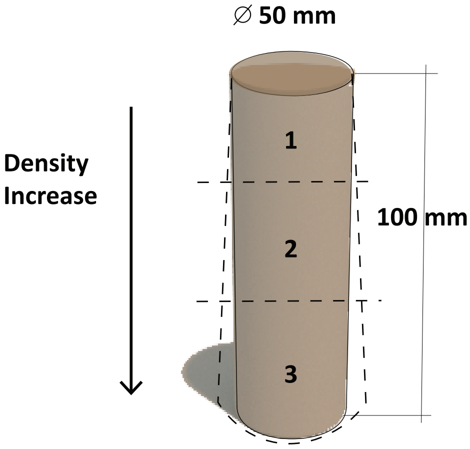


Figure 4.6. Extrudability Test





$$p = \frac{m}{v}$$

(p: density, m: mass, v: volume)

SPECIMENS	DENSITY
1	1.317 g/cm3
2	1.757 g/cm3
3	1.766 g/cm3

Figure 4.7. Density Testing

4.2.5. Soil Mix Mechanical Properties

The standard cylinder specimens required for the UCS test were all 3D printed. Printing time for each cylinder was around 8 min using the 6mm diameter nozzle and nozzle height was at 5mm from the printing table. Figures 4.8. & 4.9. show the printing process of the cylinder specimen.

The screen capture from simplify3D shows the simulation of the printing process. The color assigned to the model indicates the printing speed determined by the software. In this case, a slow speed of 2220 mm/min was determined.

Printing time = Approx 8 min

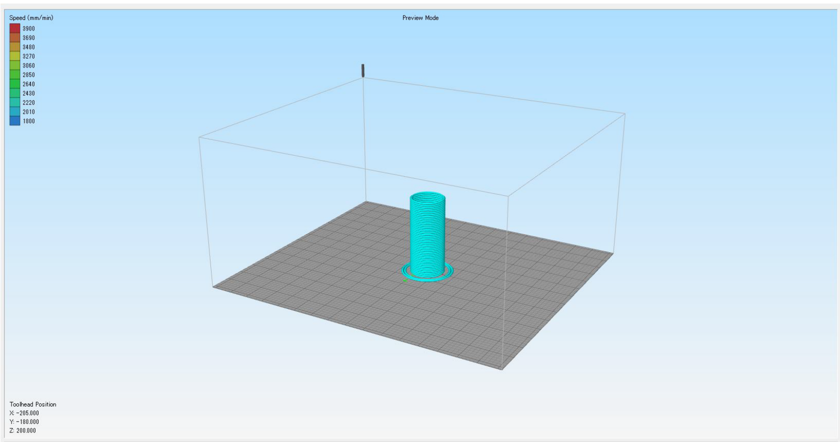


Figure 4.8. Printing Speed of Cylinder Specimen

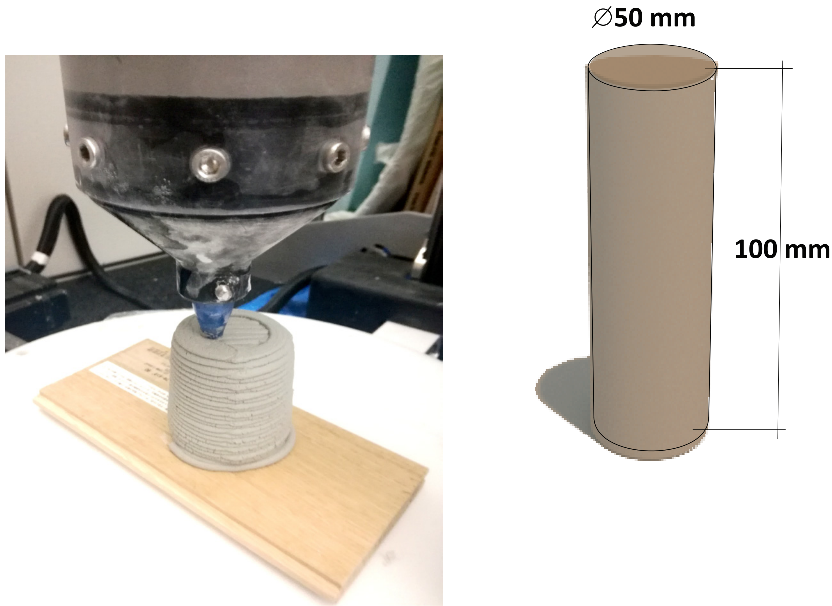


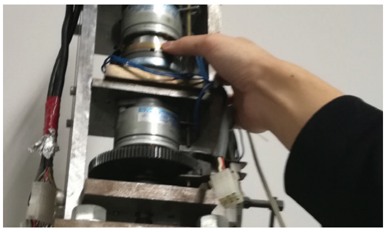
Figure 4.9. 3D Printing of Cylinder Specimen

Specimens were then allowed to dry at room temperature in accordance with their pre-determined curing times. (Figure 4.10.).

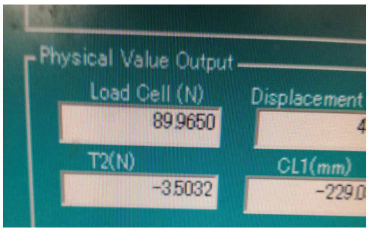
For the loading test, a speed of 226 rpm was chosen based on advice from researchers working with similar type soil composition. During the loading test, linear cracks were observed and the breaking pattern was determined to be brittle in nature. (Figures 4.11. & 4.12.)

Specimens were then allowed to dry at room temperature in accordance with their pre- determined curing times

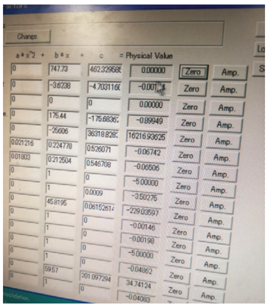
Figure 4.10. Cylinder Specimens Drying at Room Temperature

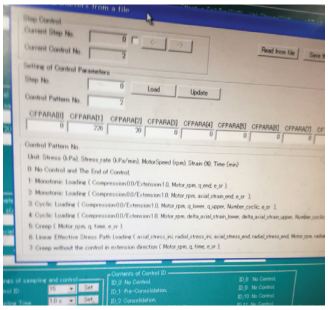


Placing Specimen in Machine



monitoring Loading and displacement values

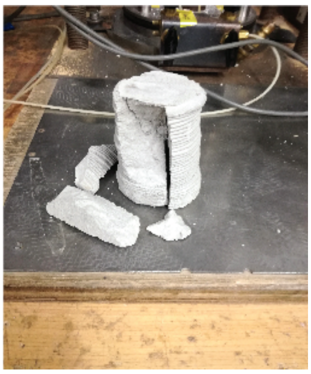




Value settings

Figure 4.11. Loading Test

During the loading test linear cracks were observed



The breaking pattern was determined to be brittle in nature

Figure 4.12. Specimen Behavio

After the loading test was completed for all specimens, the data was analyzed in Microsoft Excel. The results are shown below in Figure 4.13. Refer to Appendix 10 for more data.

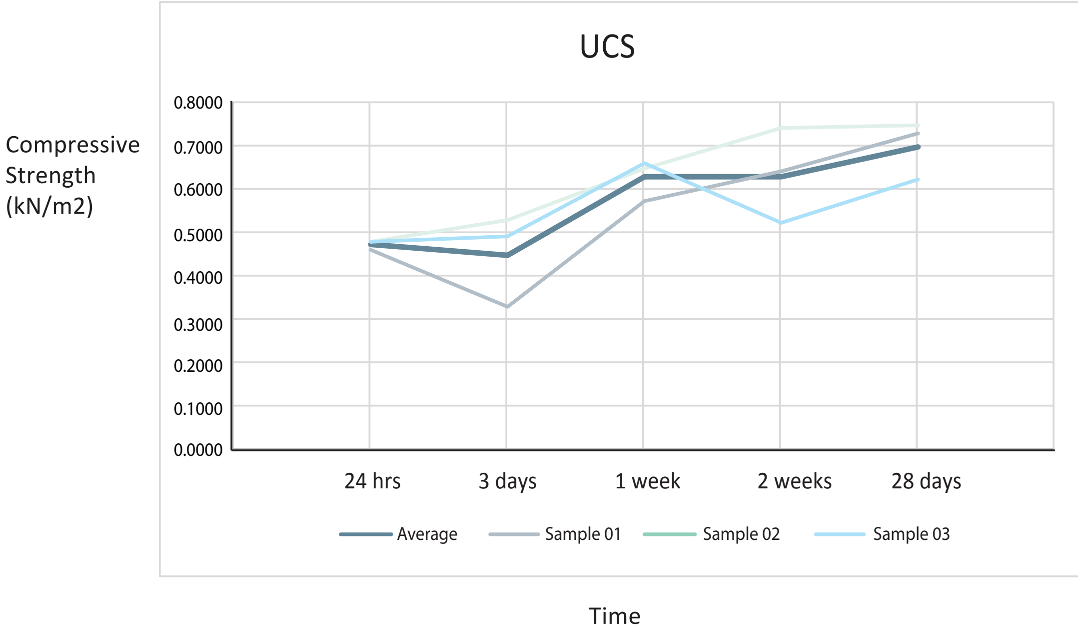


Figure 4.13. Loading Test Results

The UCS chart shows that the increase in strength dropped after specimens cured for 3 days and didn’t gain much strength from 1 week to 2 week curing time, then strength increased slightly at 28 days curing time.

4.3. Shape Design

The proposed designs discussed in the previous chapter were 3D printed after confirming the Soil Mix Design. All designs are similar in scale (Figures 4.14 - 4.16.)

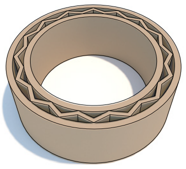
Design (A) although the simplest it took the longest (40 min) to print and used the most material (filament length is 84053.3 mm) due to the added internal support. Without the internal support (just the outer and inner rings), it would’ve taken 19 min to print and the filament length would have been around 38295.6 mm. Design (C) printed the fastest at 7 min, but it was the most un-stable, adding an internal layer and internal support would make it a lot more stable but doing so will add to the printing time the used material. Design (B) took 30 min to print and used about 54259.9 mm of the filament material, had the most detail, and was very stable.

From an economic point of view, the cost of the printed unit depends on the decisions made during the design process. As shown in the previous examples, design (B) used less time and material than design (A) although it contains more detail. This is probably due to design (B) not needing internal support because connections were created between the outer and inner walls. In Design (A) the interior and exterior walls are completely separated and a third supporting elements is needed for support, resulting in extra time and materials. Consequently, the design phase is the most important and smart decision making must be exercised.

From an architectural point of view, abiding decorative elements results in a more engaging design which in turn could help with making mud construction much more appealing to the public. In Sudan, mud building is associated with low socioeconomic groups. Thus, creating design variates and promoting customization is an important selling point.

Figures 4.17. & 4.18 show examples of a residential unit and a commercial/ multi purpose space. In designing the residential unit, circular "rooms" of different sizes and heights are organized to form the different components (bedrooms, kitchen, rest rooms, etc.). The house setting follows the cultural requirements of a traditional Sudanese residential unit where men and women quarters are separated. The overall composition also resembles the layout of a traditional African homestead. The second example uses a more angular/ sharp geometry to distinguish it from the residential units.

A



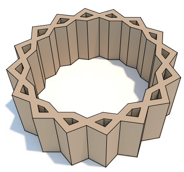
Circular design with a smooth exterior and internal Support

Print time= 40 min

Filament Length = 84053.3 mm

Figure 4.14. Simple Cylindrical Form

B



Circular design with an angular exterior

Print time= 30 min

Filament Length = 54259.9

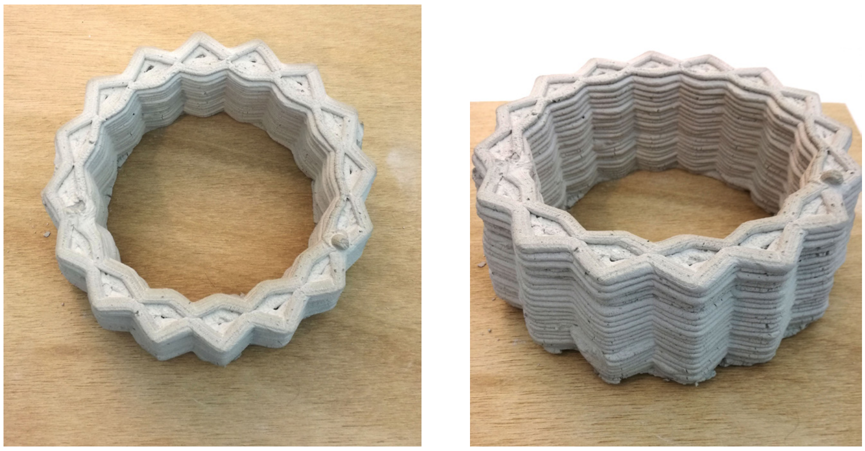
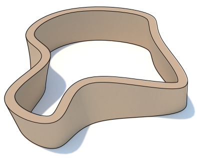


Figure 4.15. Cylinder with an Angular Exterior

C



Free- Form Design

Print time= 7 min

Filament Length = 15179.3 mm

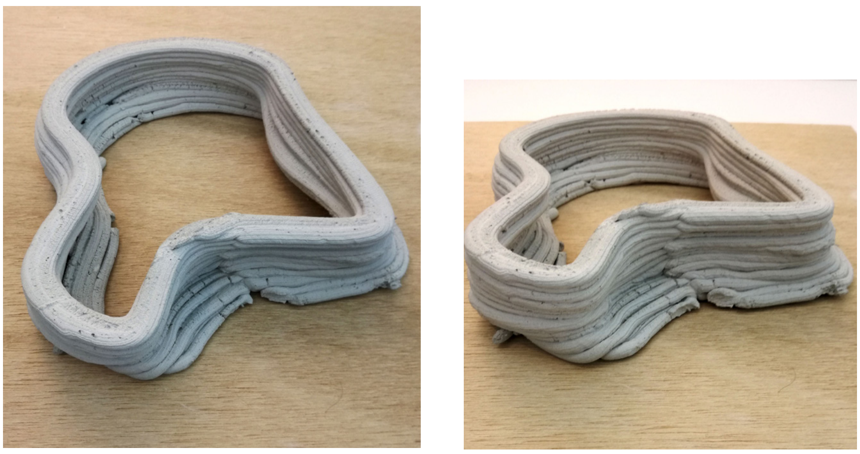
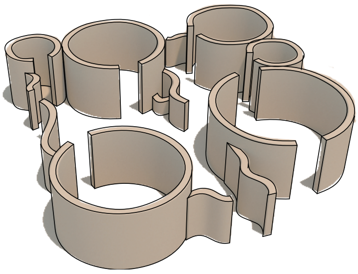


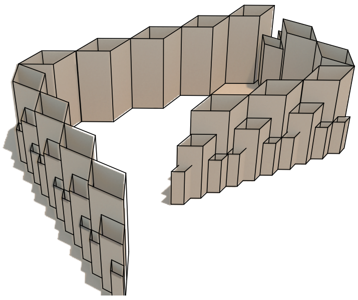
Figure 4.16. Free- form Design



Residential

Print time= 30 min

Figure 4.17. Residential Unit



Commercial/ Multi- purpose

Print time= 40 min

Figure 4.18. Commercial/ Multi-purpose Space

4.4. Economy & Time Evaluation

4.4.1. The Printing Process

During the 3D printing process, the large size of the wall section proved difficult to print and resulted in the constant stalling of the stepping motor in control of the (Y) axis movement. Therefor, a decision was made to split the wall section into two equal halves for the 3D printing process. Figure 4.19. shows the splitting of the section into two halves in Simplify 3D.

