

STUDY OF STABILIZED MUD BLOCK AS AN ALTERNATIVE BUILDING MATERIAL AND DEVELOPMENT OF MODELS

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ABBREVIATIONS

2C = 2% cement

2CS3 = 2% cement and 3% straw fiber

2CS6 = 2% cement and 6 % straw fiber

5C = 5% cement

3D= three dimension

ASTM = American Society for Testing and Materials

C=Cement

CEB = Compressed Earth Block

E = earth or soil

Fig. = figure

ILO = International Labour Organization

M_D = dry mass

MOBMM = manually operated block making machines

MOSM=manually operated sieve machines

M_W = wet mass

PI=plasticity index

S=Straw fiber

S_p =percentage of shrinkage

TWA=Total Water Absorption

V_b = Volume of the specimen

V_m = Volume of the mold

ABSTRACT

Soil or earth as a building material is available in most areas of the world. In developing countries, earth construction is economically the most efficient means for house construction with the least demand of resources. But, traditional earth construction techniques such as Wattle and Daub (in Ethiopia “Chika bet”) and Cob suffer from water attack or erosion by rain and shrinkage cracks. Therefore, they need to be continuously maintained in order to keep them in good condition.

This thesis studies the effect of the proportion between the soil and the stabilizers (such as cement and straw fiber) on stabilized earth blocks durability. It also compares mechanical properties (compressive strength and shrinkage) of stabilized earth blocks which are prepared using only local soils (which is taken from Yeka sub city Addis Ababa area) and with the addition of stabilizers (cement and straw fiber).

This research provides detailed technical information on suitable earth construction such as stabilized earth blocks production. These include information on suitable soil types for stabilized earth house construction, stabilizers and production of stabilized earth blocks. Related literatures review show that soil types, proportions between soil and stabilizer amount and compaction pressure applied to the moist soil mix affects the quality of the stabilized earth block.

Since soil in Yeka area of Addis Ababa is not much exposed to waste products (pollution), this soil was found to be the most suitable site for the test. Laboratory tests were conducted on Yeka area soil and provided detailed information on the soil grading (grain size). The result was compared with standard values to verify suitability of the soil for soil stabilized earth block production. It is possible to determine the suitability of other area soils by applying the same technique.

Using soil (from Yeka area of Addis Ababa) and stabilizers (cement and straw fiber), six different types of samples were prepared. Tests were conducted on these samples in order to evaluate their performance such as compressive strength and total water absorption on which the durability of the blocks depend. The effect of the cement and the straw fiber content in stabilized mixture was evaluated and comparisons were made. For all block samples, their shrinkage value (after drying process) was calculated in percents and compared with recommended values.

The investigation has revealed that, out of all block samples, blocks which are produced from 5% cement (5C), 2% cement with 3% straw fiber (2C3S) and 2% cement with 6% straw fiber (2C6S) have compressive strength, dry shrinkage and total water absorption values above the recommended minimum values for structural work.

Finally, a possible model for manually operating earth block making machine and sieving machine were modeled and designed using Solid works 2007. These machines could be used in production of uniform and durable stabilized earth blocks.

CHAPTER ONE

1. INTRODUCTION

1.1 Background

A hundred years ago, there were a lot of forests, which were our main material resources for building constructions [16]. However, nowadays, our forests are almost gone, and woods for constructions are rare. This is because of rapidly increasing population and their dwelling demand. Currently, the majority of developing countries are faced with a problem of providing adequate and affordable housing in sufficient numbers. In the last few decades, shelter conditions have been worsening: resources have remained scarce, housing demand has risen and the urgency to provide immediate practical solutions has become more sensitive. Adequate shelter is one of the most important basic human needs. However, 25% of the world's population does not have any fixed home, and 50% of the urban population lives in slums. Indeed, 80% of urban settlements in developing countries consist of slums and spontaneous settlements made of temporary materials [4].

In Ethiopia, adequate shelter is a main problem in most part of the country. And, soil is widely used in the traditional construction of mud houses called “Chika bet”. Unfortunately, the traditional building techniques which are practiced in most part of Ethiopia for mud house construction have serious defects. The main defects or problems are: walls can easily be eroded by rain and suffer from extended shrinkage cracks, the construction consumes natural resource such as woods, its external and internal appearance is not much attractive, the dwellers suffer from health related problems, and the mud walls require a regular repairs (wastage of material and energy regularly).

Investigation of mud house construction techniques such as Adobe, Straw bale housing, Rammed Earth and Compressed earthen construction has led to improvements in understanding of material behavior and construction practices. This will be discussed in Chapter 3. Some of these construction techniques are very well suited to application in developing countries for several reasons. First, they are all based on earthen materials which do not require significant industrial processing. They allow houses to be built with much less damage on global energy (system) and resource. Second, they all rely on materials which are locally available in a large majority of regions around the world, and minimizing energy use for transportation (during importing and

exporting).Third, they are generally intermediate-technology solutions. They do not require sophisticated machinery or specialized expertise to construct, and can be constructed quickly when compared to conventional housing techniques. These factors not only make alternative construction technologies attractive for developing countries in general, but also make them particularly well suited to solve economical, social and environmental related problems. In general, this section outlines the motivation and objectives for the research work, and explain the importance of this research.

1.2 Objectives of the thesis

General objective

In Ethiopia, like other developing countries in the third world, shelter problem is a big issue. According to the Ethiopian Urban Sector Study, Ethiopian urban population is currently estimated to be 11 Million; 80% of these live in substandard housing units and environmentally unfit living conditions in slum neighborhoods [4]. Entirely, these houses are made from mud or earth by traditional techniques. These traditional building techniques which are common in Ethiopia for mud house construction have many problems. Therefore, this thesis works to solves or minimizes these problems by introducing a stabilized earth block production technique.

Specific objectives

The specific objectives of this thesis are:

- To investigate local soils to identify their suitability in stabilized earth block production.
- To investigate present theoretical and practical methods by which soil and stabilizers are selected.
- To study experimentally the effect of altering important variables such as: cement content and straw fiber content on the properties and performance of stabilized earth blocks.
- To create awareness in the community about stabilized earth block production technique as a tool for adequate and affordable house construction.
- To recommend possible model of manually operating block making machine and sieve machine use in earth block production process.

- To meet the economic requirements of the local situation by: reducing dependence on outside sources and ensuring low cost alternatives.
- To minimize the environmental degradation by using renewable or recycle materials in building construction such as stabilized soil blocks.

1.3 Methodology

This work begins with explanation of the importance of the research (identify the problem) and objectives of the research work, followed by literature review. For the development of concepts, these are fundamental for the formulation of the whole research work. Both primary data (collected personally) from the source itself (such as experiments, observations, and photograph records) and secondary data from different research work are collected and used for the analysis. The analysis of the collected data is both qualitative and quantitative. In general the whole methodologies of this work are:

Literature review: provide detail information on different types of mud house construction techniques and materials which are required for suitable mud house construction. It also includes identifying materials which are necessary for this work.

Laboratory testing and analyzing results:

- Preparation of stabilized earth block samples from soil and stabilizer (cement and straw fiber) with their different volume ratio.
- Carry out tests on these different types of stabilized earth block samples.
- Make analysis on their results using standards or recommended values and some results analyzed using some software like MATHLAB.
- Comparison of the results with previous works.

Modeling parts using Solid work: model and design of manually operating earth block making machine and sieve machine using Solid work software.

1.4 Structure of the thesis

This thesis is divided in to 7 chapters and each chapter contains a number of sections and further subsections, and the organization of the chapters is presented as follows.

Chapter 1 provides an introduction to the whole thesis. It discusses the background to the research and the context in which the work is based. This Chapter also summarizes the general and specific objectives of the research, and lists the methodologies that have been used for the research. Chapter 1 ends by providing guidelines on the organization and structure of the thesis as a whole including the ordering of chapters, references and appendices.

Chapter 2 provides introduction on house construction; and mud house construction in past time and at present time. It also explains about traditional mud house construction in Ethiopia and the environmental impact of the traditional mud house construction.

Chapter 3 describes the historical background of earth buildings and explains the types of mud house construction techniques. It also explains in detail about materials which are required in stabilized earth block production.

Chapter 4 describes experimental set up and tests Procedure for grain size analysis, total water absorption and compressive strength tests. Chapter 4 presents the six categories of stabilized earth block types (E, 2C, 5C, 3S 2CS3 and 2CS6) which are prepared for the tests. And, it discussed production steps for stabilized earth blocks.

Chapter 5 presents grain size analysis result for the soil sample which is taken from Yeka area. It also presents the experimental results and analysis which include: compressive strength, total water absorption test, and shrinkage values for each stabilized earth block sample. Finally, empirical relation between compressive strength and young's modulus is formulated for samples and comparison is made with previous works.

Chapter 6 presents possible modeling and design for manually operated earth block making machine and sieve machine using Solid work software.

Chapter 7 is the final chapter of the thesis, integrating and summarizing the main conclusions and recommendations. At the end of the thesis, references and appendixes are presented.

CHAPTER TWO

2. LITERATURE REVIEW ON MUD HOUSE CONSTRUCTION

2.1 Introduction

Currently, the construction industry accounts for a large portion of total global consumption of material and energy. This consumption has been estimated to be 50% of global material use, and 40% of global energy use [8]. Growth in this consumption is tied directly to global economic growth. Additionally, the current state of the world economy growth is in developing nations, especially in Asia and Africa. Economic growth provides the means to develop and implement cleaner, more efficient technologies. Unfortunately, economic growth in these developing countries is often begin at the expense of the environment, until a point is reached where the accumulated wealth of a nation makes the implementation of more environmentally caring technologies feasible. Since many of the countries driving global economic growth have not yet reached this point, it is clear that there is significant expense of nature for improvement of industrial practices in these countries.