Additionally, The decided height of the wall sections required around 40 layers which exceeded the failure point for the soil mix @35 layers. Consequently the structure of the sections started failing at around 83% of the printing time at which 35 layers were completed. Figure 4.20. shows the extent of the failure observed during the 3D printing process of the two halves of the wall sections. Support was used to improve the shapes of the wall sections.

4.4.2. Time & Cost Projections

After printing was completed, the wall sections were left to dry at room temperature, the sections were completely dry after 3 days. Then, the weight of the sections was measured in order to estimate the amount of materials (fly- ash, A-A Kaolin, DL- clay, Silica #8, Water, Ca(OH)2). Figure 4.21. shows the Assumed Wall Dimensions and Table 4.1. shows the estimated amounts.

Mix composition:

Soil 42% course content (Silica #8)
+
58% fine content (23.33% Silt + 76.67% A-A Kaolin)
+
20% fly-ash

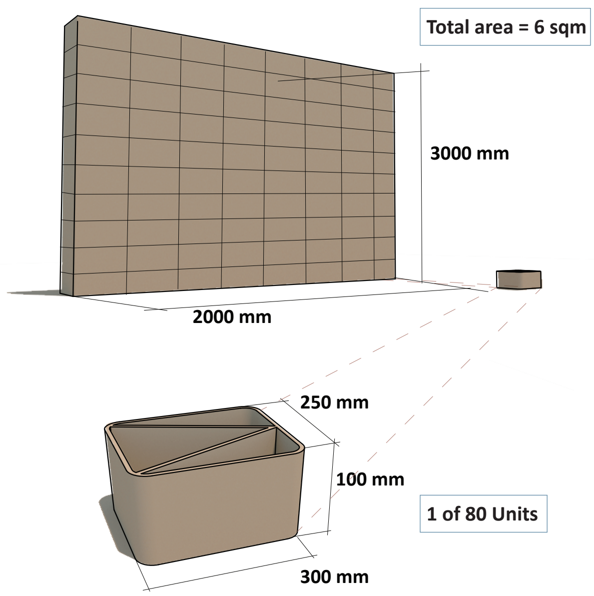
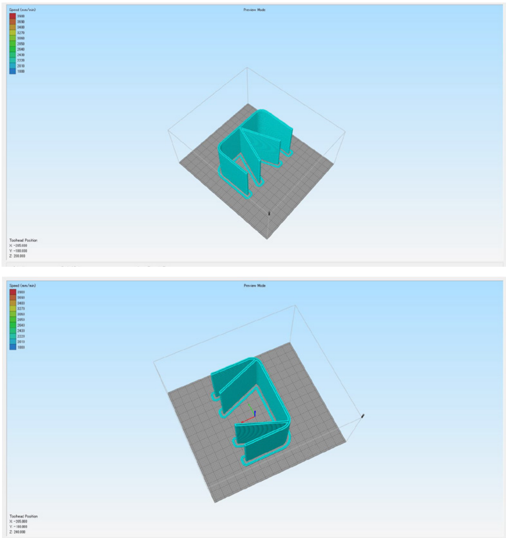
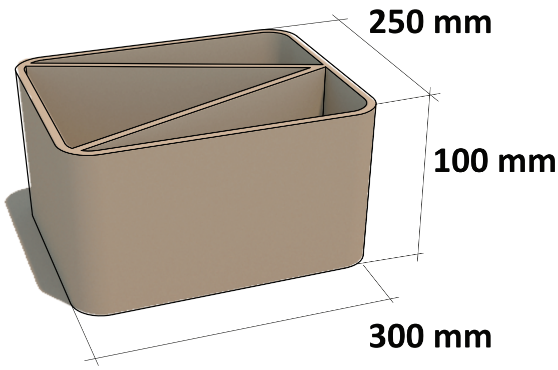


Figure 4.21. Assumed Wall Dimensions





The wall section was split into two equal halves in order to be printed successful

Figure 4.19. Wall Section Preparation for 3D printing

Printing Time: 59 min

Total number of layers: 40 layers

Failure location: layer # 35

≈ 83% print completion.

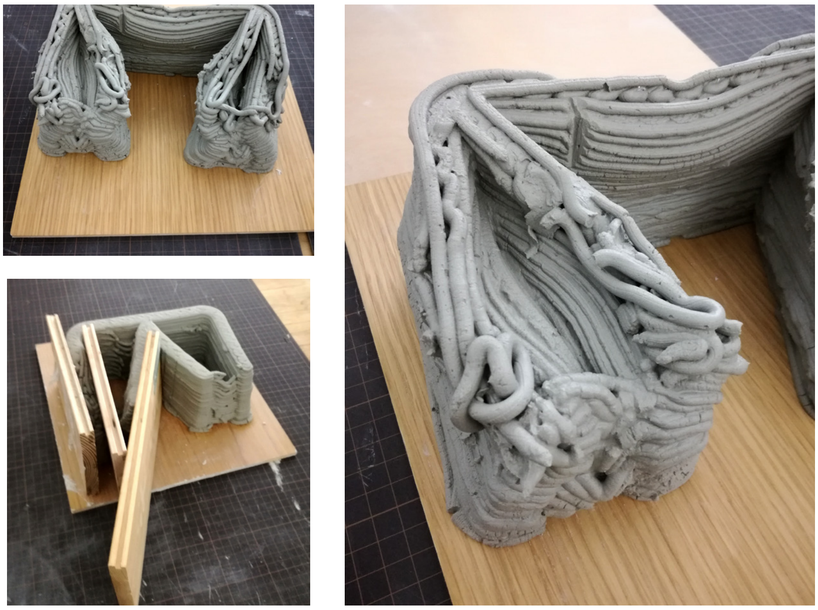


Figure 4.20. Wall Section Printing Process

Material	Amount	Price
Dry weight of each wall section half	3000 g	
Total dry weight of wall section	6000 g	
Total weight of assumed wall 80 * 6000 g	480 kg	
Fly- ash @ 20% of total weight	96 kg	Free
Soil weight = total weight of assumed wall - (weight of fly- ash + weight of Ca(HO)2)	480 - (96 + 0.89)= 383 kg	
Coarse Content of soil: (Silica #8) @ 42%	161 kg	(30 kg @ 1,728 yen) = 9,274 ¥
Fine Content of soil: (Kaolin (clay) + DL clay (silt)) @ 58%	222 kg	
Weight of Kaolin@ 76.7%	171 kg	(30 kg @ 5,400 yen) = 30,780 ¥
Weight of DL clay @ 23.3%	51 kg	(30 kg @ 1,728 yen) = 2,938 ¥
Water content weight @ 37%	178 L	(1 cubic meter (1000 L) @ 140.5 ¥) = 25 ¥
Weight of Ca(HO)2 @ 5 g/L	890 g	Free
		Total = 43,017 ¥

- All decimals were rounded to the nearest whole number
- Refer to Appendix 11 &12 for material prices
- Tax was included in all calculations
- Electrical Energy calculations were neglected due to their complexity
- Information regarding price of cubic meter of water was found at the Bureau of Waterworks, Tokyo Metropolitan Government website https://www.waterworks.metro.tokyo.jp/eng/faq/qa-2.html

Table 4.1. Estimated Amounts & Prices

When converting yen to US dollars, the total amount becomes **= 394.61$** per the price of the Yen against the Dollar as of Jan. 28, 2020.

Due to lack of information regarding the current prices of building materials in Sudan, a phone call was made to an individual in Sudan who works in construction, and was able to provide the author with the following estimate:

Cost of constructing 1 sqm using burnt brick = 100 Sudanese pound (approx.), as such:

Total area of assumed wall = 6 sqm

Price of constructing assumed wall in burnt brick = 6 * 100 = 600 Sudanese Pounds (1 Sudanese Pound = 0.022 $ as of Jan. 28, 2020)

600 Sudanese Pounds = 13.26 $

The calculations show that the price of constructing the same wall using burnt brick in Sudan is a lot less than the price of the used 3D printing process. However, the price calculations for the 3D printed wall were based on the use of synthetic materials and not organic soils. In theory, if the soil used for the 3D printing process is cultivated locally, that could result in an extreme reduction to the overall cost. Additionally, since the use of formwork in 3D printing is minimized as well as the need for labor, that could also help reduce cost.

The biggest issue when it comes to calculating costs is the high price of industrial 3D printers. However, these prices are expected to decline in the near future as their use becomes more prevalent. Companies like WASP are experimenting with low- cost mobile systems that could be transported and assembled easily on site.

Speed is a very important factor in the 3D printing process and is considered and advantage when compared to the speed of conventional construction. In this study, the printing time for the wall section was around 2 hrs in total. The prolonged printing time is a direct result of the small diameter of the printing nozzle (6 mm). Industrial 3D printers use nozzles that could go up to 22 mm diameter or more (Shakor, Nejadi, & Paul, 2019). For example, if the nozzle size in this study was increased from 6 mm to 22 mm, that is an increase of 266.67% or 3.7 times. The larger diameter will allow for higher layers so the 22 mm nozzle will print around four times faster and reduce printing time of the wall section from 2 hrs to 30 min approx.

4.5. Conclusion

- The resulting artificial soil has a Liquid limit (LL) of 55.7 %, a Plastic limit (PL) of 29.64%, and Plasticity index (PI) of 25.73% and is classified as, inorganic clay of high plasticity, fat clay(CH). The artificial soil is stickier and has more clay content, however, during the 3D printing test, the extra stickiness resulted in better adhesion between the layers.

- Earth mix composition is as follows:
Soil (42% course content (Silica #8) + 58% fine content (23.33% Silt (DL-Clay) + 76.67% Clay (A-A Kaolin) + fly-ash (JIS I) @ 20% + Liquid Content @ 37% (Distilled water mixed with $Ca(OH)_2$ @ 5 g/l)

- The Particle Size Distribution Test shows that around 7% of the mix is considered fine content and around 93% of the mix is considered course content. The convention to a majority course content could be an affect of adding the fly-ash.

- The printability tests showed that the optimum liquid content for the designed earth mix is @ 37% of the dry content weight, optimum nozzle height was @ 5 mm for the 6 mm diameter nozzle, buildability is estimated @ 35 layers, and the average height of layer @ 3 mm.

- The UCS test shows that the increase in strength was not consistent. Strength gain dropped after specimens cured for 3 days and didn't gain much strength from 1 week to 2 week curing time, then strength increased slightly at 28 days curing time at a maximum of 0.70 kN/ m2. The specimens also displayed linear cracking during testing and a brittle breakage behavior. From general observation, the printed objects were not stable and needed to be handled with care. The designed mix displayed poor structural strength.

- The shape generation process demonstrated that the cost of the printed unit depends on the decisions made during the design process. Shape and complexity are not relative when it comes to the 3D printing process as the system is capable of producing any degree of complexity with marginal differences in cost. However, smart decision making during the design process such as optimizing shape design based on environmental or structural information, could have a great impact on the practicality, material use, printing speed and therefore cost. From an architectural point of view, adding decorative elements results in a more engaging design which in turn could help with making mud construction much more mainstream. In Sudan, mud building is associated with low socioeconomic groups. Thus, demonstrating the system's capabilities through design is very important.

- In This study, cost calculations showed that the cost of constructing a wall of the same dimensions using burnt brick in Sudan is a lot less than constructing the wall using a 3D printing process. However, these calculations don't reflect the actual intended process of using local soils that are cultivated locally. Using local soils and additive materials will have a great impact on the cost and could reduce it dramatically. Additionally, calculating the cost of an AM construction process is very different to calculating the cost of a conventional construction process as there are multiple factors that need to be considered. These factors include the minimized need for formwork and labor, reductions in time and material usage, and the high degree of accuracy of the constructed part.

The biggest issue when it comes to calculating costs is the high price of industrial 3D printers. However, these prices are expected to decline in the near future as their use becomes more prevalent. Companies like WASP are experimenting with low- cost mobile systems that could be transported and assembled easily on site.

- Tests regarding speed of printing demonstrated the importance of considering the correct size of the printer's nozzle; a greater diameter or size results in a faster printing time. Nonetheless, a greater diameter means also loss of resolution and more rounding of corners. These factors need to be considered in the design process especially if the target is a low- cost process. In that case, the process's speed has more precedent over detail resolution.

CHAPTER 05

CONCLUSIONS & FUTURE RECOMMEN-DATIONS

5. Conclusions & Future Recommendations

5.1. Introduction

In this final chapter, the main concluding remarks of this study will be discussed.

The chapter starts with introducing a general "framework" that is meant to help future designers and researches understand the general steps needed for the testing and utilizations of an earth- based additive manufacturing process. The following section introduces a central additive manufacturing system meant to optimized the 3D printing process for low- cost construction by focusing on the production of a central plan unit shape (circular, free form, rectilinear, etc.). The used system is made of several parts that could be assembled on site to reduce the cost of transportation by eliminating the need for pre- fabrication off site. Finally, the chapter ends with the concluding remarks and a section for future recommendations.

5.2. Development of a General Framework

The main objective of this sections is to illustrate the general steps needed in order to streamline the process of earth based additive manufacturing.

As mentioned in earlier chapters, the earth based AM process is local- sensitive and it depends greatly on the used material and the local conditions. The process also is very dependant on the machine's capabilities and limitations. Therefore, the most important steps are the ones concerning the calibrations of the developed soil mix to match the capabilities and limitations of the chosen AM system.

As part of the conclusion of this study, a diagram containing the general steps crucial to the success of an earth- based AM process is presented in Figure 5.1. These steps were guided by the research's methodology and are geared more towards a low- cost process.

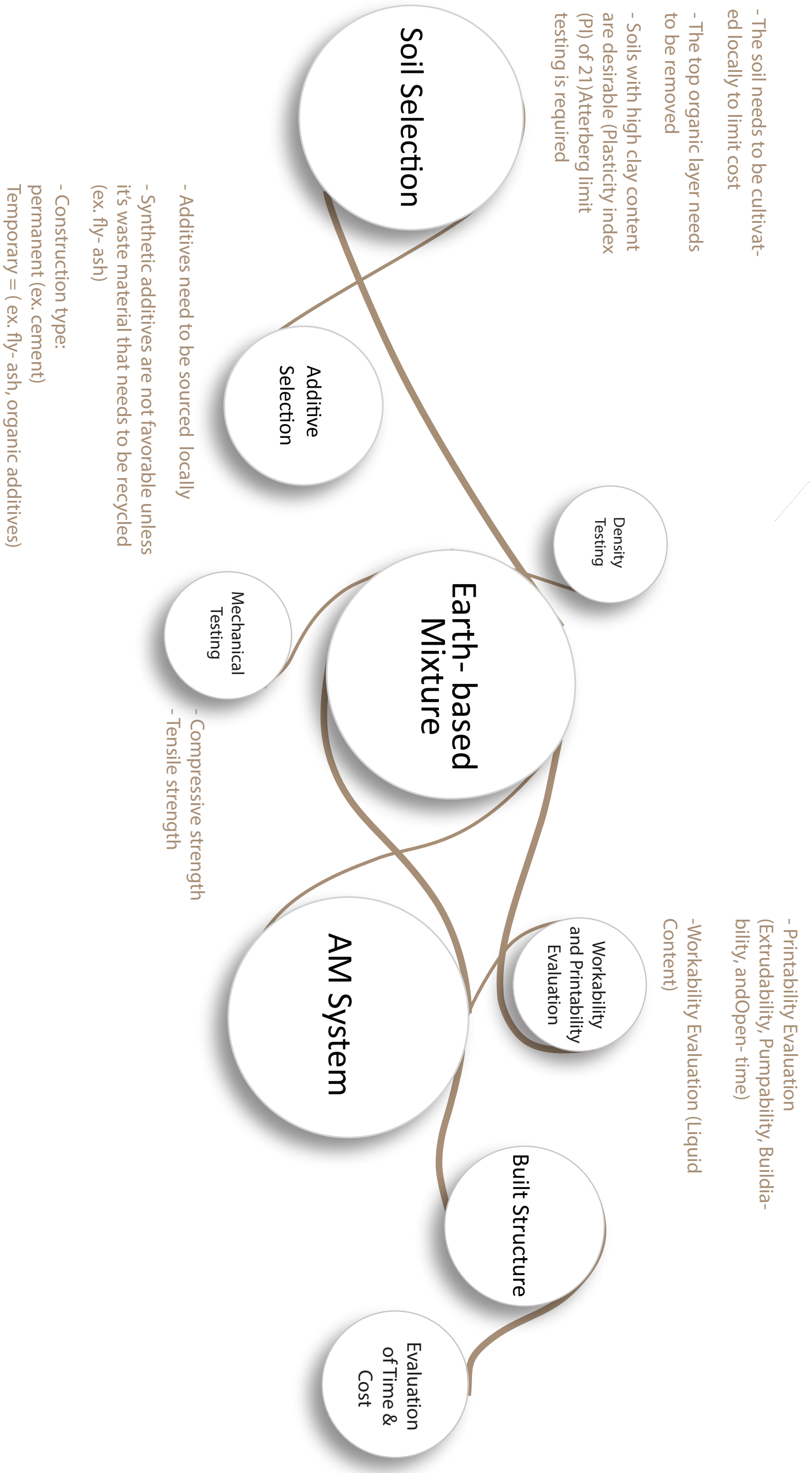


Figure 5.1. Earth- based AM framework Diagram

Of course, this diagram is only a starting point, and in order to effectively stream-line the earth-based AM process, a complete guide containing a survey of the suitable soil/ additive types, their properties (physical, mechanical and chemical) , equipment, price ranges, and geographical conditions need to be developed. This point will be further discussed in the future recommendations section.

5.3. A Central Additive Manufacturing System

The circular shape (or central plan) has be chosen as the main shape used to design the units in this study. This shape was inspired by the African hut as well its prevalent use in many early nomadic cultures represented by the yurts, trulli, tepees, igloos, etc found around the globe (Szczegielniak, 2019). Using AM technologies, the simple circle could be elevated and many variations could be created.

Form an economical point of view, an AM system designed to only construct central plan could be advantageous. As such, this section introduces an AM system that contains a rotating arm mounted to central column, Figures 5.2. - 5.5. The rotating arm is flexible and could extend or retract horizontally to achieve the desired diameter and also move up and down to create the desired height. The various components are meant to be light and mobile and are easily assembled on site. The system is designed mainly for wall construction.

The introduced system addresses many of the current issues associated with industrial AM construction one of which is the issue of size. Most of the existing construction scale 3D printers are based on gantry systems, this means that these printers are larger than the buildings they are attempting to print. In some cases the building needs to constructed off- site and then the various components are assembled on site which could generate a lot of complex issues (Zhang et al., 2018). Another issue is the high price of these printers, construction of printers using durable, light material and are portable could help reduce initial costs.

When it comes to the issue of power, using a renewable source of energy such as batteries powered by solar panels could be an active solution especially in countries like Sudan were the warm desert weather produces extreme sun exposure. Additionally, the lack of vegetation especially

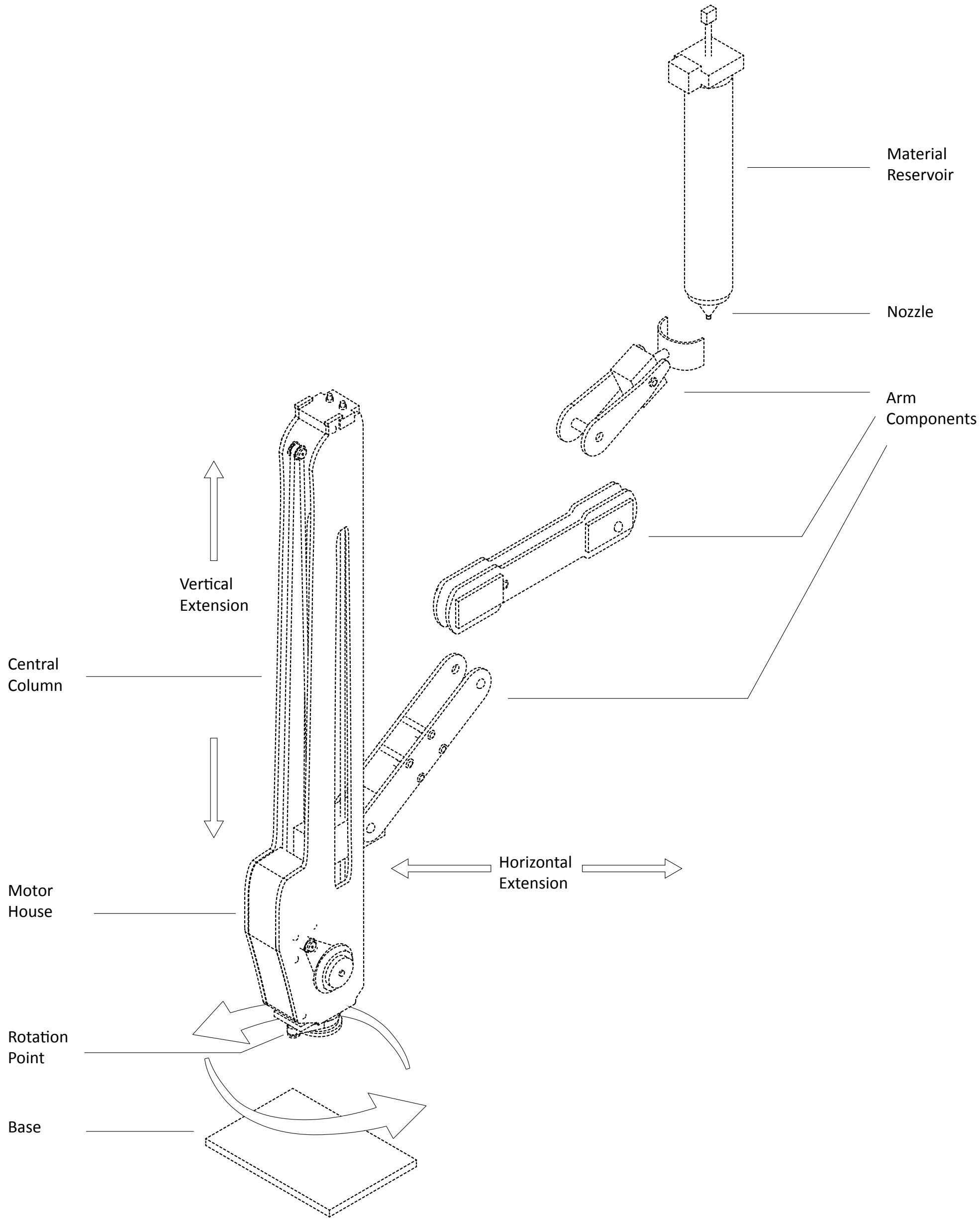


Figure 5.2. Components of a Central AM Configuration

in the northern regions and the flat typography provides little shade. The hot weather is also conducive of faster drying times.

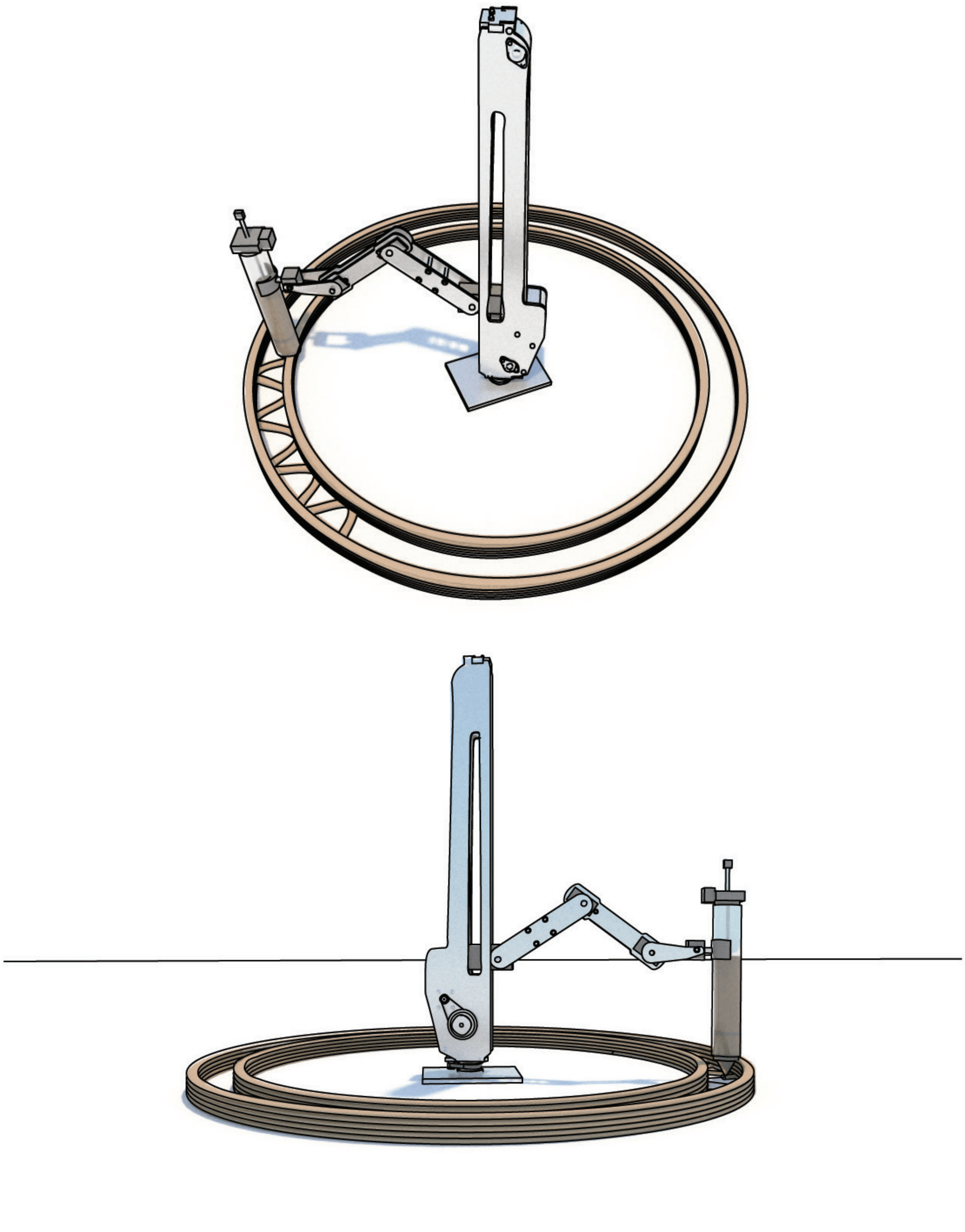
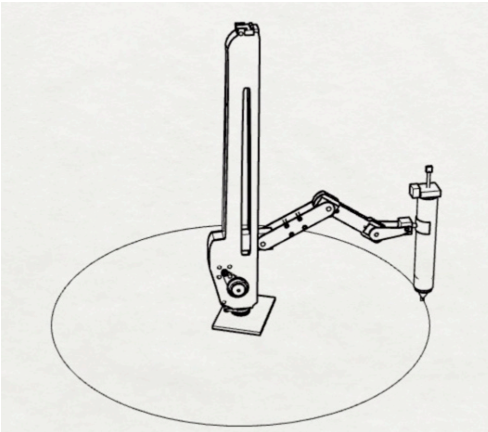
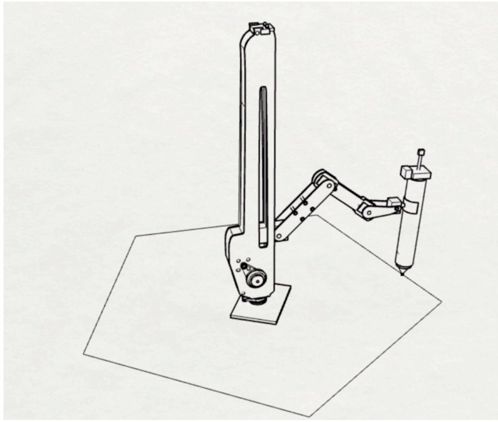


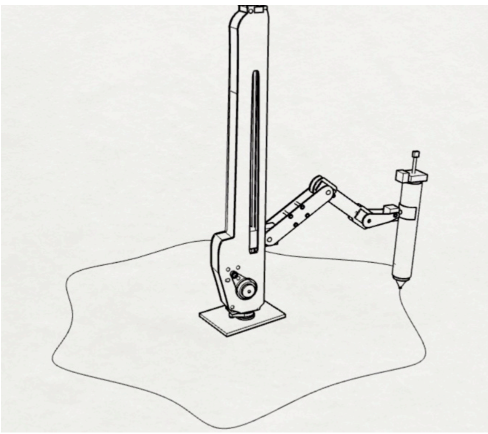
Figure 5.3. Central AM System Renderings



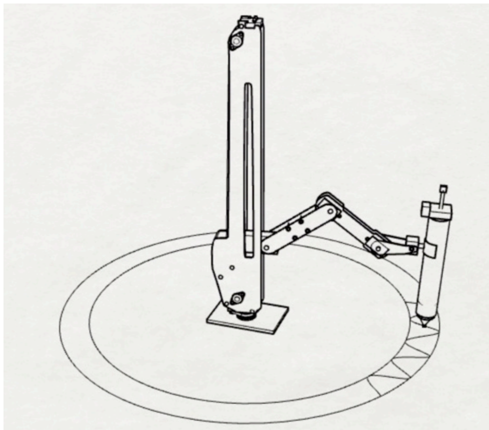
A: Printing a Circle



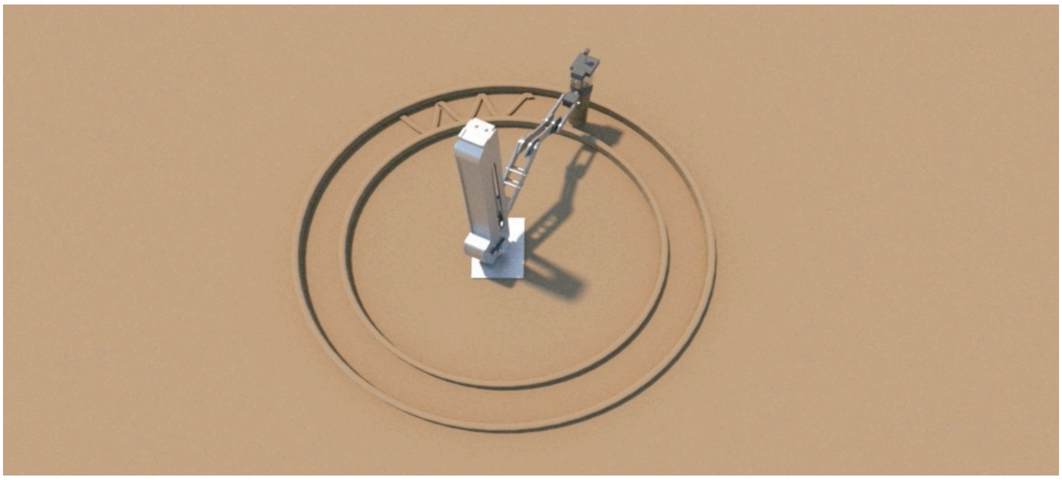
B: Printing a Polygon



C: Printing an Organic Shape



D: Printing a Double Wall



Rendered Top Elevation of a Circular Plan

Figure 5.4. Different Central Plan Examples

Figure 5.5. Perspective

5.4. Conclusion

Significant research has been done in the field of construction additive manufacturing and the many advantages associated with the process (Lim et al., 2012; Kazemian, Yuan, Cochran, & Khoshnevis, 2017; Soltan & Li, 2018) such as speed, increased design freedom, easy customization, increased construction site safety, waste reduction and limiting the need for formwork. However, the majority of the research done in construction AM focused on the use of concrete and not much research is being done on other cheap, environmentally friendly alternatives such as earth. Most importantly, there is no testing that is conducted in African countries where this technology might have the greatest impact.