Currently, there are extremely wide variety of alternative construction materials and techniques which are used around the world. Soil is one of the natural building materials, which is absolutely different from wood, rock, cement or metal. Mud can be formed for our shelters and it can be reformed or recycling ease back to nature, to be simple soil on earth. Moreover, mud can match with all environments and good for being a passive air-conditioning system. Reusability of mud creates tremendous reduction in environmental impact, energy use and capital expenditure. Mud house from earth or soil is one of the most widely used traditional building materials throughout the world. Currently, one-third of world population stills live in mud house. It can be found mostly in hot-dry and arid area such as some parts of India, Nepal, China, African continent and even in the West Side of North and South American continent [4].

2.2 Mud house construction in history

Earth has been used in the construction of ancient houses for thousand years together with others natural materials such as wood and stone. The constructional technologies (techniques) used for the earth houses construction vary with the geographical zone and with the historical period. The technology called “torchis” is based on the use of branches of shrub to build the frame of the

habitation and the mud is used to fill the cavity between the branches [21]. In another technology, called “pisè”, the earth wall is made by compacting the earth (mud) into wood formworks. A typical technology, called “amaltoni”, is used in the past century in the rural areas of the Marche region (Italy) and it is characterized by the use of cylindrical elements of earth blocks. The constructive system called “adobe” is based on the use of mud bricks to make earth buildings and it has been utilized in the Mediterranean area since the ancient era [24].

The origins of the compressed earth block technique can be traced back thousands of years to the molded sun-dried earth brick, better known by the name of "adobe". This sun-dried earth brick marks historical stages in the evolution of the human race. The oldest one can still be seen in Egypt, near Luxor, which was built around 1300 BC: the tombs of Ramasseum (fig.2.1). It was built with adobes, the sun dried mud bricks [27].



Fig.2.1 The Great Sphinx and tombs of Ramasseum [29]

2.3 Mud house construction at present

Currently, around 30% of the world’s populations live in earth-made construction. Approximately 50% of the population in developing countries, including the majority of the rural population and at least 20% of the urban and suburban population, live in earthen houses [25]. Generally; low-income urban and rural populations mainly use this type of house.

The use of adobe is very common in some of the world's most hazard regions, such as Latin America, Africa, the Indian subcontinent and other parts of Asia, the Middle East, and southern Europe. The recent progression towards the compressed earth block is a logical extension of the benefits of the industrial revolution which brought the significant development of the fired brick. The need to improve the quality of materials and the durability of buildings is linked to better productivity. In most part of the tropics, traditional mud housing is found in rural areas. This traditionally housing is designed by the owner in his spare time together with the assistance of relations, friends and neighbors using local materials. In addition, traditional house reflects cultural heritage of the dwellers.

2.4 Traditional mud house construction in Ethiopia

In Ethiopia, based on climatic conditions and altitude, traditional house construction in Ethiopia are divided into houses of Low Lands-“Kolla” (<1400m); houses of Highlands- “Woina Dega” (1400-2700m) and houses of Highlands “Dega” (2700 above sea level) [4]. In Ethiopia, soil is used extensively in the traditional mud house construction (“Chika bet”) in the “Kolla”, “Woina Dega” and “Dega” area, especially in the central, northeast, northwest and in the southern eastern rift valley area of the country. “Chika” is a mixture of Clay, fine and short straw of the Ethiopian common cereal, “Teff ” (*Eragroetis Abyssinica*) and water [4]. The mixture, after it has thoroughly been mixed by treading with the human feet, is either immediately used, or is left to ferment for some time before it is used as a filling material of the opening between wood poles and finally as plaster.

Unfortunately, the traditional building techniques adopted for mud walls in Ethiopia have serious defects as shown in fig. 2.3. The mud walls suffer from extended shrinkage cracks, which weaken the walls. Mud walls can easily be eroded by rain. Sometimes, the mud walls have been covered with protective coating consisting of animal dung. This was intended to serve as a wearing surface. The protective surface needed continued maintenance and sometimes renewal almost every year. These entire drawbacks lead most of the people to the misconception that buildings with soil are of inferior quality and should be avoided [4].

There is a big gap between the income of the majority of the population and the cost of the buildings. In 1986, the Building College of Addis Ababa made a survey among dwellers in

Ambo, a medium-sized town in the Ethiopian highlands. The aim of the investigation was to identify the problems confronting the housing sector.

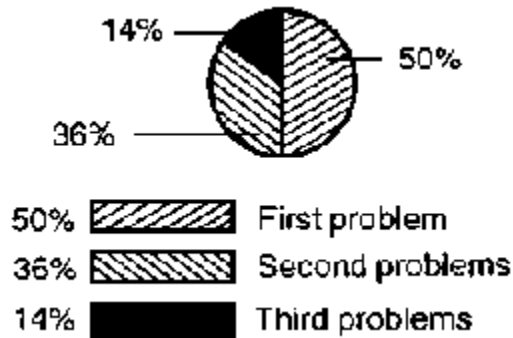


Fig.2.2 Chart of problems in housing sector [18]

As it is shown in fig.2.2, 50 % of the interviewed people classified the housing problem as the most crucial one and 36% of the people classified the house problem as a second problem [18].



Fig .2.3 Traditional mud house building in Ethiopia

Additionally, the traditional building method requires a lot of woods for the construction of walls. Especially, this is common in forestry areas. However, this accelerates deforestation

(fig.2.4). Deforestation is a major issue in Ethiopia, since it is one of the main causes of widespread land degradation. Tree cutting or deforestation is a common event which has been taking place for centuries. A long time back in history, some parts of Northern Ethiopia, which are today suffering from conditions caused by land degradation, were covered with forests. In present day Ethiopia, however, forests are being destroyed at a shocking rate and the area covered by forests at present is only 2.4 % compared to the estimated 40 % initial coverage [1]. The primary causes of forest destruction are increasing of the demand for construction material, agricultural expansion, fuel wood and charcoal.



Fig.2.4 Deforestation in a jungle burned for agriculture in southern Mexico [29]

Reducing and monitoring deforestation is a vital issue at this time. There are different methods which are appropriate and reliable for monitoring deforestation. One of these methods is minimizing consumption of materials that have direct contact with forests. This includes materials which are used in building construction. In order to tackle the problem, a concept of low-cost building construction, based on mud as the main building material, was developed.

So, one of this thesis aims is to replacing wooden mud houses by only mud blocks, which would help to restore the ecological balance and to build a house with good quality and with fair price.

The concept of reducing the cost and the environmental effect of construction material has been performed by using locally available building materials such as soil, stones, straw and water. Stabilized earth block technology is not commonly practices in Ethiopia. So, this opens ways for small-scale entrepreneurs since it does not require high investments and skills. This paper

minimizes directly or indirectly the country house problems with economical and environmentally friendship ways by introducing technology. This work can also used for developing countries or for low-income groups.

CHAPTER THREE

3. INVESTIGATION ON MUD HOUSE CONSTRUCTION

3.1 Historical background of earth buildings

From the roof of the World in Tibet or in the Andes Mountains in Peru, to the shores of the Nile in Egypt or in the fertile valleys of China, many are examples of countries those used earth as a building material in ancient time. India also shows very old earthen buildings, like the Shey Palace in Ladakh, which was built with adobe in the 17th century. And, the Tabo monastery in Spiti Vally, Himachal Pradesh was built with rammed earth in 996 AD.

Raw earth for building has been used worldwide for millennia; however, during the 20th century, most of the skills of earth builders were lost and building with earth became marginal. The new development with earth construction started in the nineteen fifties, with the technology of compressed stabilized earth blocks: by a Colombian research program for affordable houses. This has led to a renaissance of the tradition of earthen architecture and construction a revival, which is benefiting from the results of scientific research [4]. The compressed earth block is the modern descendent of the molded earth block, more commonly known as the adobe block. The idea of compacting earth is to improve the quality and performance of molded earth blocks.

3.2 Types of mud house construction techniques

For 10,000 Years, earth has been used as a building material. There are eighteen principal well-known methods using earth as a building material as shown in the fig. 3.1 [4]. Amongst these, the eight are widely employed and their detail information is presented below.

Adobe

Adobe or mud brick building technique is an ancient technique dating back at least to 8300 BC (in Jericho). The oldest continually inhabited structures in the world are adobe. Some built in North America around 900 years ago are still in use [16]. Adobe blocks are similar to compressed earth blocks (CEB) and sometimes tagged as the precursor of CEBs. Adobe blocks are usually made of a compacted mixture of clay and straw, however are less uniform in size and shape than CEB's. Adobe blocks are the simplest and easiest form of earth building. Most of

shrinkages take place in the block itself before the walls are built (during drying), so shrinkage cracking is much less of a problem.