In the following sections, the main concluding remarks of this study will be presented followed by the author's future recommendations.

5.4.1. Earth Mix Design & Calibration

In this study, an earth mix was developed for an extrusion- based additive manufacturing process (3D Potterbot 7 SUPER). Artificial soil components were mixed to create the target soil; Silica #8 was used in place of sand, DL Clay was used in place of silt, and , A-A Kaolin was used in place of clay. The target plasticity index (PI) was 21 and was based on reviewed literature. This PI falls within the range of the recommended plasticity indexes by international standards for earth construction and also represents a highly plastic soil which is a very common soil type in Sudan.

The resulting artificial soil has a Liquid limit (LL) of 55.7 %, a Plastic limit (PL) of 29.64%, and Plasticity index (PI) of 25.73% and is classified as inorganic clay of high plasticity, or fat clay(CH). The artificial soil is stickier and has more clay content, however, during the 3D printing test, the extra stickiness resulted in better adhesion between the layers.

The soil was then mixed with fly-ash class JIS-I chosen for Its high quality, fineness and high pozzolanic activity index, and a mixture of Calcium Hydroxide $Ca(OH)_2$ and water was used as the alkaline activator (liquid content). The fly- ash content was maintained at 20%, while the liquid content (water + $Ca(OH)_2$) was tested using the AM system at 30% and 40% of dry content weight. The $Ca(OH)_2$ was tested initially at 1.5 g/l and increased later to 5 g/l to improve mechanical behavior. Workability and extrudability tests reviled that the optimum liquid content was at 37%, this liquid content resulted in consistent and smooth extrusion. Further testing using the AM system showed that the optimum nozzle height was @ 5 mm for the 6 mm diameter nozzle, buildability is estimated @ 35 layers, and the average height of layer @ 3 mm.

The final earth mix composition is as follows:
Soil (42% course content (Silica #8) + 58% fine content (23.33% Silt (DL-Clay) + 76.67% Clay (A-A Kaolin) + fly-ash (JIS I) @ 20% + Liquid Content @ 37% (Distilled water mixed with Ca(OH)2 @ 5 g/l)

The Particle Size Distribution Test shows that around 7% of the mix is considered fine content and around 93% of the mix is considered course content. The convention to a majority course content could be an affect of adding the fly-ash.- The UCS test showed that the increase in strength was not consistent. Strength gain dropped after specimens cured for 3 days and didn't gain much strength from 1 week to 2 week curing time, then strength increased slightly at 28 days curing time at a maximum of 0.70 kN/ m2. The specimens also displayed linear cracking during testing and a brittle breakage behavior. From general observation, the printed objects were not stable and needed to be handled with care. The designed mix displayed poor structural strength.

5.4.2. Shape Design

The circular shape (or central plan) has be chosen as the main shape used to design the units in this study. This circular shape was inspired by the typical round African hut that could be observed in different parts of Sudan. The circle has a deep meaning in African culture, according to some researchers, it represents the 'nature's rhythm'. Another reason for drawing inspiration from African vernacular architecture is the socialist structure by which it operated; there were no obvious differences between the housing designs of the rich and poor aside from extra courses of material or decorations. Everyone lived in almost similar conditions and all participated in the building process of their homesteads. A circular hut in addition to two variations of the same scale and layer number were 3D printed and evaluated.

The evaluation of the 3D printed units showed that the simplest design took the longest (40 min) to print and used the most material. The design with the most detail took 30 min to print and used less material. This is probably due to the second design not needing internal support because connections were created between the outer and inner walls while in the first design the interior and exterior walls were completely separated and a third supporting elements was needed for support . This demonstrated that the cost of the printed unit based on the amount of material used depends on the decisions made during the design process.

From an architectural point of view, adding decorative elements results in a more engaging design which in turn could help with making mud construction much more mainstream. In Sudan, mud building is associated with low socioeconomic groups. Thus, demonstrating the system's capabilities through design is very important.

5.4.3. Cost & Time Assessment

In This study, cost calculations showed that the cost of constructing a wall of the same dimensions using burnt brick in Sudan is a lot less than constructing the wall using a 3D printing process. However, these calculations don't reflect the actual intended process of using local soils that are cultivated locally. Using local soils and additive materials will have a great impact on the cost and could reduce it dramatically. Additionally, calculating the cost of an AM construction process is very different to calculating the cost of a conventional construction process as there are multiple factors that need to be considered. These factors include the minimized need for formwork and labor, reductions in time and material usage, and the high degree of accuracy of the constructed part.

The biggest issue when it comes to calculating costs is the high price of industrial 3D printers. However, these prices are expected to decline in the near future as their use becomes more prevalent. Companies like WASP are experimenting with low- cost mobile systems that could be transported and assembled easily on site.

Tests regarding speed of printing demonstrated the importance of considering the correct size of the printer's nozzle; a greater diameter or size results in a faster printing time. Nonetheless, a greater diameter means also loss of resolution and more rounding of corners. These factors need to be considered in the design process especially if the target is a low- cost process. In that case, the process's speed has more precedent over the detail resolution.

5.4.4. Construction 3D Printing, a Paradigm shift

Using 3D printing to construct buildings requires redefining words such as 'shape' and 'decoration'. The building blocks in 3D printing are the material 'voxels' and as such, there is no incentive to make any generated voxel volume identical to the other due to the fact that no cast, model, die, or stamp is used regardless of the size or scale (Carpo, 2017). As a result, 3D printing processes are capable of producing any degree of complexity with marginal differences in cost.

`Shape` as it pertains to 3D printing is the culmination of the mathematical locations of the voxels in space; their arrangements, volumes, and densities can be easily controlled using software code. Consequently, it is no longer adequate to think of decoration or ornaments as waste and additional cost, moreover, the used terms don't apply any more because they reflect the traditional western understanding that ornaments are an addition or supplement (Carpo, 2017).

In the age of Big Data opportunities for building improvement are plentiful; simulation, optimization, and retrieval using the power of Big Data renders the formulaic approach used in modern structural engineering obsolete (Carpo, 2017). As such more complex forms are easier to realize. Working in the digital environment also facilitates combining 3D printing processes with 3D scanning, typography and design optimization software as well as environmental simulations which could result in architectural designs that are capable of responding accurately to any desired criteria such as cost, while maintaining a great deal of complexity.

5.5. Future Recommendations

- Research focused on architectural geometry and shape generations is needed in order to further explore the limits of earth- based mixes developed for the AM process.
- The construction of roofs and openings was not discussed in this research as it only focused on wall construction. Therefore, future studies that explore the 3D printing of roofs and the design requirements need for creating openings are needed.
- Further testing of soil mixes and machines needs to be done in order to improve the overall process. Some of the key areas that need testing are mix fresh properties, printability, buildability, and strength of printed structures.
- Future research should also target the development of low- cost, low- energy consuming 3D

printers to address the low- cost housing needs and further reduce cost of construction.

-Due to the low structural- strength of fly-ash, alkaline- activator soil mix, more research that focuses on better kinds of alkaline- activators needs to be done.

- Studies of mixes that include organic/ synthetic fibers are needed as adding fibers to the soil mix could help improve in tensile/ flexural strength.

- A survey of the suitable soil/ additive types, their properties (physical, mechanical and chemical) , equipment, price ranges, and geographical conditions need to be developed. The list also reflect the types of additives suitable for permanent construction and additives that result in temporary construction and should also include general standards, guidelines, and needed tests.

- Environmental studies, typography optimization, and density optimization studies need to be done in order to create more reactive architectural designs.

- Detailed long- term economical studies are needed especially studies that focus on the life-cycle of the mud 3D printed units.

- Research targeting the use of the earth-based AM technology in Africa is greatly needed as it has the potential to create a great impact on the region.

5.6. Final words

".....what is needed at the beginning of the new millennium is an architectural perspective in which valuable vernacular knowledge is integrated with equally valuable modern knowledge..." (Asquith & Vellinga, 2006, p.18).

This quote encapsulates the spirit of this research perfectly as it strives to join earth, the oldest building material known to man, with a state of the art construction technology represented by Additive Manufacturing. The two are then threaded together with inspiration from African Vernacular architecture.

As the population of our planet keeps increasing, and need for shelter keeps increasing, innovative solutions need to be considered in order to meet the housing quota. This study was one such attempt.

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APPENDICES

Appendix 1

A-A Kaolin Properties

⊙ クニミネ(土木建設部)
03-3866-7251

斉藤商店 (Saito shoten)
中澤氏 (Mr. Nakazawa)
03-3354-2791

2013年・5月改訂

品種 / 記事		B.Iカオリン	A.Aカオリン	SMC	M.Cクレー	M.Bクレー	H.Aクレー	O.Aクレー	O.Sクレー	T.Pクレー	カタルポ	オカライト	SMT	タルク85	タルク83	タルクH	タルクD	胡粉	記事
一袋入目		15kg	15kg	20kg	20kg	20kg	20kg	25kg	25kg	25kg	25kg	25kg	15kg	25kg	25kg	25kg	25kg	20kg	コンテナーBag使用可 入目は任意可
一般性質 白色度(%)		87以上	80以上	85以上	86以上	86以上	85以上	70以上	78以上	78以上	68以上	60以上	86以上	85以上	83以上	80以上	65以上		ハンター白色計
ふるい残分(%)		全通	0.03以下	0.01以下	0.01以下	0.01以下	0.03以下	0.50以下	0.50以下	0.20以下	0.20以下	0.10以下	0.02以下	1.0以下	1.0以下	1.0以下	1.0以下		JIS標準フルイ(湿式方) 330メッシュ
水分(%)		1.5以下	2.0以下	1.0以下	1.0以下	1.0以下	1.0以下	1.0以下	0.7以下	1.0以下	1.0以下	0.5以下	0.5以下	1.0以下	1.0以下	1.0以下	1.0以下	—	JIS K 5101
P.H		5±1	4.5±1	6±1	5±1	5±1	6±1	6.5±1	6±1	6±1	6±1	6±1	8.5±1	8.5±1	8.5±1	8.5±1	8.5±1		ガラス電極式PHメーター JIS K 5101
吸油量(c.c./%)		48〜53	50〜55	48〜53	48〜53	43〜47	40〜45	25〜30	28〜33	28〜33	25〜30	25〜30	43〜47	27〜32	27〜32	25〜30	20〜25		亜麻仁油、ヘラ JIS K 5101
粒度分布例	−2μ(%)	75〜80	35〜40	65〜70	65〜70	45〜55	35〜45	15〜20	25〜35	20〜25	20〜25	25〜30	45〜50	30〜35	30〜35	20〜25	12〜15		沈降法による粒度測定
	−3μ(%)	85〜90	40〜50	75〜80	70〜80	55〜75	45〜55	20〜25	35〜40	25〜40	25〜40	30〜40	50〜60	35〜40	35〜40	25〜35	15〜20		(ストークスの法則により計算)
	−5μ(%)	90〜95	55〜60	85〜90	85〜90	80〜85	65〜75	30〜40	50〜55	50〜60	50〜60	45〜50	70〜80	40〜45	40〜45	35〜45	20〜25		
	−7μ(%)	95〜99	70〜75	90〜95	95〜97	90〜95	80〜90	40〜45	60〜70	60〜65	60〜65	55〜60	80〜90	50〜60	50〜60	50〜60	25〜30		
	−10μ(%)	—	80〜85	95〜98	97〜99	95〜99	90〜98	45〜60	70〜80	65〜70	65〜70	65〜70	95〜99	65〜70	65〜70	65〜70	35〜40		
	−15μ(%)	—	95〜99	98〜100	—	—	96〜99	60〜70	80〜90	75〜80	75〜80	75〜85	—	75〜85	75〜80	70〜80	55〜60		
化学分析例	Igℓoss	13〜14	13〜14	3.5〜5.0	4.5〜5.0	4.0〜4.7	3.5〜4.0	2.5〜3.0	2.7〜3.3	3.5〜4.0	2.5〜3.0	2.0〜2.5	4.5〜5.0	4.0〜4.5	4.0〜4.5	8〜13	15〜20		その他の試験
	$A\ell_2O_3$	35〜40	35〜38	20〜24	23〜25	20〜25	20〜23	15〜18	18〜22	20〜23	15〜18	15〜18	0.2〜0.3	0.2〜0.3	0.2〜0.3	〜10	1.0〜2.0		吸油量、かさ比重、各種分析(JIS規格)
	SiO_2	40〜50	45〜50	65〜70	65〜73	65〜75	70〜75	75〜80	75〜80	70〜75	75〜80	75〜80	60〜65	60〜65	60〜65	50〜60	40〜50		吐粉性、金網磨耗度、沈降度
	Fe_2O_3	0.05〜0.1	0.3〜0.5	0.1〜0.3	0.1〜0.2	0.2〜0.3	0.2〜0.3	0.4〜0.5	0.15〜0.25	0.2〜0.5	0.3〜0.5	0.5〜0.8	0.2〜0.4	0.2〜0.4	0.2〜0.4	0.2〜0.4	5〜8		透明度、粘性、分散性等試験可
	CaO	0.04〜0.1	0.2〜0.3	0.1〜0.3	0.05〜0.1	0.02〜0.05	0.02〜0.05	—	0.03〜0.07	0.02〜0.05	0.01〜0.03	0.02〜0.07	0.2〜0.3	0.2〜0.3	—	0.1〜0.3	2.0〜3.0		その他県工業技術センターにおいて
	MgO	0.05〜0.1	0.3〜0.4	0.05〜0.1	0.05〜0.1	0.02〜0.05	0.02〜0.05	—	0.03〜0.07	0.02〜0.05	—	0.02〜0.07	30〜35	30〜35	30〜35	25〜30	25〜35		各種分析可
主な特徴		超微粉 高級品種 製紙・塗料 接着剤	製紙・塗料 接着剤	超微粉 陶器用 接着剤	超微粉 高級品種 製紙・医薬用等	医薬用 製紙・塗料等	製紙 パテ・塗料 接着剤等	ゴム・接着剤 塗料・中和品等	接着剤 塗料・農薬等	接着剤 塗料・農薬等	接着剤 ゴム等	ゴム 塗料・農薬等	製紙用ピッチコントロール剤 ゴム補強剤 塗料・プラスチック等	製紙 合成樹脂 塗料等	製紙 合成樹脂 塗料等	塗料 製紙・パテ ゴム・合成樹脂等	塗料・農薬 接着剤 ゴム等	天然カキ殻粉砕品	製紙・塗料・ゴム・建材・農薬など超微粉から粗粉の多品目にいたり高品質の弊社製品が最適です。

(数字はすべて標準データー)

Appendix 2

DL- Clay Properties

試　験　表

平成 30年4月23日

検印

昭和ＫＤＥ株式会社

納入先
東京大学生産技術研究所　御中

LOT No　30129

発送年月日　平成　30年　4月　20日

試験年月日　平成　年　月　日

銘柄　昭和DLクレー

種目		化学成分 %				備考
粒度 (−45 μm %)	96.8 %	SiO_2		lg. Loss		
仮比重	1.04	Al_2O_3				
水分	0.10 %	Fe_2O_3				
P・H	5.63 %	K_2O				
色相 Blue		Na_2O				
〃 Red		CaO				
		MgO				合
		TiO_2		Total		

HEAD OFFICE (81-3-5422-9525)

Appendix 3

Silica #8 Particle Size Distribution

Sympatec GmbH
System-Partikel-Technik

QICPIC Particle Size Analysis
WINDOX 5

QICPIC (0177 Q) & GRADIS, 1.00 63.0 mm - M7 (10...3410µm)
Silica8_MO_100_200_masahide_2 **2019-11-01, 12:14:11**,125

x_{10}, x_{30}, x_{50}, x_{60}, x_{80}, x_{90} =
88.99 µm
124.79 µm
149.95 µm
163.42 µm
191.75 µm
210.85 µm

Number of Particles, Measurement Duration, Optical Concentration, Max Opt. Concentration
504451
64.38
0.290
<E04>

Standard Deviation of PSD
44.480

cumulative distribution				**density distribution (log.)**	
upper band limit x_0/µm	**cumulative distribution Q_3/%**	**residue distribution $(1-Q_3)$/%**	**fraction in band dQ_3/%**	**mean size for band x_m/µm**	**density distribution q_3lg**
25.00	0.00	100.00	0.00	11.88	0.00
50.00	0.00	100.00	0.00	35.36	0.00
75.00	3.57	96.43	3.57	61.24	0.20
100.00	15.06	84.94	11.49	86.60	0.92
125.00	30.12	69.88	15.07	111.80	1.55
150.00	50.04	49.96	19.92	136.93	2.52
175.00	68.59	31.41	18.55	162.02	2.77
200.00	85.62	14.38	17.04	187.08	2.94
225.00	95.70	4.30	10.08	212.13	1.97
250.00	99.56	0.44	3.86	237.17	0.84
275.00	100.00	0.00	0.44	262.20	0.11
300.00	100.00	0.00	0.00	287.23	0.00
325.00	100.00	0.00	0.00	312.25	0.00
350.00	100.00	0.00	0.00	337.27	0.00
375.00	100.00	0.00	0.00	362.28	0.00
400.00	100.00	0.00	0.00	387.30	0.00
425.00	100.00	0.00	0.00	412.31	0.00
450.00	100.00	0.00	0.00	437.32	0.00
475.00	100.00	0.00	0.00	462.33	0.00
500.00	100.00	0.00	0.00	487.34	0.00
525.00	100.00	0.00	0.00	512.35	0.00
550.00	100.00	0.00	0.00	537.35	0.00
575.00	100.00	0.00	0.00	562.36	0.00
600.00	100.00	0.00	0.00	587.37	0.00
650.00	100.00	0.00	0.00	624.50	0.00
700.00	100.00	0.00	0.00	674.54	0.00
750.00	100.00	0.00	0.00	724.57	0.00
800.00	100.00	0.00	0.00	774.60	0.00
850.00	100.00	0.00	0.00	824.62	0.00
900.00	100.00	0.00	0.00	874.64	0.00
11570.00	100.00	0.00	0.00	3226.92	0.00

evaluation: WINDOX 5.4.1.0
calculation mode: USER_1
class limits: LILY

product: Silica8_MO_100_200_masahide_2
density: 2.60 g/cm³
C_{opt}: 0.29 %

Appendix 4

LIquid Limit & Plastic Limit Test Method

Japanese Geotechnical Society Standard (JGS 0141-2009) Test method for liquid limit and plastic limit of soils

1 Scope

This standard specifies test methods to obtain the liquid limit, plastic limit, and plastic index of soils that have passed through a sieve with a mesh of 425 μm.

2 Normative references

The following standards shall constitute a part of this standard by virtue of being referenced in this standard. The latest versions of these standards shall apply (including supplements).

JIS A 1201 Practice for preparing disturbed soil samples for soil testing
JIS A 1203 Test method for water content of soils
JIS K 6253-3 Rubber, vulcanized or thermoplastic – Determination of hardness (Part 3: Durometer method)

3 Terms and definitions

The terms and definitions used in this standard are as follows:

3.1 Liquid limit

The water content of a soil in transition from the plastic state to the liquid state, which can be obtained by means of liquid limit test

3.2 Plastic limit

The water content of a soil in transition from the plastic state to the semi-solid state, which can be obtained by means of plastic limit test

3.3 Plastic index

Difference between the liquid limit and the plastic limit

4 Equipment

4.1 Test apparatus for liquid limit

Test apparatus used to measuring the liquid limit shall meet the following criteria.

4.1.1 Liquid limit measuring instrument

The liquid limit measuring instrument shall consist of a brass dish, a dropper device for the dish, and a hard rubber pad. Shape and dimensions shall be as shown in Fig. 1. The following criteria shall also be met.

a) The dropper device shall be capable of being set to a drop height of 1 cm. It shall be suitable for freely dropping the brass dish at a rate of twice per second.

b) The hard rubber pad shall have a hardness of 88±5 according to a durometer hardness test Type A in accordance with JIS K 6253-3.

Remark: Because rubber hardens with time, it is recommended that the hardness of the rubber pad be measured at least once per year to ensure that it satisfies the required conditions.

4.1.2 Grooving tool and gauge

a) The grooving tool shall be made of stainless steel and have the shape and dimensions shown in Fig. 2.

b) The gauge shall be in the form of a stainless steel or brass plate with a thickness of 10±0.1 mm.

Remark: The gauge may be in the form of a stand-alone plate.

4.1.3 Other apparatus

a) Apparatus for Obtaining Soil Water Content The apparatus for obtaining soil water content shall be in accordance with JIS A 1203.

b) Glass Plate The glass plate should consist of sheet glass with a thickness of a few millimeters (mm).

c) Spatula

d) Distilled Water

4.2 Test apparatus for plastic limit

The test apparatus used to measure the plastic limit shall meet the following criteria.

a) Frosted Glass Plate The frosted glass plate shall be a sheet glass with a thickness of a few millimeters (mm).

b) Round Rod The round rod shall be about 3 mm in diameter.

c) Other apparatus Other apparatus shall be the same as in 4.1.3 above.

5 Samples

Samples shall be prepared as follows.

a) Samples shall consist of material which has passed a sieve with a 425 μm mesh and which originated from soil with a natural water content and which was obtained in accordance with JIS A 1201. Air-dried samples may be used if air drying has no influence on the test results for liquid or plastic limit.

b) Minimum mass of samples shall be about 200 g for the liquid limit test and about 30 g for the plastic limit test.

c) Place a sample on a glass plate and mix it fully.

   1) The moisture content of samples shall be such that they are putty-like for the liquid limit test and dumpling-like for the plastic limit test. If the water content in a sample is too low, distilled water shall be added. If too high, the sample shall be suitably dehydrated through natural drying.

   2) If air-dried material is used for the samples, add distilled water and mix thoroughly before allowing the material to sit for a little over ten hours. Care shall be taken to avoid evaporation and ensure that the soil and water are fully blended.

6 Test method

6.1 Liquid limit test

The liquid limit test shall be performed as follows.

a) Insert a gauge between the brass dish and the hard rubber pad, and adjust the dropper such that the drop height of the brass dish is 10±0.1 mm.

b) Use a spatula to place a sample in the brass dish to a maximum thickness of about 1 cm and shape it. While holding the grooving tool perpendicular to the bottom of the brass dish, cut a groove in the sample along the diameter of the brass dish, aligned with the center line of the cam's bearing surface as shown in Fig. 3, thereby dividing the sample into two.

c) Place the brass dish in the dropper device. Lift and drop the dish repeatedly at a rate of twice per second, continuing until the divided soil at the bottom of the groove has joined together again for a length of about 1.5 cm.

d) Record the number of drops at the time when the groove joined and obtain the water content of the sample near the joining point.

e) Either add distilled water to the sample or allow some moisture to evaporate, then mix the sample fully and repeat steps b) to d). This process shall be repeated until two samples of 10 to 25 drops and two of 25 to 35 drops have been obtained.

6.2 Plastic limit test

The plastic limit test shall be as follows.

a) Rolling the mixed sample on the glass plate under the palm of the hand, as shown in Fig. 4, form it into a string until it matches the 3 mm round rod in diameter. When a string of 3 mm diameter has been obtained, form the sample into a mass again and repeat the above process.

b) Repeat the above process until the string breaks apart as it reaches a diameter of 3 mm, as shown in Fig. 5, and then collect the broken parts. Obtain the water content of the soil promptly.

7 Test results

7.1 Liquid limit

The liquid limit shall be calculated as follows.

a) Using semilogarithmic graph paper, plot the number of drops on the logarithmic axis and the soil water content on the arithmetic axis.

b) Obtain a best-fit straight line, known as a flow curve.

c) Determine the soil water content corresponding to 25 drops on the flow curve. This shall be the liquid limit, w_L (%).

d) If unable to complete the procedure in 6.1 above, classify the sample as NP (nonplastic).

7.2 Plastic limit

The plastic limit shall be calculated as follows.

a) The water content of the sample obtained in 6.2 shall be the plastic limit, w_P (%).

b) If unable to obtain the plastic limit in the step 6.2, classify the sample as NP.

7.3 Plastic index

The plastic index shall be calculated using the following equation. However, if it is not possible to obtain either the liquid or plastic limit or if there is no significant difference between the two, give this index as N_P.

$$I_p = w_L - w_P$$

where

I_p: plastic index

w_L: liquid limit (%)
w_P: plastic limit (%)

8 Reporting

The following results of the tests shall be reported.

a) Flow curve

b) Liquid limit (%)

c) Plastic limit (%)

d) Plastic index

e) If the method used deviates in any way from this standard, give details of the method used.

f) Other reportable matters

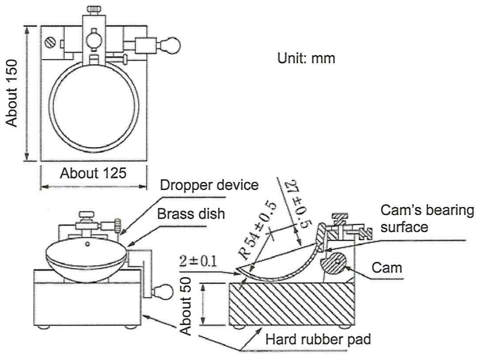


Fig. 1 Example of liquid limit measuring instrument

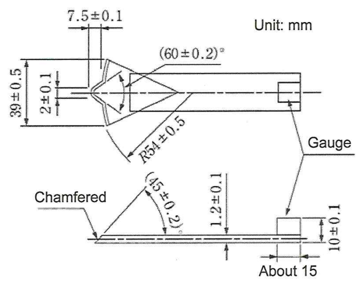


Fig. 2 Example of grooving tool and gauge

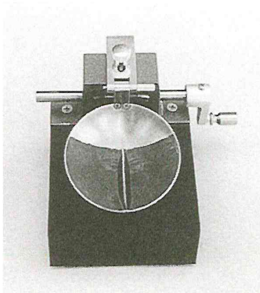


Fig. 3 Grooved sample

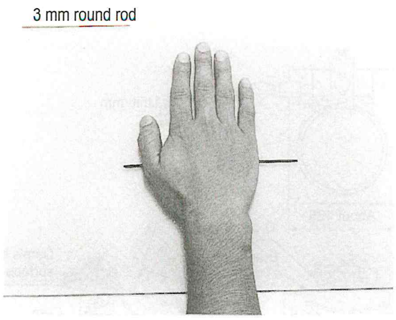


Fig. 4 Method of forming string.

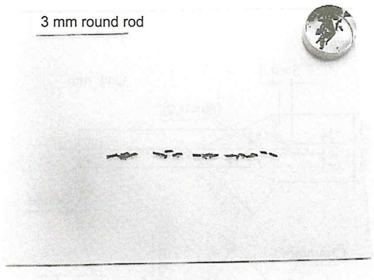


Fig. 5 String breaking into parts

Appendix 5

Particle Size Distribution Test Method

Japanese Geotechnical Society Standard (JGS 0131-2009)
Test method for particle size distribution of soils

1 Scope

This Japanese Geotechnical Standard covers the test method for determining the distribution of particle sizes in soils, other than highly organic soils, passing a metal wire cloth sieve with an aperture width of 75 mm specified in JIS Z 8801-1.

2 Normative references

The following standards shall constitute a part of this standard by virtue of being referenced in this standard. The latest versions of these standards shall apply (including supplements).

JIS A 1201:	Practice for preparing disturbed soil samples for soil testing
JIS A 1202:	Test method for density of soil particles
JIS A 1203:	Test method for water content of soils
JIS A 1205:	Test method for liquid limit and plastic limit of soils
JIS R 3503:	Glass apparatus for chemical analysis
JIS R 3505:	Volumetric glassware
JIS Z 8801-1:	Test sieves – Part 1: Test sieves of metal wire cloth

3 Terms and definitions

The terms and definitions used in this standard are as follows:

3.1 Particle size distribution

The distribution of particle sizes in soils expressed by mass percentage.

3.2 Maximum particle size

The particle size of soils expressed by the minimum aperture width of the metal wire cloth sieve through which the total amount of a soil sample passes.

4 Types of test method and test sequence

4.1 Types of test method

This standard provides the following two types of test methods.

a) Sieve analysis Sieve analysis is a particle size test by using metal wire cloth sieves and shall apply to soil particles remaining on the metal wire cloth sieve with an aperture width of 75 µm.

b) Sedimentation analysis Sedimentation analysis is a particle size test by measuring the density soil suspension and shall apply to soil particles passing a metal wire cloth sieve with an aperture width of 75 µm.

4.2 Test sequence

The test shall be conducted according to the following sequence.

a) Sieving of a soil sample using a sieve with an aperture width of 2 mm

b) Sieve analysis of the portion remaining on a sieve with an aperture width of 2 mm

c) Sedimentation analysis of the portion passing a sieve with an aperture width of 2 mm. If the distribution of particle sizes below 0.075 mm is not required, the sedimentation analysis may be omitted.

d) Sieve analysis of the portion passing a sieve with an aperture width of 2 mm and the portion remaining on a sieve with an aperture width of 75 µm

Remark: The standard sequence of particle size analysis is shown in Fig. 1.

5 Equipment

5.1 Test apparatuses

Test apparatuses shall be as follows.

a) Sieves A series of sieves, of metal wire cloth, with the following aperture widths specified in JIS Z 8801-1: 75 µm, 106 µm, 250 µm, 425 µm, 850 µm, 2 mm, 4.75 mm, 9.5 mm, 19 mm, 26.5 mm, 37.5 mm, 53 mm and 75 mm

b) Density hydrometer A hydrometer graduated in a 0.001 g/cm^3 division scale between 0.995 g/cm^3 and 1.050 g/cm^3 (See Fig. 2.)

c) Dispersion device A dispersion device capable of sufficiently dispersing soil particles by mechanical means (See Fig. 3.)

d) Measuring cylinders Measuring cylinders of 250 mL and 1,000 mL in nominal capacity specified in JIS R 3505. The measuring cylinder of 1,000 mL in nominal capacity may have only 1,000 mL mark.

e) Thermometer A thermometer readable to 0.5 °C or 1 °C.

f) Constant-temperature water bath A constant-temperature water bath capable of maintaining the temperature of a soil suspension in a measuring cylinder nearly constant. If the sedimentation analysis is carried out in a constant-temperature room, the bath is not required.

g) Beaker A beaker of 500 mL of more in nominal capacity specified in JIS R 3503.

h) Balances Balances, sensitive to 0.01 g for weighing a sample 100 g and below, 0.1 g for weighing 100 g to 1 kg, and 1 g for weighing over 1 kg.

i) Vernier calliper A vernier caliper with a minimum reading of 0.05 mm or less.

j) Water content measuring apparatus The water content measuring apparatus specified in JIS A 1203.

k) Loosening apparatus

l) Rubber spatula

5.2 Reagents

Reagents shall be as follows.

a) Hydrogen peroxide Hydrogen peroxide of 6 % solution.

b) Dispersing agent Dispersing agent shall be the saturated solution[1)] of sodium hexametaphosphate.

Remark: The dispersing agent shall be capable of dispersing soil particles by chemical means, and instead of sodium hexametaphosphate, the saturated solution of sodium pyrophosphate, sodium tripolyphosphate or the like may be used.