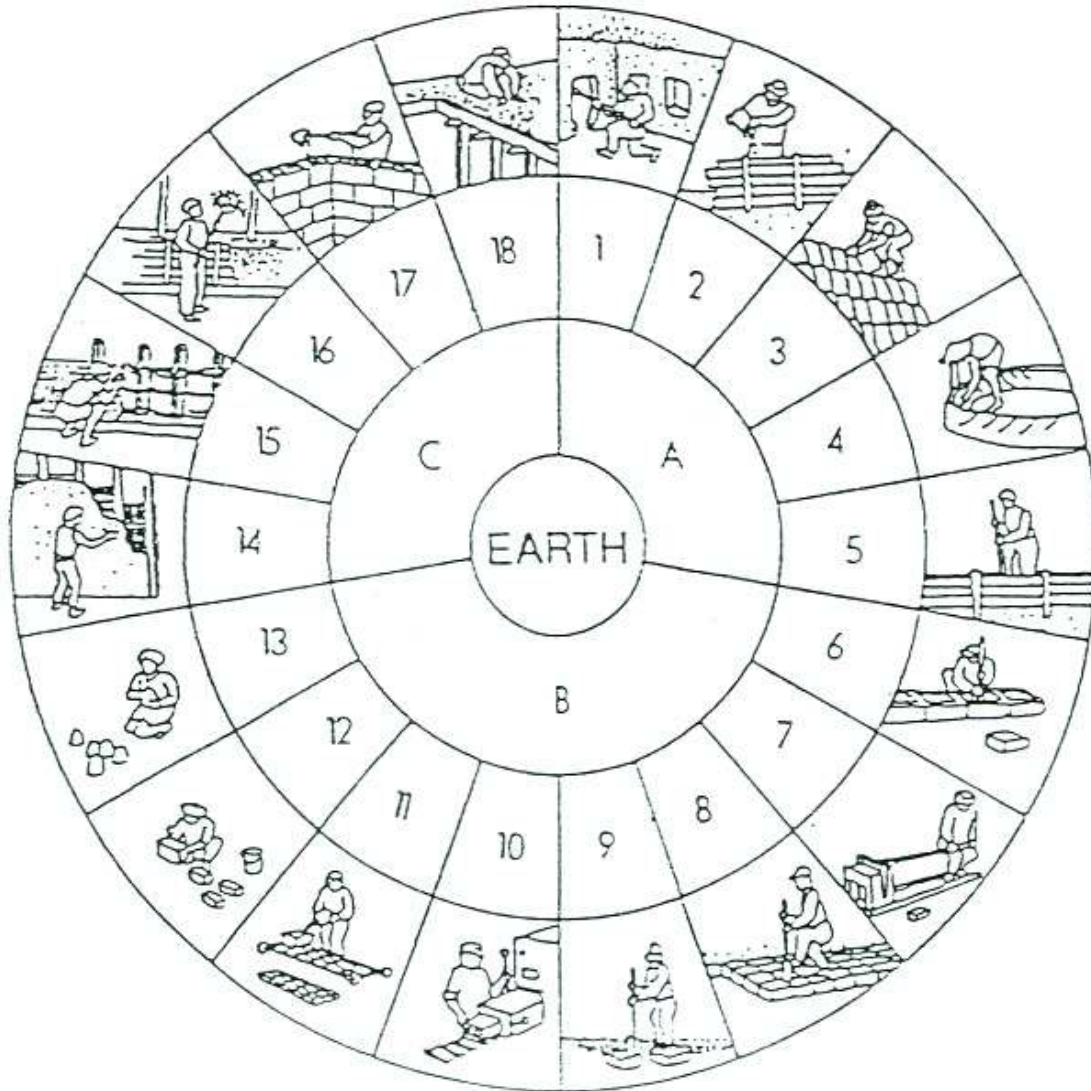


Fig.3.1 Use of earth as building material [4]

Adobe blocks can also be made by mixing soil with straw fiber and water and letting them dry in the sun (fig.3.2). Soils which are suitable for adobe production should have clay between 15 and 30% [16]. Adobe buildings have thick walls and have good thermal mass. Thermal mass is the ability of a material to absorb heat. On the other hand, Thermal inertia is the rate at which heat

moves through the material. Materials with high thermal mass also exhibit slow rates of thermal inertia. However, adobe has poor insulation. This means that un-insulated adobe buildings tend to hover around the average daily temperature. Also, adobe houses degrade more quickly when exposed to severe wet weather. In general, adobe brick is a sun-dried brick .it can be a mixture of soil, water and local fiber materials or straw fibers.



Fig.3.2 Bonding sun-dried adobe brick with clay mortar [16]

Cob

This is another old method of mud house construction technique. Some of the oldest man-made structures in Afghanistan are composed of cob and rammed. Cob work was used in the Maghreb and al-Andalus in the 11th and 12th centuries and was described in detail by Ibn Khaldun in the 14th century [16]. Cob is similar to adobe; however, cob has higher percentage of straw and has no production of uniform blocks. One advantage over adobe is the ability to better incorporate curves and allowing more sculptural forms (i.e. artworks created by shaping or combining the material) as shown in fig.3.3. The addition of more straw makes the building a bit more insulated than adobe, however not sufficiently to make it comfortable in extreme climates.

Cob homes are cheap to build and the technique is not much complex for builders. To construction cob, straw and small gravel are mixed into a sandy soil. The mixture is formed into lumps or cobs, then it is thrown on to the wall and stamp or work into the previous layer. The

rough surface is later trimmed up, and it is usually rendered to give a smooth surface. In addition, extra thickness or curved walls can easily be built, and it is also ease to taper inwards or outwards the top of the wall. In this construction technique, the wall is very sensitive to shrinkage cracking during drying. So, this technique requires careful analysis of materials and design. However, many successful cob buildings have now been built and the use of other fibers such as wood and cellulose, or aggregates such as pumice (highly micro vesicular glass pyroclastic with very thin, translucent bubble walls of extrusive igneous rock) provides less dense, durable and better insulating walls than traditional cob mixes.



Fig.3.3 Cob house [19]

Wattle and Daub

This technique has been used since at least the Bronze Age. It was not only common for houses of the Linearbandkeramic and Rössen cultures of Central Europe, but it is also found in Western Asia (Çatalhöyük, Shillourokambos) as well as in North America (Mississippian Culture) and South America (Brazil). Its usage dates back at least 6000 years.



Fig.3.4 Mud covering on bamboo wattle wall [29]

Wattle and daub is the term for the panels of woven wood and mud used to fill between the timbers. Brick noggin might also have been used to fill in between the timbers (the openings in a wooden frame). The construction for wattle and daub starts with a lattice-work of light branches or timber. An earth (mud) mix is then daubed or cover onto the lattice-work, forced into the gaps, and finished to give a serviceable surface. The earth is generally not load-bearing; the load bearing is the timber. This is a very practical form of construction. The roof can go on before the walls; however it has some engineering defects related with shrinkage and with achieving earthquake-resistant connections between the earth panels and the timber structure. Since in this technique timber is the main basic material for the construction, this construction technique accelerates deforestation. So, this technique is not suitable since it has environmental impact on our globe. In general, wattle and daub construction is made by woven work of sticks intertwined with twigs (a small thin terminal branch of a woody plant) or sometimes bamboo framework covered with mud (fig.3.4).

Cordwood

The exact origin of cordwood construction technique is unknown. Remains of cordwood structures still standing in northern Greece and Siberia, and they date back as far as one thousand years. More current versions of cordwood houses are found in some part of Europe, Asia, and the Americas. In this technique, short, equal and round pieces of wood are stacked and joined together with mortar as shown in fig.3.5. Cordwood walls can be load-bearing or laid within beam framework which provides structural reinforcement and is suitable for earthquake areas. The compressive strength of wood and mortar allows the roof to be tied directly into the wall. Cordwood homes have both thermal mass (the mortar) and insulation (the wood) properties. Like straw bale, a post and beam support structure is sometimes required with the cordwood. In this technique, wood usually accounts for about 40 - 60% of the wall system, the remaining portion consisting of a mortar mix and insulating fill. Therefore, this technique also accelerates deforestation (i.e. environmental unfriendly).



Fig.3.5 Mud plastering over stones and twigs wall [9]

Rammed Earth

This is an ancient technique used in the construction of the Great Wall of China. Rammed-earth buildings are found on every continent, except Antarctica. The availability of useful soil and appropriate local climatic conditions are the factors for rammed earth construction. It is similar to adobe and cob. The soil for this technique is mostly a composition of clay and sand. Rammed-

earth walls are simple to construct, non-combustible, thermally massive, strong, and durable. However, they are susceptible to water damage if they are inadequately protected or maintained. Modern rammed earth techniques use heavy machinery to compress the soil. Walls tend to be at least a foot thick for stability and also thermal mass. Insulation is often applied on the outside. The compressive strength of rammed earth can be up to 4.3 MPa. This is less than that of concrete, but more than strong enough for use in domestic buildings [6].



Fig. 3.6 Compacting of mud in the wall-mould rammed earth [9]

Rammed earth construction is a labor-intensive technique for making earthen walls without using machinery (powered tampers). In this technique, the primary material is soil that can be dug up at the building site. Formwork for the walls are prepared using metal plate or wooden plate, then filling the formwork with a mix of sand, gravel and clay or sometime cement. The mixture is then compressed with a pneumatic tamper or a hand tamper (as shown in Fig.3.6) to create a dense, stone-like structure that can last for centuries and even millennia. In general, rammed earth construction is made by laid a moist earth (soil) between formwork and mould and compacted by hand or machinery.

Earthen Bag

Earth bag building utilizes the ancient technique of rammed earth in conjunction with woven bags and tubes as a flexible form. It is a natural building technique that is evolved from historic military construction techniques and temporary flood-control building methods. Unlike other earth techniques, a wide range of soil types can be used to build house with earth bag. Used bags from plaster, grains, or cement packaging which are available around the world, can be used as bag. Since the bags or tubes are light, they can be transported easily for building in remote areas. Earth bag construction is an inexpensive method to create structures which are both strong and can be quickly built. The basic construction procedure is simple. The bags or tubes are filled on the wall using a suitable pre-moistened earth or moist soil (fig.3.7). After a row has been placed, it is thoroughly compacted with hand tampers.

Earth bags don't deplete scarce local resources, like wood or brick buildings do. Bags and wire form a very small percentage of an earth bag wall. Most of the material used is local, natural subsoil. Thus earth bag buildings have a very low carbon footprint and environmental effect. This technique often associated with flood protection, and some disasters to create stable and safe home structures. These walls are stable in harsh weather and sandbag homes are quick and easy to construct. Outside surfaces can be plastered for further protection.



Fig.3.7 House made of earthen bags [20]

Straw-bale

Straw, grass, and reeds have been used as building materials for centuries. Straw houses have been built on the African plains since the Paleolithic. Straw bales were used in construction 400 years ago in Germany; and straw-thatched roofs have long been used in northern Europe, Africa and Asia. Straw bale houses were developed in America and are rising in popularity.