Note 1): To prepare the sodium hexametaphosphate solution, dissolve approximately 20 g of sodium hexametaphosphate in 100 mL of distilled water at about 20 °C.

c) Distilled water

6 Sample preparation and sieving of soil sample using a sieve with an aperture width of 2 mm

A soil sample shall be prepared as follows. If the total amount of the soil sample passes the sieve with an aperture width of 2 mm, omit b), c), and d) and use the sample as the portion that have passed the sieve with an aperture width of 2 mm.

a) Use a wet or air-dried sample taken by the method specified in JIS A 1201.

Remark 1: Use Table 1 as a guide for the minimum mass of a soil sample to be separately taken for the test, depending on the maximum particle size of the sample.

When the sedimentation analysis is carried out, the minimum oven-dried mass of a sample passing a sieve with an aperture width of 2 mm shall be approximately 115 g for sandy soil and 65 g for silty or clayey soil.

Remark 2: If the sample contains rocky materials that have remained on a sieve with an aperture width of 75 mm, it is recommended to determine the mass percentage of the materials.

b) Take approximately one-fourth of the sample and determine the water content of the sample w (%).

c) Take the total amount of remaining sample (hereinafter referred to as the total sample) as the sample for particle size test and weigh the mass of the sample m (g).

d) Sieve the total sample through a sieve with an aperture width of 2 mm. Take the soil particles passing the sieve as the portion passing the sieve with an aperture width of 2 mm and the particles remaining on the sieve as the portion retained on the sieve with an aperture width of 2 mm. During the sieving operation, pass as many fine fraction as possible adhering to the surface of coarse particles retained on the sieve through the sieve. If wet clayey soil is used for the test, add a suitable amount of water to the sample, and sieve the sample by straining as specified in JIS A 1201.

7 Sieve analysis of the portion remaining on the sieve with an aperture width of 2 mm

7.1 Sample preparation

The sample shall be prepared as follows.

a) Wash the portion remaining on the sieve with an aperture width of 2 mm with water on the sieve, and thoroughly wash away the soil particles passing the sieve with an aperture width of 2 mm.

b) Dry the total amount of sample remaining on the sieve in an oven at (110±5) °C to a constant mass, and weigh the mass of the sample m_{0s} (g).

7.2 Sieving of soil sample

The sample shall be sieved as follows.

a) Sieve the oven-dried sample through the sieves with an aperture width of 75 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 9.5 mm, and 4.75 mm. Sieve the sample continuously for one minute until the portion passing the sieve becomes approximately 1 % or less of the portion remaining on the sieve. During the sieving operation, move the sieve laterally and vertically while vibrating the sieve so as to keep the sample moving continuously over the surface of the sieve.

b) Weigh the mass of the sample remaining on each sieve, and take the mass of the sample remaining on the sieve with an aperture width of d_i as $m(d_i)$ (g). Further, weigh the mass of the sample passing the sieve with an aperture width of 4.75 mm, and take the mass of the sample remaining on the sieve with an aperture width of 2 mm as m (2 mm) (g).

8 Sedimentation analysis of the portion passing the sieve with an aperture width of 2 mm

8.1 Test of hydrometer

The hydrometer shall be tested as follows.

a) Float the hydrometer in distilled water, take the readings at the top of the meniscus r_U and the bottom r_L in the decimal part of the hydrometer. Wash in advance the stem of the hydrometer with alcohol or a detergent.

b) Measure the length of the bulb of the hydrometer L_B (mm) to the nearest 0.1 mm, and the volume V_B (cm^3) to the nearest 1 cm^3 by using a measuring cylinder of 250 mL in nominal capacity.

c) Measure the length l_1 (mm) from the top[2)] of the hydrometer bulb to the 1.000 mark and the length l_2 (mm) to the 1.050 mark to the nearest 0.1 mm (See Fig. 2.)

Note 2): The top of the hydrometer bulb means the joint surface of the bulb and stem.

d) Determine the cross-sectional area A (cm^2) of the measuring cylinder with a nominal capacity of 1,000 mL to the nearest 0.01 cm^2.

8.2 Sample preparation

The sample shall be prepared as follows.

a) Take the oven-dried mass of about 115 g for sandy soil and about 65 g for silty or clayey soil as the sample from the portion passing the sieve with an aperture width of 2 mm.

b) Take approximately one-fourth of the sample and determine the water content of the sample w_1 (%).

c) Take the total amount of the remaining sample as the sample for sedimentation analysis, and measure the mass of the sample m_1 (g).

8.3 Dispersion of soil sample

Dispersion of soil sample shall be accomplished by either of the following methods according to the plasticity index determined by JIS A 1205.

a) For soil sample less than 20 in plasticity index

   1) Add distilled water to the sample contained in a beaker, stir to mix the soil-water mixture uniformly and disperse soil particles in the water.

   2) After letting the mixture stand for 15 hours or more, transfer the total amount of the mixture in the beaker into a container of the dispersion device and add distilled water until the total volume is approximately 700 mL.

   3) Add 10 mL of a dispersing agent, and stir the mixture by using the dispersion device for approximately 1 min.

b) For soil sample not less than 20 in plasticity index

   1) Gently add approximately 100 mL of hydrogen peroxide 6% solution to the sample contained in a beaker, and stir to mix the soil mixture uniformly and disperse soil particles in the solution.

   2) Place a glass plate cover or the like on the beaker and put it inside a constant-temperature drying oven at (110±5) °C. If the sample in the beaker boils over the beaker, repeat the operation from 8.2 a).

   3) After approximately 1 hour, take the beaker out of the constant-temperature drying oven, add approximately 100 mL of distilled water to disperse soil particles in the water.

4) After letting the mixture stand for 15 hours or more, transfer the total amount of the mixture in the beaker into a container of the dispersion device, and add distilled water until the total volume is approximately 700 mL.

5) Add 10 mL of a dispersing agent, and stir the mixture by using the dispersion device for approximately 1 min.

8.4 Sedimentation measurement

The sedimentation measurement shall be carried out as follows.

a) Transfer the total amount of dispersed sample to a measuring cylinder and fill to the 1 L mark with distilled water.

b) Place the measuring cylinder in a constant-temperature water bath or constant-temperature room, and let it stand until the temperature of the sample in the measuring cylinder is almost the same as the temperature of the water in the constant-temperature water bath or the room temperature in the constant-temperature room. During that time, stir the soil sample with a rod from time to time.

c) Place a cover on the measuring cylinder, turn the cylinder upside down and back to upright for approximately 1 min after the sample in the measuring cylinder is uniformly suspended, and let it stand. At that time do not lose any soil sample even if it is a small amount.

d) After letting the measuring cylinder stand, float the hydrometer in the cylinder, take the reading (r) of decimal part of the scale at the top of the meniscus to the nearest 0.0005, and at the same time the temperature T (°C) of the suspension at specific intervals of time. The intervals of time t (min) for taking the reading after letting the cylinder stand are 1 min, 2 min, 5 min, 15 min, 30 min, 60 min, 240 min, and 1440 min.

Remark 1: When reading at 1 min and 2 min after letting the cylinder stand, the hydrometer may be left in the measuring cylinder as it stands, but for readings thereafter, remove the hydrometer from the cylinder after taking the reading, and without fail wipe off stains adhering to the hydrometer.

Remark 2: If soil particles become massed together during measurement, do the sedimentation analysis again. In this case, increase the amount of dispersing agent or use another dispersing agent. If the amount of dispersing agent is increased, add the increased amount of the dispersing agent to distilled water until the total volume is 1 L, take readings of the hydrometer in this solution, and correct the measured values based on these readings.

9 Sieve analysis of the portion passing the sieve with an aperture width of 2 mm and the portion remaining on the sieve with an aperture width of 75 µm

9.1 Sample preparation

Take the total amount of the sample used for sedimentation analysis as the sample.

Remark: In the case where the sedimentation analysis is not carried out, take the oven-dried mass of approximately 90 g for sandy soil and 50 g for silty or clayey soil from the portion passing the sieve with an aperture width of 2 mm, add distilled water, stir to mix the soil-water mixture uniformly, add distilled water until the total volume is approximately 700 mL, and stir the mixture using the dispersion device for approximately 1 min.

9.2 Washing of soil sample with water

Wash the sample on the sieve with an aperture width of 75 µm with water, and after sufficiently washing away fine particles, dry the total amount of residue in an oven at (110±5) °C to a constant mass.

9.3 Sieving of soil sample

Soil sample shall be sieved as follows.

a) Sieve the oven-dried sample through sieves with an aperture width of 850 μm, 425 μm, 250 μm, 106 μm and 75 μm, in the same manner as 7.2 a).

b) Weigh the mass $m(d_i)$ (g) of the sample retained on each sieve.

10 Test results

10.1 Calculation of particle size based on sieve analysis results

The particle size based on sieve analysis results shall be calculated as follows.

a) From the results in Section 7, calculate the mass percentage passing of soil samples remaining on the sieves with an aperture width of 2 mm or more using the following equations.

$$P(d_i) = \left(1 - \frac{\Sigma m(d_i)}{m_s}\right) \times 100$$

$$m_s = \frac{m}{1 + \dfrac{w}{100}}$$

where

d_i: aperture width of a sieve (mm)
$P(d_i)$: mass percentage passing the sieve with an aperture width of d_i (%)
m_s: oven-dried mass of total sample (g)
m: mass of total sample (g)
w: water content of total sample (%)
$m(d_i)$: oven-dried mass of the sample that had remained on the sieve with an aperture width of d_i (g)
$\Sigma m(d_i)$: sum of the oven-dried mass of samples that had remained on the sieves with an aperture width of not less than d_i (g)

b) From the results in Section 9, calculate the mass percentage passing the sieve with an aperture width of 2 mm and those that had remained on the sieve with an aperture width of 75 μm using the following equations.

$$P(d_i) = \frac{m_s - m_{0s}}{m_s}\left\{1 - \frac{\Sigma m(d_i)}{m_{1s}}\right\} \times 100$$

$$m_{1s} = \frac{m_1}{1 + \dfrac{w_1}{100}}$$

where

m_{0s}: oven-dried mass of the sample that had remained on the sieve with an aperture width of 2 mm (g)
m_{1s}: oven-dried mass of the sample for sedimentation analysis (g)
m_1: mass of the sample for sedimentation analysis (g)
w_1: water content of the sample for sedimentation analysis (%)

10.2 Calculation of particle size based on sedimentation analysis results

From the results in Section 8, calculate the mass percentage passing the sieve with an aperture width of 75 μm as follows.

a) From the results in Section 8.1 (a), calculate the meniscus correction value using the following equation.

$C_m = r_L - r_U$

where

C_m: meniscus correction value
r_L: reading of decimal part of hydrometer at the bottom of the meniscus
r_U: reading of decimal part of hydrometer at the top of the meniscus

b) From the results in Section 8.1 b), c) and d), calculate the effective depth of hydrometer based on the reading r of decimal part of hydrometer using the following equation (See Fig. 4.)

$$L = L_1 + \frac{1}{2}\left(L_B - \frac{V_B}{A} \times 10\right)$$

$$L_1 = l_1 - 20(r + C_m)(l_1 - l_2)$$

where

L: effective depth of hydrometer bulb center (mm)
L_1: length from the top of hydrometer bulb to the reading r (mm)
l_1: length from the top of hydrometer bulb to the mark 1.000 (mm)
l_2: length from the top of hydrometer bulb to the mark 1.050 (mm)
r: reading of decimal part of hydrometer
L_B: overall length of the hydrometer bulb (mm)
V_B: volume of hydrometer bulb (cm^3)
A: cross-sectional area of measuring cylinder (cm^2)

c) Calculate the diameter of particle based on respective hydrometer readings using the following equation.

$$d = \sqrt{\frac{30\eta}{g_n(\rho_s - \rho_w)} \frac{L}{t}}$$

where

d: diameter of particle based on the reading r of decimal part of hydrometer (mm)
t: interval of time from the beginning of sedimentation to the taking of the reading (min)
η: coefficient of viscosity of water at the temperature T (°C) of the suspending medium when taking the reading of the hydrometer, listed in Table 2 (Pa•s)
ρ_s: density of soil particles determined according to JIS A 1202 (g/cm^3)
ρ_w: density of water at the temperature T (°C) of the suspending medium when taking the reading of the hydrometer, listed in Table 2 (g/cm^3)
g_n: acceleration of gravity (980 cm/s^2)

d) Calculate the mass percentage passing $P(d)$ (%) the sieve with an aperture width of 75 μm using the following equation.

$$P(d) = \frac{m_s - m_{0s}}{m_s} \bullet \frac{V}{m_{1s}} \bullet \frac{\rho_s}{\rho_s - \rho_w} \times (r + C_m + F)\rho_w \times 100$$

where

V: volume of suspension (= 1,000 cm^3)

F : the correction factor at the temperature of the suspension when taking the reading of hydrometer, listed in Table 3

10.3 Particle size accumulation curve

Particle size accumulation curve shall be determined as follows.

a) Take the aperture width d_1 (mm) and particle size d (mm) based on the hydrometer reading on a logarithmic scale as the abscissa and the mass percentage passing $[P(d_1)]$ and $P(d)$ to an arithmetic scale as the ordinate of a semi-logarithmic graph paper. Plot the relation between d_1 and $P(d_1)$ and d and $P(d)$, obtain the smooth curve representing the relation, and take it as the particle size accumulation curve.

b) From the particle size accumulation curve, read the particle size D (mm) when the mass percentages passing are 10 %, 30 %, 50 %, and 60 %, and take them as the particle size at 10 % passing by mass D_{10} (mm), the particle size at 30 % passing by mass D_{30} (mm), the particle size at 50 % passing by mass D_{50} (mm), and the particle size at 60 % passing by mass D_{60} (mm), respectively.

c) From the particle size accumulation curve, read the percentages passing at particle sizes 2 mm, 0.425 mm, and 0.075 mm.

d) From the particle size accumulation curve, read the mass percentages passing of the following samples.

1) Coarse gravel of 19 to 75 mm in the soil particle size range
2) Medium gravel of 4.75 to 19 mm in the soil particle size range
3) Fine gravel of 2 to 4.75 mm in the soil particle size range
4) Coarse sand of 0.850 to 2 mm in the soil particle size range
5) Medium sand of 0.250 to 0.850 mm in the soil particle size range
6) Fine sand of 0.075 to 0.250 mm in the soil particle size range
7) Silt of 0.005 to 0.075 mm in the soil particle size range
8) Clay of not more than 0.005 mm in the soil particle size range

10.4 Calculations of coefficient of uniformity and coefficient of curvature

The coefficient of uniformity and coefficient of curvature shall be calculated using the following equations.

$$U_C = \frac{D_{60}}{D_{10}}$$

$$U_C' = \frac{(D_{30})^2}{D_{10} \times D_{60}}$$

where

U_C : coefficient of uniformity
U_C' : coefficient of curvature
D_{10} : particle size at 10 % passing by mass
D_{30} : particle size at 30 % passing by mass
D_{60} : particle size at 60 % passing by mass

11 Reporting

The following test results shall be reported.