Fig.3.8 Mud plastering over Straw-bundle wall [29]

Straw-bale construction is a building method that uses bales of straw (commonly wheat, rice, rye and oats straw) as structural elements, building insulation, or both (fig.3.8). In this technique, mud has been plastered or coated over straw-bundle wall. This construction method is commonly used in natural building or "green" construction projects. Straw bale houses have enormously good insulation values, and they can be built with relative ease and speed. They may be load-bearing, but more often they incorporate a post-and-beam frame. The bales are finished with a coat of plaster – often earth (mud). The design issues are similar to earth buildings, but the need to avoid moisture and weathering is even more crucial. The bales must be dry before installation and remain dry throughout their life, as once wet they are more likely to compost than dry out.

Advantages of straw-bale construction over conventional building systems include the renewable nature of straw, low cost, easy availability, and high insulation value. Disadvantages include susceptibility to rot, very sensitive for firing, and high space requirements for the straw itself.

Compressed Earth block

The compressed earth blocks became widely used around the world in the last 30 years or more, not only in third world countries, but also in developed countries like the USA, France, Canada and Australia. In the past, the earth was compressed into block form in the mould by means of a small pestle, or by tamping a very heavy lid forcefully on the mould. Nowadays, a wide variety of presses is used. The production technique of CEBs differs from rammed earth in that the latter uses a larger formwork into which earth is poured and tamped down, creating larger forms such as a whole wall or more at one time. Materials which are used in CEB production are similar with rammed earth. CEB blocks are installed onto the wall by hand and mortar made of a soupy version of the same dirt/clay mix, is spread or brushed very thinly between the blocks for bonding. The advantages of CEB are:

- Reduction of deforestation
- Uniformity of the blocks
- Decreasing both the labor and materials costs
- Non-toxic: materials are completely natural and not harmful for our environment
- Sound resistant: for residential areas adjacent to industrial zones
- Fire resistant: earthen walls do not burn
- Insect resistant: the walls are solid and very dense, discouraging insects.



Fig.3.9 Typical compressed earth block [4]

Out of the 8 techniques, Wattle and Daub technique is well known in our country, Ethiopia. In Ethiopia, this technique has been practiced for long time in the traditional construction way of mud house construction called “Chika bet”. However, mud walls that are constructed using this traditional building technique have many defects. The main defects are: the

- Can easily be eroded by rain
- Walls suffer from extended shrinkage cracks
- Consume natural resource like woods (accelerate deforestation)
- External and internal appearance not much attractive
- The dwellers suffer from health problems due to dust
- Requires a regular repair.

Due to these all drawbacks, this technique is not suitable for adequate mud house construction. However, Adobe and Compressed Earth construction techniques have many advantages over this and other techniques. Some of their common advantages are:

- Has good compressive strength mild-stone
- Durable
- Environmental friendly (zero deforestation)
- Can be used as load bearing structure

This paper works to solve the problems of traditional mud house construction technique in Ethiopia (widely in rural houses) by taking adobe and compressed earth blocks construction techniques as reference (focus on the integration of both techniques).

3.3 Materials required for stabilized soil block production

This portion covers about the materials required for production of stabilized earth blocks. It also includes classification, specifications, availability and properties of materials which are necessary for stabilized earth blocks production (such as soil, cement and straw fiber).

3.3.1 Soil

Soil is a sediments or accumulation of mineral particles produced by the physical or chemical disintegration of rock, plus the air, water, organic matter, and other substances that may be

included in the soil. In addition, soil is a non-homogeneous, porous, earthen material whose engineering behavior is influenced by changes in moisture content and density [4].

Classification of soil

Soils are classified in many different ways: by their use, origin, grain size, texture, color and density. Based on the origin of soil can be divided to two basic types [14]:

a. Residual soils: are caused by the weathering (decomposition) of rock by chemical or physical action. Residual soils may be very thick in areas of intense weathering such as the tropics, or they may be thin or absent in areas of rapid erosion such as steep slopes. Residual soils are usually clayey, and their properties are related to the climate and the location of the soil. Residual soils are usually preferred to support foundations, and they have better, more predictable engineering properties.

b. Transported or deposited soils: are derived by the movement of soil from one location to the other by natural means. The means are generally wind, water, ice, and gravity. The character of the resulting deposit often reflects the modes of transportation and deposition and the source material. Deposits by water include floodplains, coastal plains, and beaches. Deposits by wind include sand dunes and loess. Deposits by melting ice include glacial till and outwash. Each of these materials has behavioral characteristics dependent on geological origin, and the geological name, such as loess, conveys much useful information. Transported soils, particularly by wind or water, are often of poor quality in terms of engineering properties. In addition, topsoil or agricultural soil, which contains a high proportion of organic matter, forms a layer above the bed-rock and which may be more or less weathered. When the upper layers of earth are made up of loose material and contain little organic matter, they can be used for building purpose.

For building purpose soil can be generally characterized in two ways: by a particle size distribution analysis and by plasticity index. The particle size analysis will give information on the soil ability to pack into a dense structure and the quantity of fines present (combined silt and clay fraction), while the plasticity index gives an idea of cohesion of the fines. Cohesion is the molecular bonding or attraction between soil particles. It is a function of clay mineralogy,

moisture content, particle orientation (soil structure), and density. Cohesion is associated with fine grain materials such as clays and some silt.

A. Classification by particle size distribution

Soils are made up of varying proportions of materials such as gravels, sands, fine (silts and clays). Each of these have different characteristic, for example, when they are exposed to variations in humidity, some will change in volume, while others will not. The first two of these materials are stable, the other two are unstable. Stability is the ability of the material to withstand alternating of humidity and dryness without its properties changing. This is a fundamental importance property for a building material.

a) Gravels: are made up of pieces of rock of varying hardness, and their size ranges between approximately 2 and 20 mm. They form a stable constituent of the soil. Their mechanical properties undergo no detectable change in the presence of water.

b) Sands: are made up of mineral particles, and their size ranges between approximately 0.06 and 2 mm. They also form stable constituents of the soil. They lack cohesion when dry, but have a very high degree of internal friction between the particles which make them up. When moistened, however, they display apparent cohesion as a result of the surface tension of the water occupying the voids between the particles. Sand is used as a releasing agent during the molding of a block. It prevents the wet mud from sticking to the sides of the mould. It is also sometimes used as a stabilizer and mixed with very clayey soils to prevent the blocks from cracking when drying.

c) Silts: are made up of particles the size of which range between approximately 0.002 and 0.06 mm. They have little cohesion when dry. Since their resistance to movement is generally lower than that of sands. However, they display cohesion when wet. When they are exposed to different levels of humidity, they swell and shrink, changing clearly in volume. Gravels, sands, and to a lesser extent silts, are characterized by their stability in the presence of water. However, when they dry, they have little cohesion. Therefore, they cannot be used on their own as the principle materials of a building.

d) Clays: form the finest fraction of soils 0.002mm, and have completely different characteristics than those of the other particle types. They consist mainly of microscopic clay mineral particles, including kaolinites, illites and montmorillonites. Clay particles are coated in a film of absorbed

water. Since, they are so small in size; they are very light in weight compared with the surface tension forces occurring in the film of absorbed water. Thus volume forces (the particles weight) are low relative to surface forces. The film of absorbed water which sticks strongly to the clay-layers, links the micro-particles of the soil together, and it is this which gives clay its cohesion and most of its mechanical strength. This can be eliminated only by very advanced desiccation. Desiccation is the state of extreme dryness, or the process of extreme drying. The desiccation process may result cracks for earth block that have large amount of clay in the soil (fig.3.10).



Fig.3.10 Cracks in clay soil resulting from desiccation [29]

A more useful range of particle sizes suitable for building with earth block is from 40 - 75% sand and from 25 - 60% fine (silt and clay) [11]. Gravel is not usually used in soil- cement mixture production, as the large particle size may lead to a poor (rough) surface finish. A suitable soil for building construction contains a mixture of sand and fine (silt and clay) particles. The properties of each of these fractions influence the properties of the stabilized earth block.

From the recommendation, there is no need of gravel particles in soil which is used for stabilized earth block productions. Therefore, the sieve that is used for filtering or screening the soil should have a diameter the same as the minimum diameter of the grave particle size (i.e. 2mm). The 3D solid work modeling for manual operated sieving machine will be discussed in chapter 6.

B. Classification by plasticity (Fine content)

Soil plasticity is the ability of a soil to undergo irreversible deformation when it is subjected to an increasing load. It is indicated by the plasticity index. The plasticity index is the amount of

water required for a soil to pass from a plastic to a liquid state. In addition, soil is a mixture of irregularly shaped mineral particles of various sizes containing voids between particles. These voids may contain water if the soil is saturated, water and air if partly saturated, and air if dry. Under unusual conditions, such as sanitary landfills, gases other than air may be in the voids. The particles are a by-product of mechanical and chemical weathering of rock and described as gravels, sands, silts, and clays. Based on plasticity (fine content), soil classified as cohesive and cohesionless soils.

(a) Cohesive soil. Cohesive soils are fine-grained materials consisting of silts, clays, and/or organic material. These soils exhibit from low to high strength when the air is dried in the voids. Most cohesive soils are relatively impermeable compared with cohesionless soils. Some silt soil may have bonding agents between particles such as soluble salts or clay aggregates.

(b) Cohesionless Soil. Cohesionless soil is composed of granular or coarse-grained materials with visually detectable particle sizes and with little cohesion or adhesion between particles. These soils have little or no strength when they dry and little or no cohesion when they submerged. Strength occurs from internal friction when the material is confined. Apparent adhesion between particles in cohesionless soil may occur from capillary tension in the pore water. Cohesionless soils are relatively free-draining compared with cohesive soils. The silt and clay content of a soil are responsible for soil cohesion and these fines provide fresh blocks with load bearing ability.

The degree of cohesion provided to the earth block production is dependent on both the fines present and the degree of compaction used to form the block. In addition, a low-pressure molding process requires higher fines content than a high pressure molding process. This is because increased compaction pressure will force the soil particles into more closed contact, thus strengthening the fresh (the first added particles) compact. And, by their nature fine particles can easily be compacted with low pressure since they are smaller in size.

Exploitation

Usable layers of soil (fig.3.11) are rarely found at the surface of the ground (except in dry areas), because at the surface soils contain too much organic matter. This organic top soil is rarely used for stabilized soil blocks and it is mostly found in the first 0.50 m depth of the soil layers. In

addition, usable soil is rarely found at great depths, where there are too many stones, or even solid rock. Therefore, the depth or height of usable layers of soil varies greatly, from a few centimeters to several meters ranges.



Fig.3.11 Picture for layers of soil [29]

3.3.2 Cement

Cement is a fine grey powder which is mainly composed of Lime (CaO) and Silica (SiO_2). When water is added, it forms combinations of Tri-calcium silicate and Di-calcium silicate referred to as C3S and C2S in the cement literature [9]. The chemical reaction eventually generates a matrix of interlocking crystals that cover any inert filler (i.e. aggregates) and provide a high compressive strength and stability. Depending on their hardening property cements are divided into two types: hydraulic and non-hydraulic. Hydraulic cements (Portland cement) harden due to the chemical reaction of added water and cement which is called hydration, while the non-hydraulic cements harden without the need of water.

Earlier studies have shown that cement is a suitable stabilizer with soil in the production of compressed stabilized soil block. Portland cement is the most commonly used stabilizer and cheapest. The minimum amount of cement required to stabilize a block depends on the type of soil, the degree of compaction force and the final application of the blocks [4]. Generally cement can be used with any soil type, but with clays it is uneconomical because more cement is

required. The range of cement content needed for good stabilization is between 3% and 18% by weight according to soil type [6].

3.3.3 Straw

Straw is one of the finest and the renewable building material which is available around the world in abundance. It is the strong stalk of tall grain plants such as wheat, rye, hemp or rice that remains in the field after the seed grains have been harvested. Its chemical composition is primarily cellulose, just like trees. When the straw is bundled together into a bale, it becomes a solid block. That is highly resistant to decomposition in its dry form. The straw is used mainly for reinforcing wooden walls of mud house buildings and for livestock feed. It can also be used as stabilizer in stabilized earth block production. Straw is sometimes added to mud to prevent the brick from cracking when curing. In addition, straw is added to decrease drying shrinkage and prevent cracking in earth block constructions.

3.3.4 Water

The amount of water add in to mixture must be known in stabilized earth block production. The quality and quantity of the water plays a significant role in compressed earth block production. Impurities in water may interfere with the setting of the mixture, may adversely affect the strength of the block or cause staining of its surface, and may also lead to corrosion or decomposition of the reinforcement. For these reasons, the suitability of water for mixing and curing purposes should be considered.

Combining water with a soil material forms soil paste by the process of hydration. The soil paste joins the aggregate together, fills the voids or gaps between soil particles and allows it to flow more freely. Less water in the soil paste will yield a stronger and more durable earth block, whereas more water will give a free-flowing block with a higher slump [4]. Some very experienced people can judge the correct amount of water without measuring, but this is not recommended for first time producers. Because adding more water to the mixer make easier to work, however the blocks will have a poorer quality. The excess water can also cause the block to crack due to shrinkage and break during drying. Adding the correct amount of water during

earth block preparation is critical for making good quality blocks. The less water used, the better the quality. If the amount of water is too much in the mixture, the block will:

- Deform easily under its own weight after molding;
- Deform when placed on uneven or bumpy ground;
- Results shrinkage crack during drying;
- Take much more time to dry.

CHAPTER FOUR

4. EXPERIMENTAL SET UP AND TEST PROCEDURE

4.1 Total water absorption test of earth blocks

The aim of the water absorption test is to determine the percentage moisture absorption capacity of the block samples. Knowledge of the water absorption levels of blocks could serve as useful criteria for setting limits and for investigating possible ways of reducing the defects in order to improve the durability of stabilized earth blocks. Total water absorption test was carried out to determine the water absorption values of blocks and to compare their value with standard values.

Test Equipment

Equipments required for total water absorption test are:

- Drying oven (Fig.4.1)
- Tank with bottom grid to ensure free circulation of water
- Electronic weighing scale
- Thermometer



Fig.4.1 Drying oven

Test procedure

The test procedures (steps) for total water absorption test are:

- Dry the specimens from each category of blocks in the oven at temperatures between 110°C and 115°C.
- When cool, weigh each specimen by electronic weighing scale.
- Immerse the specimens in a single layer tank after weighing so that water can circulate freely on all sides and bottom of the sample. Leave a space of about 10 mm between adjacent samples in the tank.
- Remove the specimens after 24 hours, wipe off the surface water while shaking lightly with a damp cloth and reweight each specimen.
- Calculate the total water absorbed (TWA) for each sample which is expressed as a percentage of the dry mass using equation 4.1.

$$TWA = \frac{M_W - M_D}{M_D} \times 100\% \dots\dots\dots 4.1$$

Where: TWA = total water absorption (%)

M_w = wet mass (g)

M_D = dry mass (g)

4.2 Grain size analysis test for the soil

Early attempts to classify soils were based primarily on grain size. The grain shows texture of mechanical and chemical origin, in which mechanical texture is predominant on most of the grains. It was observed that the grains were mostly sub angular to sub rounded in shape with variable size ranges. A number of other soil classification systems are in use throughout the world, and the American Society for Testing and Materials standards D1140-54 and D422-63 [5] is the most common ones. It presents a standard for testing for grain-size distribution. The interpretation of the grain-size distribution is typically carried out manually. The principal objective of any soil classification system is predicting the engineering properties and behavior of a soil based on a few simple laboratory or field tests. Laboratory and/or field test results are then used to identify the soil and put it into a group that has soils with similar engineering

characteristics. The distribution of different grain sizes affects the engineering properties of soil. Grain size analysis provides the grain size distribution, and type of soil grade suitable for stabilized earth block production.

Test Equipment

Equipments required for total water absorption test are:

- Electronics weighting scale (balance)
- Set of sieves (fig.4.2)
- Cleaning brush and
- Sieve shaker



Fig.4.2 Electronics balance and set of sieves [22]

Purpose: This test is performed to determine the percentage of different grain sizes contained within a soil. The mechanical or sieve analysis is performed to determine the distribution of the fine and coarser or larger-sized particles.

Standard Reference: ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils

Test Procedure

This test consists of filtering the soil through a series of standard mesh sieves placed one above the other in decreasing order (i.e. the finest mesh at the bottom) and in determining the proportion of soil particles left in each sieve. The test final result gives a complete and quantitative proportion of the different grain sizes within the soil mass. The procedure for the test is given below:

1. Write down the weight of each sieve as well as the bottom pan to be used in the analysis.
2. Record the weight of the given dry soil sample.
3. Make sure that all the sieves are clean, and assemble them in the ascending order of sieve numbers (number 4 sieve at top and number 200 sieve at bottom). Place the pan below number 200 sieve. Carefully pour the soil sample into the top sieve and place the cap over it.
4. Place the sieve stack in the mechanical shaker and shake for 10 minutes.
5. Remove the stack from the shaker and carefully record the weight of each sieve with its retained soil. In addition, remember to weigh and record the weight of the bottom pan with its retained fine soil.

4.3 Compressive strength tests of stabilized earth blocks

The compressive strength of stabilized earth blocks (i.e. the amount of pressure they can resist without collapsing) depends upon the soil type, and the type and amount of stabilizer used to form the block. Maximum strengths are obtained by proper mixing of suitable materials and proper soil type. The compressive strength of a block is one of its most important engineering properties. It was established from the literature that the durability of stabilized earth blocks increases with increase in its strength. Knowledge of the compressive strength value of a block can be used in a number of ways. This includes:

- To check the uniformity of block quality;
- To compare a given block sample with a specified requirement;
- To evaluate the blocks performance and durability;
- To classify a block in terms of its resistance to abrasive conditions.

The tensile strength of a block is about 90% lower than its compressive strength [3] and the blocks carry a vertical load. For this reason, the block sample subjected to compression force only in the test.

Equipment list for compressive strength test are:

- Scale
- Compression test machine (fig. 4.3)



Fig 4.3 Compression test machine

Production process of samples

The composition of sample is prepared based on volume ratio of each material as given below.

1. 2% cements + 98% soils (2C)
2. 3% straw fiber + 97% soils (3S)
3. 5% cements + 95 % soils (5C)
4. 2% cements + 3% straw fiber + 95% soils (2C3S)
5. 2% cements + 6% straw fiber + 92% soils (2C6S)
6. Only earth (E)

The stabilized earth block production steps

1. Sieving

From literature, a suitable soil for stabilized earth blocks construction contains a mixture of sand and fines (silt and clay) particles. There is no need of gravel in soil for earth block production, so the sieve that is used for filtering or screening the soil should have holes' diameter the same as the minimum diameter of the gravel particles size (i.e. 2mm). Therefore, the dry soil is screened using this sieving machine.

2. Mixing

The materials which are used to manufacture the stabilized earth block are earth (soil), cement, straw fiber and water. These materials are mixed together with specified proportion or ratio. The type of soil which was used for this work (test) was taken from Yeka area of Addis Ababa. The cement which was used in stabilized earth block sample preparation is Portland cement. The straw fiber which was used in this work has been cut into a fiber of average length equal to 4cm (in a range between 2cm and 6cm). These natural fibers have 1 to 2 mm in diameter and a hollow structure. Finally, tap water which is supplied by Addis Ababa water and sewerage authority was used in all prepared samples at room temperature. All of these materials are shown in fig.4.4.