If rocky materials retained on a sieve with an aperture width of 75 mm are contained in the sample, it is recommended to report the mass percentage of the materials (%).

a) Maximum particle size of a soil sample (mm)

b) Dispersing agent used, the concentration of a solution (%), and the amount of a solution added (mL)

c) Particle size accumulation curve and the relation between particle size (mm) and mass percentage passing (%).

d) Particle size at 10 % passing by mass (mm), particle size at 30 % passing by mass (mm), particle size at 50% passing by mass (mm) and particle size at 60 % passing by mass (mm)

e) Mass percentages passing at particle sizes 2 mm, 0.425 mm and 0.075 mm (%)

f) Mass percentages passing of coarse gravel, medium gravel, fine gravel, coarse sand, medium sand, fine sand, silt and clay (%)

g) Coefficient of uniformity and coefficient of curvature

h) Details of any difference between the method specified in this standard and the method actually used

i) Other reportable matters

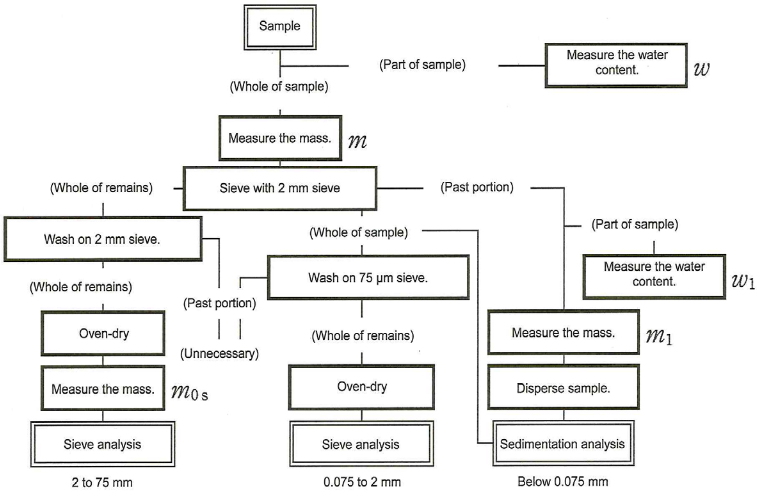


Fig. 1 Standard sequence of particle size analysis (for reference)

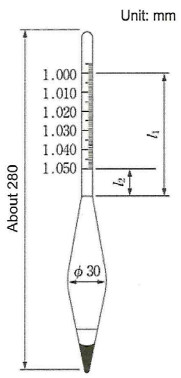


Fig. 2 Typical density hydrometer

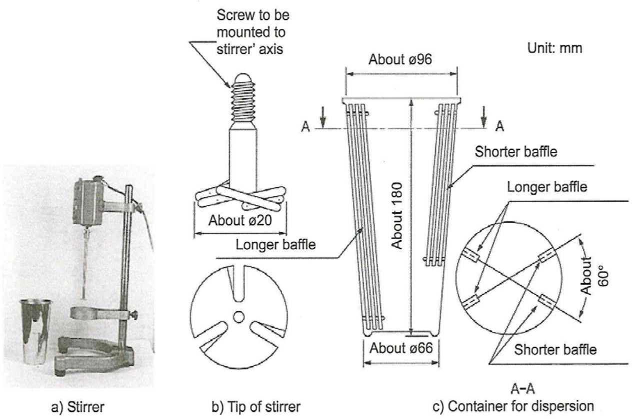


Fig. 3 Typical dispersion device

Table 1 Table 1 Guide for the minimum mass of a soil sample to be separately taken (for reference)

Maximum particle size of sample mm	Mass of sample
75	30 kg
37.5	6 kg
19	1.5 kg
4.75	400 g
2	200 g

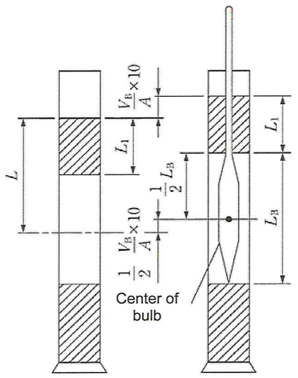


Fig. 4 Explanation drawing for the calculation of effective depth of hydrometer

Table 2 Coefficient of viscosity and density of water

Temperature (°C)	4	5	6	7	8	9
η $\times 10^{-3}$ Pa·s	1.568	1.519	1.473	1.428	1.386	1.346
ρ_w g/cm^3	1.000	1.000	1.000	1.000	1.000	1.000

Temperature (°C)	10	11	12	13	14	15
η $\times 10^{-3}$ Pa·s	1.307	1.270	1.235	1.201	1.169	1.138
ρ_w g/cm^3	1.000	1.000	1.000	0.999	0.999	0.999

Temperature (°C)	16	17	18	19	20	21
η $\times 10^{-3}$ Pa·s	1.109	1.080	1.053	1.027	1.002	0.977 9
ρ_w g/cm^3	0.999	0.999	0.999	0.998	0.998	0.998

Temperature (°C)	22	23	24	25	26	27
η $\times 10^{-3}$ Pa·s	0.954 7	0.932 4	0.910 9	0.890 2	0.870 3	0.851 0
ρ_w g/cm^3	0.998	0.998	0.997	0.997	0.997	0.997

Temperature (°C)	28	29	30	31	32	33
η $\times 10^{-3}$ Pa·s	0.832 5	0.814 6	0.797 3	0.780 6	0.764 4	0.748 8
ρ_w g/cm^3	0.996	0.996	0.996	0.995	0.995	0.995

Temperature (°C)	34	35	36	37	38	39
η $\times 10^{-3}$ Pa·s	0.733 7	0.719 1	0.705 0	0.691 3	0.678 0	0.665 1
ρ_w g/cm^3	0.994	0.994	0.994	0.993	0.993	0.993

Table 3 Correction factor *F*

T (°C)	4 to 12	13 to 16	17 to 19	20 to 22	23, 24	25, 26	27, 28
F	-0.000 5	0.000 0	0.000 5	0.001 0	0.001 5	0.002 0	0.002 5

T (°C)	29, 30	31, 32	33	34, 35	36, 37	38	39
F	0.003 0	0.003 5	0.004 0	0.004 5	0.005 0	0.005 5	0.006 0

Japanese Geotechnical Society Standard (JGS 0511-2009)
Method for unconfined compression test of soils

1 Scope

This standard specifies test methods to determine the unconfined compression strength of specimens that are self-standing without the presence of confining pressure. This standard applies mainly to undisturbed cohesive soils but can also be applied with modifications to self-standing specimens made from remolded samples, compacted soils, sandy soils, etc.

2 Normative references

The following standard shall constitute a part of this standard by virtue of being referenced herein. The latest version of this standard shall apply (including supplements).

JIS A 1203 Test method for water content of soils

3 Terms and definitions

The terms and definitions used in this standard are as follows:

3.1 Unconfined compression strength

The maximum compressive stress that the specimen can sustain under no confining pressure

4 Equipment

Test apparatus meeting the following criteria shall be used.

4.1 Unconfined compression test apparatus

The unconfined compression test apparatus shall consist of a strain-controlled compression device, pressure plates, a load cell, and a displacement gauge. The apparatus shall satisfy the following conditions (refer to Fig. 1).

a) The apparatus shall be capable of applying compressive strain to the specimen at a constant rate of movement until the strain reaches 15 % of specimen height. The working axes of the load cell, upper pressure plate, specimen, lower pressure plate, and compression device shall fall along a single line.

b) The apparatus shall be capable of measuring compressive force to an accuracy of ±1 % of the maximum compressive force applied to the specimen. The load cell shall be capable of indicating the load using a probing ring or by an electrical method. For this purpose, several load cells with different capacities between 0.2 kN and 2 kN shall be available for use according to the expected unconfined compression strength.

c) The apparatus shall be capable of measuring an amount of compression to an accuracy of ±0.1 % of the height of the specimen. The displacement gauge shall have a measurement range of 20 mm or greater and a minimum reading of 1/100 mm, or it shall be an electrical device of equal or greater performance.

4.2 Tools for specimen preparation

The tools used for specimen preparation shall be as follows (refer to Fig. 2).

a) Trimmer

b) Miter Box The miter box shall be divisible into two parts. The inner diameter shall be slightly larger than the diameter of the specimen, with the two end faces parallel and perpendicular to the axis.

c) Wire Saw and Straight edge The diameter of the steel wire used for the wire saw shall be about 0.2 mm to 0.3 mm. The straight edge shall be made of steel, single-edged, and 25 cm or longer.

4.3 Miscellaneous equipment

The following miscellaneous equipment shall be available.

a) Vernier caliper

b) Stopwatch or chronometer

c) Balance The balance shall have a sensitivity of 0.1 g.

d) Apparatus for obtaining water content The apparatus for obtaining water content shall be in accordance with JIS A 1203.

5 Specimen

5.1 Shape and dimensions of specimen

Each specimen shall be cylindrical in shape, typically with a diameter of 3.5 cm or 5.0 cm and a height 1.8 to 2.5 times the diameter. Exact specimen dimensions shall be determined according to the state of the sample material such that the test is representative of the sample.

Remark: Depending on the type of soil and the state of the sample, a sample extracted from a sampling tube may be used as a specimen by shaping the end faces and without altering the existing diameter.

5.2 Preparation of specimen

Each specimen shall be prepared according to the procedure outlined in a) to f) below. Preparation of the specimen shall be carried out quickly so as to avoid any change in the water content of the sample. Moreover, adequate care shall be exercised to avoid disturbance of the sample.

a) Any parts of the sample disturbed during the sampling process or other operations shall be removed, leaving material with a diameter and height large enough for a specimen to be prepared.

b) The side face of the specimen shall be shaped using a trimmer, wire saw, straight edge, or similar to give it a cylindrical shape with the specified diameter. If using a trimmer for shaping, care shall be exercised to avoid torsion or compressive forces on the sample. In preparing a specimen, a wire saw shall normally be used to cut the sample; however, if the sample is hard, a straight edge may be used.

c) The end faces of the specimen shall be shaped using a miter box, wire saw, straight edge, or similar so that the two end faces are parallel and perpendicular to the axis.

d) Determine the mean height, H_0 (cm), and the mean diameter, D_0 (cm), of the specimen. Use a vernier caliper or similar to measure the specimen at several places to an accuracy of 0.1 mm and then determine the mean value of each.

e) Measure the mass, m (g), of the specimen.

f) Extract a representative sample from the cut soil during the process of preparing the specimen. Obtain the water content and establish this as the water content of the specimen. If the water content of the specimen is to be obtained later by oven drying the specimen, this measurement of the cut soil may be omitted.

6 Test method

The test shall be performed using the following procedure. The test shall be started as promptly as possible after the specimen has been prepared.

a) Set up the specimen in the unconfined compression test apparatus. Place the specimen in the center of the lower pressure plate and bring the upper pressure plate into contact with the top while avoiding any compression on the specimen. Once the specimen is in place, adjust the origin of the displacement gauge and load cell.

b) Begin applying continuous compression to the specimen at a basic compressive strain rate of 1 % per minute.

c) Measure the amount of compression, ΔH (cm), and the compressive force, P (N), during compression. Measurements of compression and force shall be taken at intervals small enough to allow a smooth stress-strain curve to be drawn. Where measurements are not recorded continuously, it is recommended to measure compression at intervals of no more than 0.2 mm until compressive force reaches a maximum, and thereafter at maximum intervals of 0.5 mm.

d) Stop the compression either when the increase in strain exceeds 2 % after the point of maximum compressive force, or the compressive force reading has fallen to about 2/3 of its maximum value, or a compressive strain of 15 % has been reached.

e) Observe and record the deformed shape and failure mode of the specimen as well as other observations. Observations shall be made from the most characteristic direction of the specimen. Also, if a slip surface is found, it shall be observed from the orientation in which the steepest slope is determined. It shall be recorded such that the angle of steepest slope can be approximately read. Any heterogeneity in the specimen and the presence of foreign matter shall be observed and recorded.

7 Test results

The calculation shall be performed as follows.

a) The compressive strain of the specimen shall be calculated using the following equation.

$$\varepsilon = \frac{\Delta H}{H_0} \times 100$$

where

ε: compressive strain of specimen (%)
ΔH: amount of compression (cm)
H_0: height of specimen before compression (cm)

b) The compressive stress at compressive strain ε shall be calculated using the following equation.

$$\sigma = \frac{P}{A_0} \times \left[1 - \frac{\varepsilon}{100}\right] \times 10$$

$$A_0 = \frac{\pi D_0^{\ 2}}{4}$$

where

σ: compressive stress (kN/m^2)

P: compressive force acting on specimen at compressive strain ε (N)
A_0: cross-sectional area of specimen before compression (cm^2)
D_0: diameter of specimen before compression (cm)

c) Draw a stress-strain curve with compressive strain on the horizontal axis versus compressive stress on the vertical axis.

d) Using the stress-strain curve, obtain the maximum value of compressive stress before the point where the compressive strain reaches 15 %. Establish this value as the unconfined compression strength, q_u (kN/m^2), and establish the strain at this point as the strain at failure (%). If an inflection point such as shown in Fig. 3 occurs in the initial phase of the stress-strain curve, the straight section after the inflection point shall be extended and the point at which the extended line crosses the horizontal axis shall be established as the point of origin for correction of the strain calculation.

Remark: The method used to calculate the deformation modulus, E_{50} (MN/m^2), shall be as follows.

$$E_{50} = \frac{\frac{q_u}{2}}{\varepsilon_{50}} \times \frac{1}{10}$$

where

E_{50}: deformation modulus (MN/m^2)
q_u: unconfined compression strength (kN/ m^2)
ε_{50}: compressive strain (%) at compressive stress $\sigma = q_u/2$. If an inflection point such as shown in Fig. 3 is present in the initial phase of the stress-strain curve, make a correction in the same manner as in 7 d) above.

8 Reporting

The following results of the test shall be reported.

a) Diameter (cm), height (cm), mass (g), and water content (%) of the specimen

b) State of failure of the specimen

c) Stress-strain curve

d) Unconfined compression strength (kN/m^2) and strain at failure (%)

e) Other reportable matters.

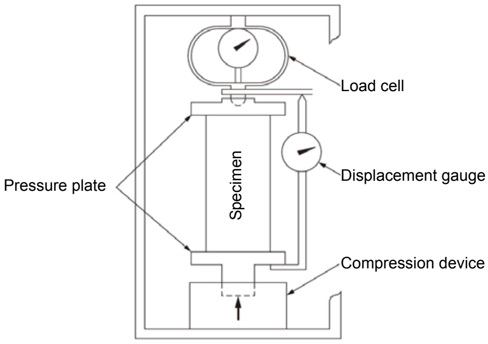
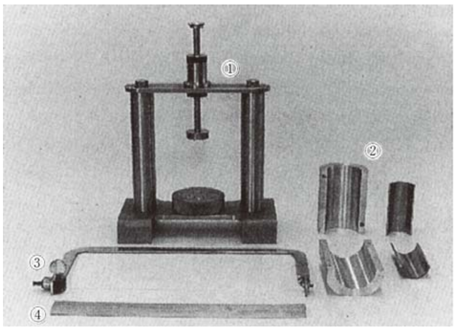


Fig. 1 Example of strain-controlled unconfined compression test apparatus



① Trimmer ③ Wire saw
② Miter box ④ Straight edge

Fig. 2 Example of tools for specimen preparation

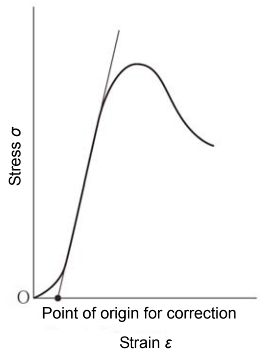


Fig. 3 Method for correction in the case of an inflection point occurring in the initial phase of the stress-strain curve