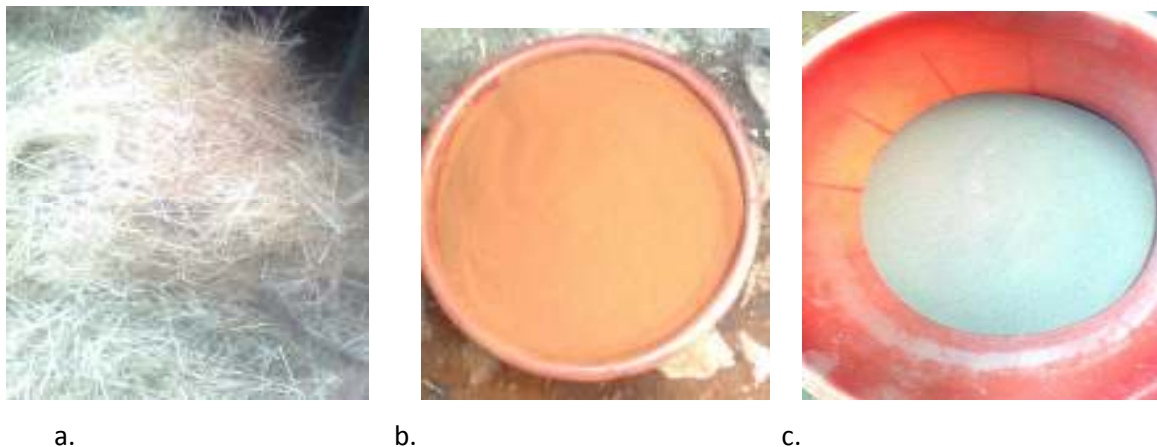


Fig 4.4 The materials for the stabilized earth block production a, Straw fiber b, Soil c, Cement

And, never try to make a mixture more workable by just adding more water because this lowers the strength and durability of the mixture. Finally, this prepared mixture can also use as a mortar

to connect the blocks each other during construction. Since the mixture has some amount of cement, it creates good joining property, as glue, between earth blocks.

3. Molding

There are 6 wood formworks of block pattern with a dimension of 14cm×21cm×9cm. which are shown in fig.4.5.



Fig. 4.5 Wood brick pattern picture

Each mixture which was compacted manually by hands into wood formworks of internal dimensions (14 × 21 × 9) cm; the 6 samples were molded manually by hand and 2 for each type of sample were prepared. Used motor oil was used as lubricant during molding. This is because; the oil prevents sticking of the wet mud with the wooden pattern during casting.

4. Drying process

In the Laboratory, after molding, the samples can be dry using oven from 110⁰C -115⁰C for 24 hours. But when the sample dries using oven with high temperature, some crack may be occur. This is because of rapid drying process. In rapid drying process, evaporation rate is high. This causes the moisture in the inner part of the mud blocks to escape with force. This force pushes the outer surface apart to remove the moisture, which results cracking. From literature, drying should be take place with slow process with medium temperature (average 25⁰C) for 3 to 4 weeks, with uniform temperature distribution and in shielded area.



Fig .4.6 Stabilized earth blocks pictures

In general, the stabilized earth block production steps are:

Sieving (dry soil using sieving machine) → Mixing (soil, stabilizer (cement and straw fiber) and water) → Molding (using compressed block machine or manually by hand) → Drying (using sun in shielded area for 3 to 4 weeks)

Compressive strength tests procedure

Compressive strength tests of blocks were carried out on the 6 different types of composition samples and 2 samples (fig.4.6) for each type of composition (total 12 blocks). The pictures of stabilized earth blocks and compressive strength test are shown in appendix D. And, the main procedures for compressive strength test are:

- Put the samples on compression test machine and apply a vertical load on sample by lowering the two plates of the machine.
- Record the applied vertical force and the resulting displacements at the breaking point, which is identified with the appearance of vertical cracks near the corners of blocks and in the middle of vertical surfaces. This method is for samples that have straw fibers in the mixture. This is because; they have larger elastic value and are not brittle. Whereas samples, that have only cement and soil, have brittle character. Therefore, for those samples the maximum load record when the peak light gives signal in compression test machine.

CHAPTER FIVE

5. RESULTS AND DISCUSSION

Total water absorption, shrinkage and compressive strength tests were carried out on the stabilized earth blocks to make comparison of their results with standard recommended values and to examine their performance and durability.

5.1 Grain size analysis test and result for soil

This test was carried out to identify the type of soil whether it is suitable for stabilized earth block production or not. A particle size analysis test helps to determine the fraction of a soil's particles in a given soil sample. To produce a dense and durable block, it is important that the soil used should be “well graded” [14]. The value of a well-graded soil for soil-cement block is that such a distribution of sizes gives a dense structure with a low specific surface area. A dense structure is important for several reasons. A densely packed arrangement will have a higher number of contacting particles, and giving a better load-bearing capacity. And, the number and size of the inter-particle voids will be reduced, these will reduce the porosity of the soil and hence also its permeability, thereby reducing susceptibility to water penetration.

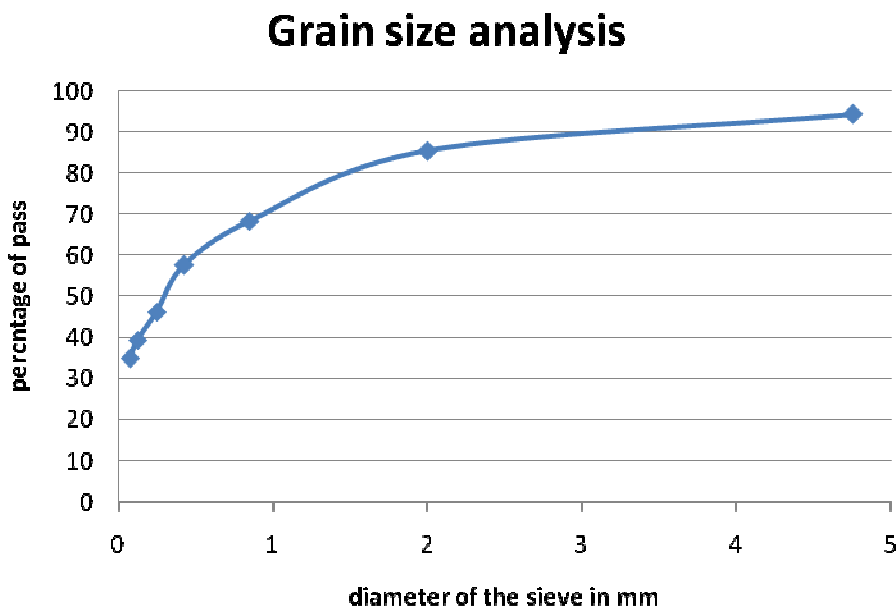


Fig.5.1 Percentge of passed of the soil sample in sieves

In this test, the weight of the given dry soil sample is 500g which was taken from Yeka area (Yeka sub city, Addis Ababa) and the grain size analysis value is shown in table 5.1 and the graph in fig.5.1.

Table 5.1 Grain size analysis results of the soil from Yeka area

Sieve Number	Diameter of the sieves (mm)	Mass of Empty Sieve	Mass of Sieve and Soil Retained (g)	Soil Retained (g)	Percent Retained	Percent Passed
4	4.75	429.0	457.5	28.5	5.7	94.3
10	2	399.5	444.0	44.5	8.9	85.4
20	0.85	511.0	596.5	85.5	17.1	68.3
40	0.425	291.5	345	53.5	10.7	57.6
60	0.25	461.0	518.0	57.0	11.4	46.2
140	0.125	447.0	481.0	34.0	6.8	39.4
200	0.075	272.0	295.0	23.0	4.6	34.8
Pan	0	254.0	428.0	174.0	34.8	0.0

From the above Grain Size experimental result, there is 5.7 % gravel, 59.5 % sand and 34.8% fine (silt + clay) in the soil. And, from UN recommendation range of particle distribution suitable for building of earth block is: 40 - 75% sand and 25-60% fine (silt + clay). This implies that the sample soil which was taken from Yeka area of Addis Ababa fulfills this requirement. So, the experimental result range for this soil sample is acceptable and suitability for stabilized earth block production. In other word, the soil is considered as suitable for mud house construction.

Using a suitable soil for soil-stabilized block production will result in [5]:

- Strong blocks which have good strength and erosion resistance.
- Handleable blocks that immediately upon remolding can be transferred to a curing area.
- Block that will not seriously distort or crack during curing.
- Blocks that will not expand and contract excessively in the building if are subjected to wetting and drying cycles or different weather.

Specifically disqualified soils which are used for stabilized earth block construction are:

- Containing high excessive organic impurity.
- Are highly expansive.
- Containing excessive soluble salts e.g. gypsum and chalk.

5.2 Total water absorption test

Almost all earth blocks can absorb water by capillarity [15]. The existence of pores of varying magnitudes in these materials confers marked capillarity in them. The total amount of water absorbed is a useful measure of bulk quality. The reason for this is that the total volume of voids (or pore space) in a block can be estimated by the amount of water it can absorb. Knowledge of the value of the total water absorption (TWA) of a block is important because it can be used for:

- Quality checks on blocks
- Comparison purposes with set standards and values for other like materials
- The classification of blocks according to required durability and structural use
- Approximation of the voids content of a block

Generally, the less water a block absorbs and retains the better is its performance likely to be. Reducing the TWA capacity of a block has often been considered as one of the ways of improving its quality and durability.

Total water absorption test was conducted on all the six samples types and the value for each sample and their average value is shown in table 5.2. The experimental results of the water absorption test show the effect of cement and straw fiber content on the water absorption capacity of the blocks. According to the tabulated results in Table 5.2, the mean water absorption values for the various samples tested range from 12.15% for the 5% cement content samples

(5C) to 21.1% for the soil (E) samples. From the literature the recommended maximum water absorption value for suitable blocks is below 15%.

Table 5.2 Total water absorption for stabilized earth block

Types of samples	samples	dry mass (g)	wet mass (g)	Water absorption (%)	Average total water absorption (%)
E	1	2026	2462	21.5	21.1
	2	2018	2437	20.7	
C2	1	2089	2395	14.65	15.02
	2	2093	2415	15.38	
C5	1	2031	2286	12.55	12.15
	2	2043	2284	11.79	
S3	1	1984	2406	21.27	20.86
	2	1995	2403	20.45	
C2S3	1	1989	2257	13.47	13.26
	2	1993	2253	13.04	
C2S6	1	2012	2268	12.72	12.92
	2	2019	2284	13.12	

According to Table 5.2, an increase in cement content has the effect of reducing the water absorption value of the blocks. An increment of the cement content in the mixture from 2% to 5%, results into a reduction in water absorption of 14%. This shows that the increase in cement

content in the mixture results into a reduction in water absorption. In contrary, a doubling of the straw fiber content from 3% to 6% results into a reduction in mean water absorption of 2.5%. This shows that the increase in straw fiber content results in reduction of water absorption, but it has no much insignificant effect as the cement does. Therefore, from the result the three samples (5C, 2C3S and 2C6S) fulfill the recommended value i.e. 15%.

5.3 Shrinkage in drying process

The shrinkage is contraction of a given block sample during drying. It gives an overall idea of the mixture behavior and suitability for construction. In other word, shrinking of soil is the opposite of swelling soils. A volume change soil swells with increasing moisture content, but it will shrink with decreasing moisture content. Soil shrinkage can cause serious distress to a foundation/structure and, the mechanism is the same as the expansive, but in the opposite direction.

Table 5.3 Average value of shrinkage after drying of the stabilized blocks

Samples	Average shrinkage(cm^3)	Percentage shrinkage (%)
E	287.8	10.8
C2	169.8	6.4
C5	126.2	4.7
S3	226.5	8.5
C2S3	156.4	5.9
C2S6	135.25	5.1

During dry process there is volume change or shrinkage. The shrinkage value differs from sample to sample depends on their composition. The shrinkage value for each sample is given in appendix B and the average value is shown in table 5.3 and the bar graph in fig.5.2. The percentage of shrinkage (S_p) of earth block samples can be calculated using equation 5.1.

$$Sp = \frac{V_m - V_b}{V_m} \dots\dots\dots 5.1$$

Where:

Sp= percentage of shrinkage

Vb = volume of the specimen (cm³)

Vm = volume of the mold (cm³), the volume of the mold in this test is 2646 cm³ (14×21×9) cm.

From literature, the recommended range of percentage of shrinkage is less than 6 % [23].So, the three samples' (2C5C, 2C3S and 2C6S) values are within the recommended ranges of suitable soils stabilized blocks.

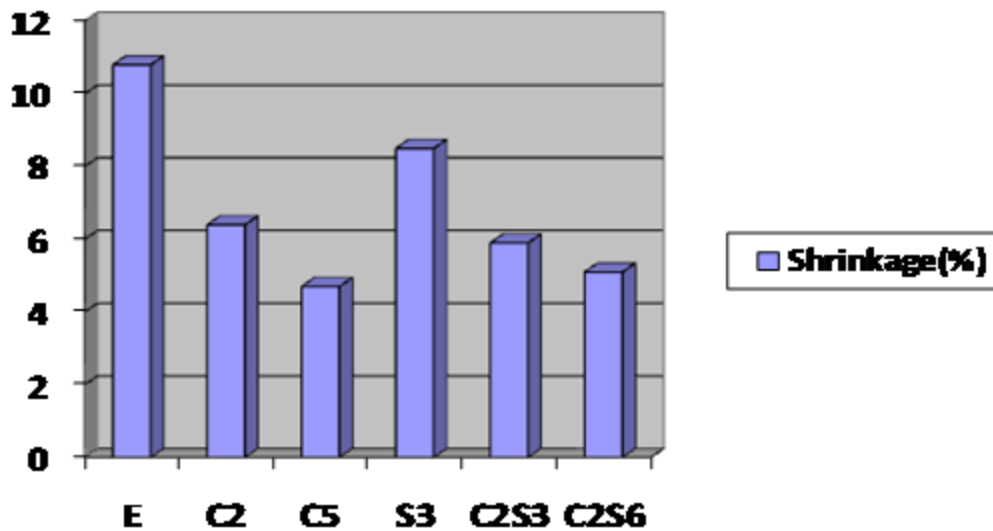


Fig. 5.2 Percentage of shrinkage of stabilized blocks

The shrinkage (volume change) value depends on the composition of mixtures in the samples. When the amount of the cement and the straw fiber is increased, the shrinkage value will decrease or vice versa. Compaction and the amount of water added in the mixture also affect the block's shrinkage value. If the amount of water added is increased, the shrinkage value will also increase. This is because, during drying process, the evaporated water will create openings (voids) between particles and that results shrinkage to fill the openings. Compaction is removing the air from blocks and fills the gap between particles. Proper compaction in blocks results dense structure which is stronger and more durable by reducing shrinkage cracks. In general, during

manufacturing stabilized earth blocks the shrinkage range must be consider. The shrinkage has effect on the output block's dimension.

5.4 Compressive strength test result and analysis

5.4.1 Compressive strength test results

In practical, compressive strength value for stabilized earth building blocks may be less than 4MPa. When building loads are small (e.g. in the case of single store constructions), a compressive strength value from 2MPa to 4MPa may be sufficient for building purposes. Many building authorities around the world their recommend values are within this range. The minimum British Standard requirements for precast earth blocks and load bearing fired clay blocks is above 2.8MPa [6]. The experimental value of the compression strength and Young's modulus for each sample is shown in appendix A and their average result is shown in table 5.4 and the bar graph in fig.5.3 and 5.4.

Table 5.4 Average compression strength, strain and young's modulus results of stabilized blocks

Samples	Average Max.Compressive strength (MPa)	Average strain(ϵ)	Average Young's modulus (MPa)
E	0.914	0.077	11.84
C2	2.43	0.095	25.57
C5	5.43	0.101	54.31
S3	1.67	0.130	12.79
C2S3	3.63	0.147	24.62
C2S6	3.86	0.210	18.33

In general, the compression stress results are obtained by dividing the maximum force by the area of the specimen, and the strain calculated by measuring the vertical displacements of the block during compressive test. In compressive test, a large content of the straw fiber causes small value of the Young's modulus (E). The presence of straw fibers in the mixture provides the plastic property of the stabilized earth block. The strain performances of the blocks are influenced by the straw fiber content. As the straw content increases, the strain value increase for the same cement content. In the contrary, a large content of cement in composite block causes large value of young's modulus. However, when the cement and the straw fiber content increase in the mixture, they results an increase in compressive strength value. Based on the results obtained in this test, it was found that the three block samples (5C,2S3S and 2C6S) have compressive strengths greater than the recommended value of the British Standard (BS 5628 Part 1) of 2.80 N/mm²(MPa).