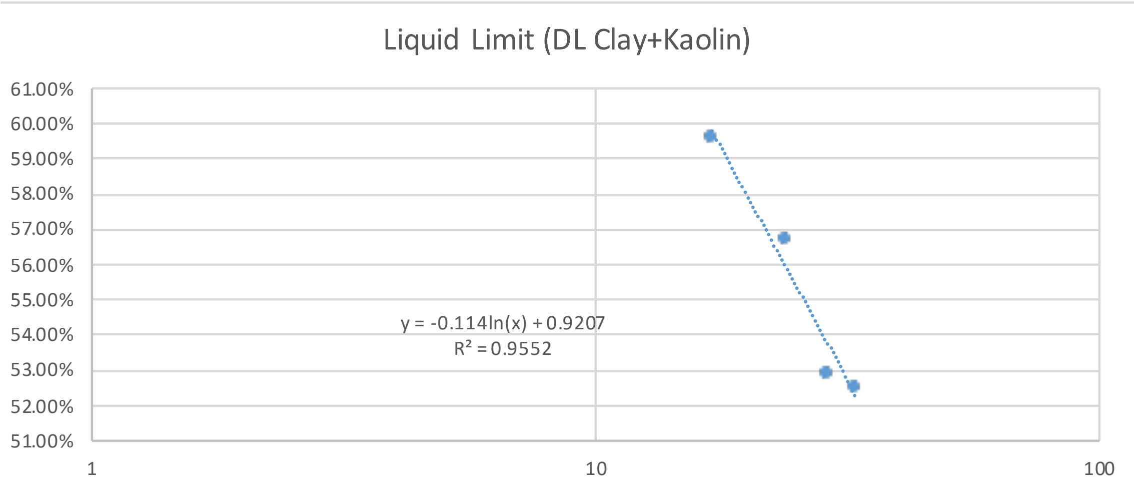
Appendix 7

Liquid Limit & Plastic Limit Data

Plasticity Index

Samples	N	Wa	Wb	W plate	w (%)
A	33				52.49%
C	29				52.85%
D	24				56.68%
F	17				59.56%
H		44.517	41.033	29.46	30.10%
E		44.502	41.111	29.49	29.18%

LL	55.37%
PL	29.64%
PI	25.73%



Appendix 8

Particle Size Distribution Data Test 01

Type of Experiment:	Particle Size Analysis	Legend	
Type of Soil:	Fly Ash		Input necessary
Date Conducted:	15-Mar-19		Calculations

Mass of Wet Sample + Pan:	
Mass of Pan:	
Mass of Wet Sample:	
Mass of Dry Sample + Pan:	239.8
Mass of Dry Sample:	1194.5

1.) Particle Size greater than 2mm — occupies: 0.80 of total

Sieve Size	Mass of Pan and Soil	Mass of Pan	Mass of Soil	Mass cumulative	% retained cumulative	% passing
mm	g	g	g	g		
19	0.00	0.00	0.00	0.00	0.00	100.00
9.5	0.00	0.00	0.00	0.00	0.00	100.00
4.75	0.00	0.00	0.00	0.00	0.00	100.00
2	239.80	230.20	9.60	9.60	0.80	99.20

D60=	227.17	µm
D50=	193.16	µm
D30=	125.14	µm
D10=	82.30	µm
curvature=	0.83755	
uniformity=	2.760174	

2.) Particle Size 0.075mm<x<2mm — occupies: 93.67 of total

Sieve Size	Mass of Pan and Soil	Mass of Pan	Mass of Soil	Mass cumulative	% retained cumulative	% passing	% passing incorporated to part 1
µm	g	g	g	g			
850	379.10	373.70	5.40	5.40	7.52	92.48	91.74
425	340.70	335.70	5.00	10.40	14.48	85.52	84.83
250	339.50	326.00	13.50	23.90	33.29	66.71	66.18
106	334.80	304.40	30.40	54.30	75.63	24.37	24.18
75	273.8	260.3	13.50	67.80	94.43	5.57	5.53
		Total:	67.80				
		Initial Mass:	71.8				

3.) Particle Size less than 0.075mm — occupies: 5.53 of total

initial temp:	23		
l1 (mm):	107	VB (ml):	25
l2 (mm):	27.0	d (cm) of cyl:	6.45
LB (mm):	137	AB (sq.cm):	32.67
Gs	2.65	m1: (g)	4

$$L = L_1 + \frac{1}{2}(L_B - 10\frac{V_B}{A})$$

$$L_1 = l_1 - 20(r + C_m)(l_1 - l_2)$$

$$M = \frac{V}{m1}\frac{\rho_s}{\rho_s - \rho_w}\rho_w x100$$

$$P(d) = \frac{m_s - m_{0s}}{m_s}(1 - \frac{\Sigma m(d)}{m_{1s}})x100$$

① Time min	② r	③ r+Cm	④ Temp °C	⑤ L (mm)	⑥ $\sqrt{\frac{30\eta}{g_n(\rho_s-\rho_w)}}$	⑦ ⑥* $\sqrt{\frac{L}{t}}$	⑧ F See standards p.34	⑨ M * (③+F)	⑩ P(d)
1	0.0325	0.0330	22.50	118.87	0.00418	0.0456	0.00125	1370.78	4.22
2	0.0315	0.0320	22.50	120.47	0.00418	0.0324	0.00125	1330.75	4.10
5	0.0300	0.0305	22.50	122.87	0.00418	0.0207	0.00125	1270.72	3.91
15	0.0245	0.0250	22.50	131.67	0.00418	0.0124	0.00125	1050.60	3.23
30	0.0210	0.0215	22.50	137.27	0.00418	0.0089	0.00125	910.52	2.80
60	0.0175	0.0180	22.50	142.87	0.00418	0.0065	0.00125	770.44	2.37
240	0.0110	0.0115	22.50	153.27	0.00418	0.0033	0.00125	510.29	1.57
1440	0.0070	0.0075	21.50	159.67	0.00423	0.0014	0.001	340.19	1.05

Appendix 9

Particle Size Distribution Data Test 02

Particle diameter (mm	Percent passing by weight (%
19	100.00
9.5	100.00
4.75	100.00
2	99.20
0.85	91.74
0.425	84.83
0.25	66.18
0.106	24.18
0.075	5.53
0.0325	4.220205472
0.0315	4.096987794
0.0300	3.912161277
0.0245	3.234464048
0.0210	2.803202175
0.0175	2.371940302
0.0110	1.571025395
0.0070	1.047350263

Appendix 10

UCS Test Data

Curing Time= 1 day

Sample 01

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.46
Strain at Failure		0.61

Sample 02

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.48
Strain at Failure		0.61

Sample 03

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.46
Strain at Failure		0.54

Curing Time= 3 Days

Sample 01

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.33
Strain at Failure		0.45

Sample 02

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.53
Strain at Failure		0.42

Sample 03

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.49
Strain at Failure		0.84

Curing Time= 1 Week

Sample 01

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.57
Strain at Failure		0.44

Sample 02

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.65
Strain at Failure		0.47

Sample 03

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	9	
Unconfined Compression Strength		0.66
Strain at Failure		0.65

Curing Time= 2 Weeks

Sample 01

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.64
Strain at Failure		0.84

Sample 02

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.74
Strain at Failure		0.71

Sample 03

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.52
Strain at Failure		0.19

Curing Time= 28 Days

Sample 01

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.73
Strain at Failure		0.69

Sample 02

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.75
Strain at Failure		0.47

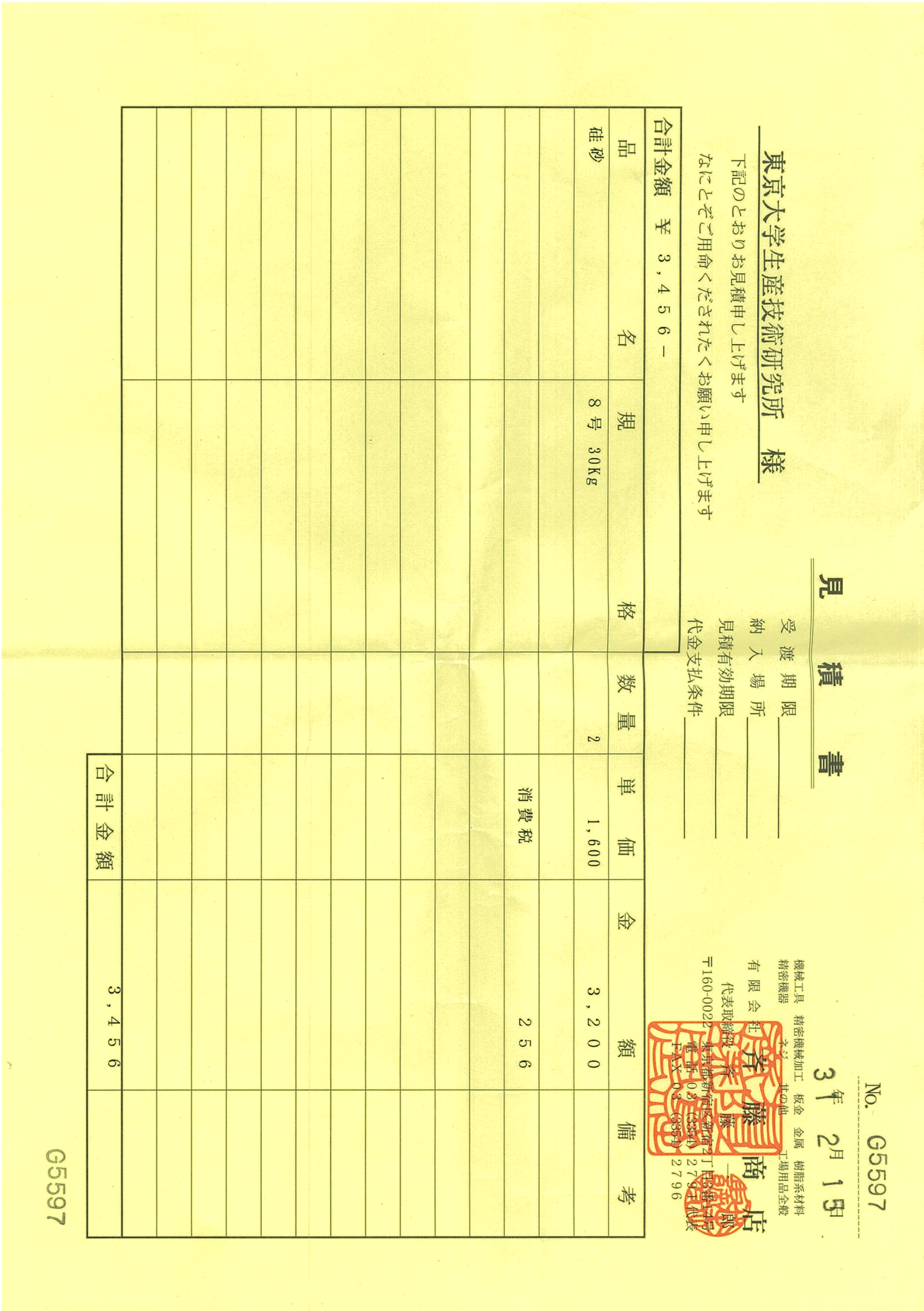
Sample 03

A0(cm2)	19.64286	
D0(cm)	5	
H0(cm)	10	
Unconfined Compression Strength		0.62
Strain at Failure		0.84

Appendix 11

Silica #8 & DL- Clay Purchase Receipt

Both were labeled as Silica #8



見積書

No. G5597

3年 2月 15日

東京大学生産技術研究所 様

下記のとおりお見積申し上げます

なにとぞご用命くだされたくお願い申し上げます

受渡期限

納入場所

見積有効期限

代金支払条件

合計金額 ￥3,456－

品名	規格	数量	単価	金額	備考
硅砂	8号 30kg	2	1,600	3,200	
			消費税	256	
			合計金額	3,456	

機械工具 精密機械加工 板金 金属 樹脂系材料

精密機器 その他 工場用品全般

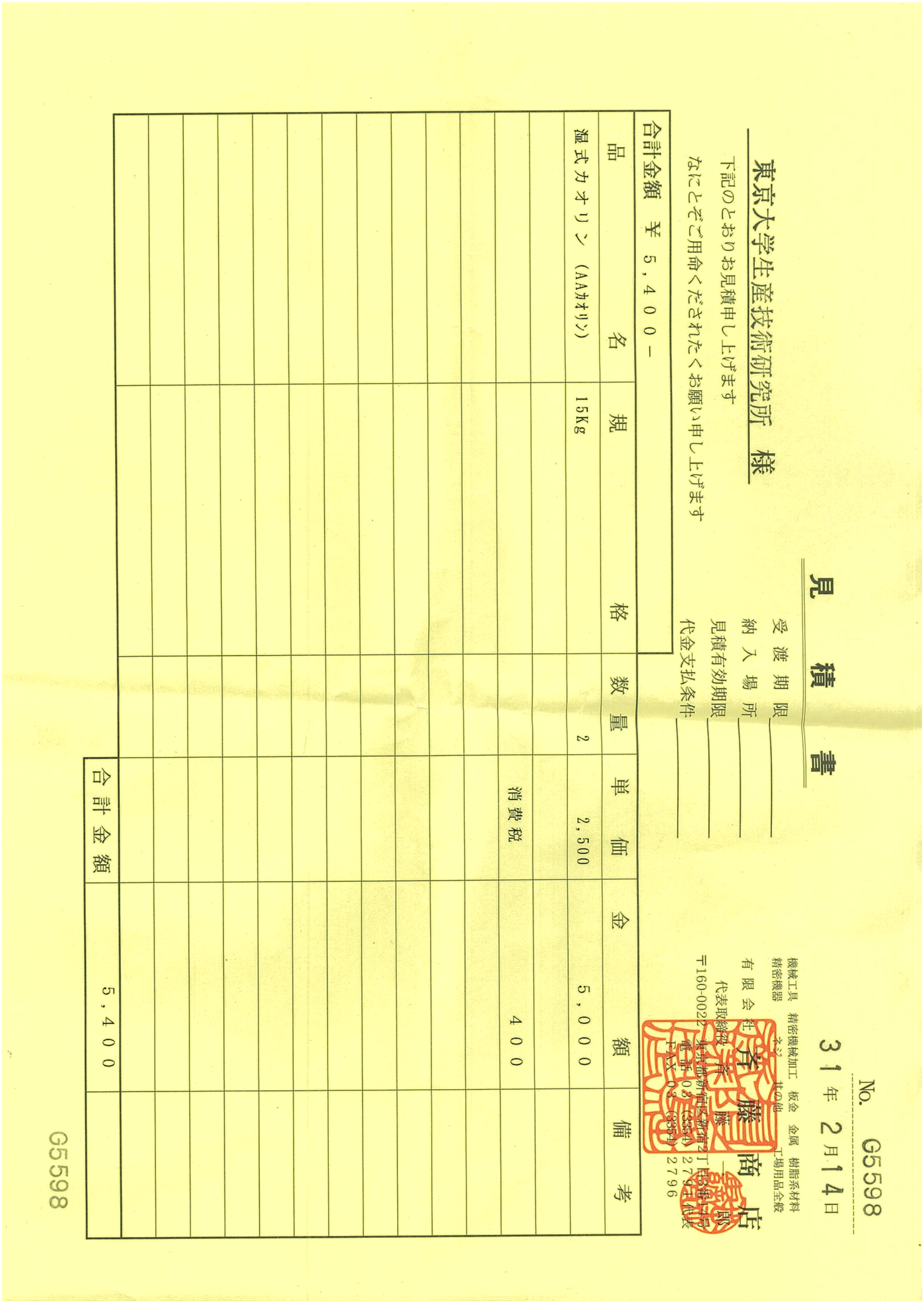
有限会社 斉藤商店

〒160-0022

G5597

Appendix 12

A-A Kaolin Purchase Receipt



見積書

No. G5598

31年2月14日

東京大学生産技術研究所 様

下記のとおりお見積申し上げます

なにとぞご用命くだされたくお願い申し上げます

受渡期限

納入場所

見積有効期限

代金支払条件

合計金額 ¥ 5,400－

機械工具 精密機械加工 板金 金属 樹脂系材料

精密機器 ネジ その他 工場用品全般

有限会社 斉藤商店

〒160-002

FAX 03 2796

品名	規格	数量	単価	金額	備考
湿式カオリン（AAカオリン）	15Kg	2	2,500	5,000	
			消費税	400	
			合計金額	5,400	

G5598