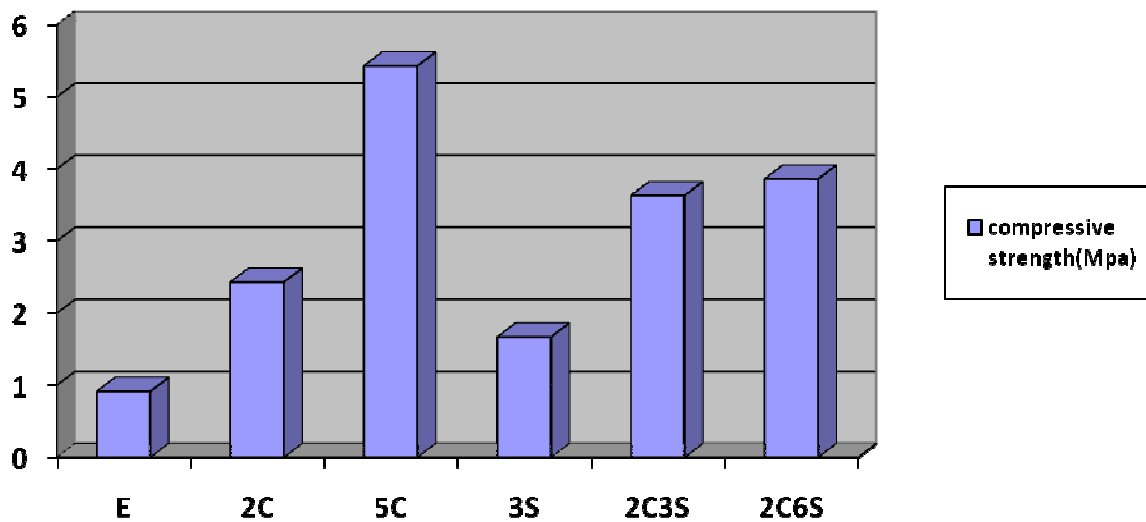


Fig.5.3 Average compression strength values of stabilized blocks

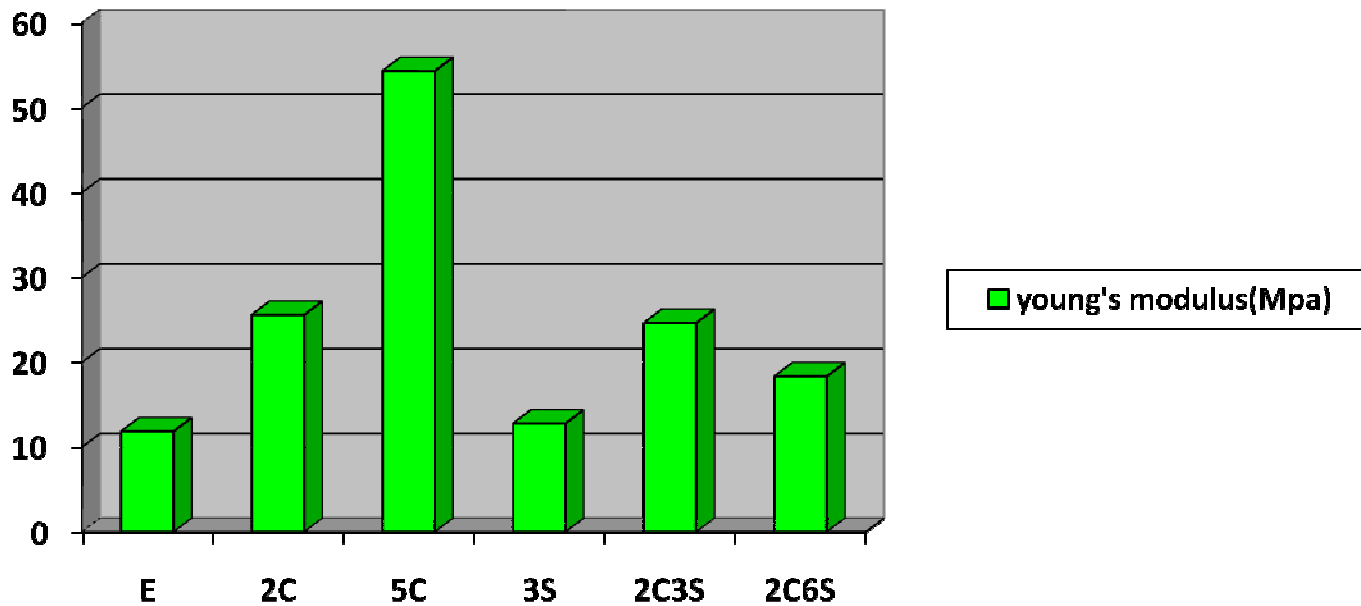


Fig.5.4 Average young's modulus values of stabilized blocks

The amount of straw and cement in the mixture has effect on the shape and the width of cracks that is created during compressive strength test. In fact, the increase of straw fiber decreases the size and the number of cracks. This is because the straw fibers have good plastic property that keeps the composite particle close together. On the contrary, an increment of cement causes few but large size cracks in the block during test (fig 5.5). This is because the cement has good glue and compactness property. However, when it is exposed to compressive force, it results large crack within limited width. In general, this experiment work demonstrates the mechanical behavior of earth blocks with different soil, cement and straw fibers volume fractions.



Fig .5.5 Large cracks in cement stabilized block (sample 5C) during compressive test

5.4.2 Empiric relation of compressive strength and young's modulus for earth blocks

There are different empirical correlations between the compressive strength and the experimental Young's modulu were proposed by different scholars. On the base of the results of previous researches it is possible to assert that the theoretical prediction of the compressive strength is a difficult task, specially because there are many failure phenomena which are usually involved in the composite: failure of each component, failure of the interfaces, microscopic buckling of components, etc [21]. However, in this work, the experimental result and previous proposed works are compared to predict the empirical relation of compressive strengths and young's modulus. The empirical formula or theoretical predictions were determined based on the dependence of compressive strength on the young's modulus.

Empirical relation compressive strength and young's modulus for straw fibers stabilized earth block

The empirical linear correlation between these variables, for blocks, is found similar to Piattoni equation (equ.5.3):

$$R_c = -0.008E + 3.51 \dots\dots\dots 5.3$$

R_c= compressive strength

E=Young's modulus

As it is shown from the graph of the experimental result (fig.5.7), the empirical relation between compressive strength and young's modulus of straw fiber earth blocks may have a form of linear function: $y=ax + b$.

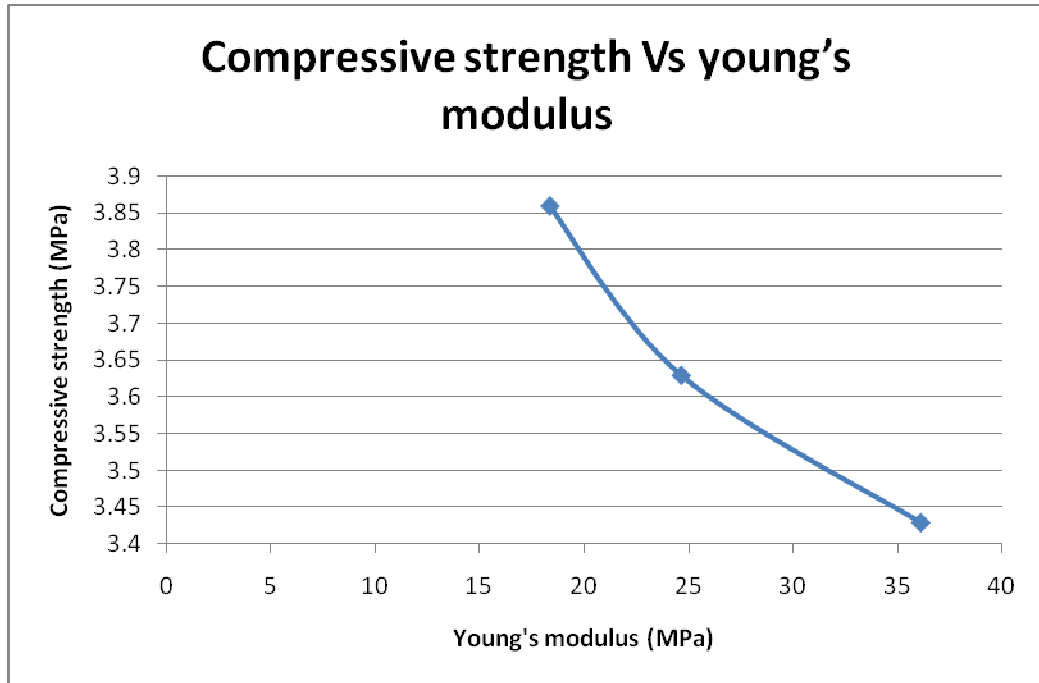


Fig.5.6 Relation between compressive strength and young's modulus values for straw fiber's stabilized blocks

Similarly, the coefficients of the equation can be determined by using Math lab.

Math lab codes:

$x = [18.33 \ 24.62 \ 36.1];$

$y = [3.86 \ 3.63 \ 3.43];$

Plot (x,y)

$p = \text{polyfit}(x,y,1)$

The value of the coefficients for $y=ax + b$ will be:

$a = -0.0234 \quad b = 4.2558$

$y = -0.0234x + 4.2558$5.4

The main characteristic of this relation is that the compressive strength is a decreasing function of the young's modulus (stiffness). That means the increment of the volume fraction of straw

fiber in the mixture produces an increment of the compressive strength and a reduction of the Young's modulus. This equation is much similar to the empirical relation of the Piattoni equation (fig.5.8) [24].

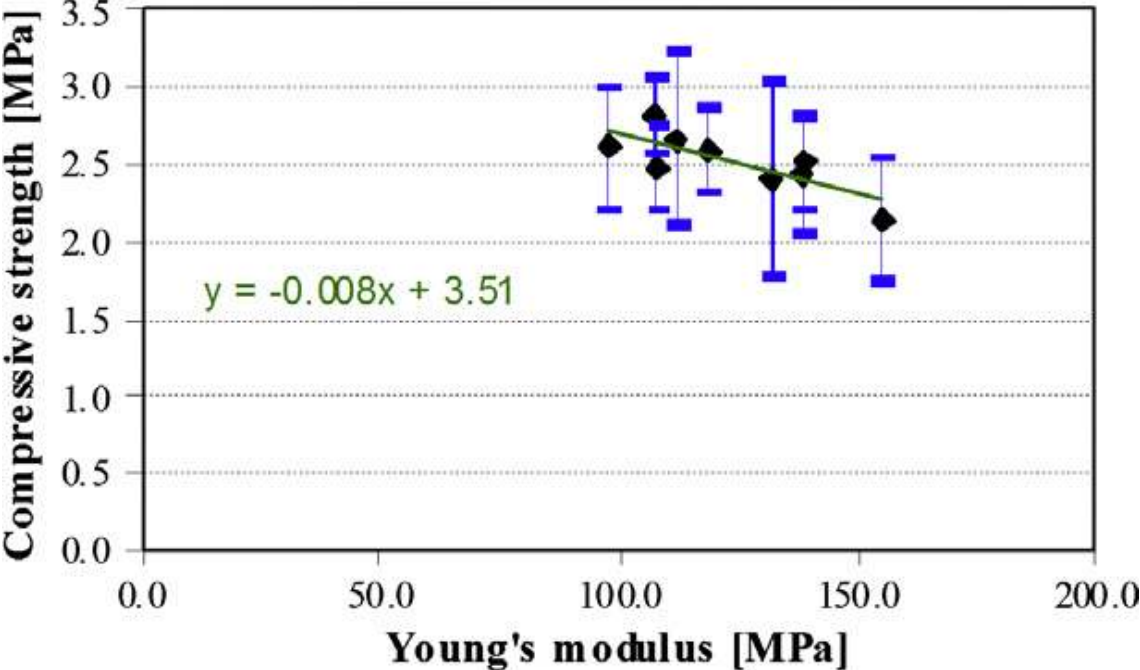


Fig.5.7 Relation between compressive strength and Young's modulus of the blocks for Piattoni equation [24]

CHAPTER SIX

6. MODELING AND DESIGN

6.1 Part modeling and design using Solid work for manually operating block making machine

Introduction

There are different of types of block molding machines. Still today, some people make the blocks by beating soil into a wooden mold with a stick. Modern equipment, with hydraulics driven by diesel, gas or electric motors, may be useful in urban areas or for large multi-house sites. However, the difficulty of using motor-driven equipment for smaller and more rural projects is hard to grasp. So, this manually operated earth block making machine can be one of the solutions to this difficulty. In addition, this machine is simple in use and inexpensive for manufacturing in local workshops. The main function of the manually operated brick making machine (MOBMM) is shaping uniformly and compacting the block at the same time. Main parts of manually operated earth block's 2-D view and their dimensions are given below (and the assembly drawing is shown in appendix C):

a. Slider

It is used to support the compressive plate and to transfer rotational motion in to translational motion. Since it is subjected to friction force, it should be made from wear resistance material.

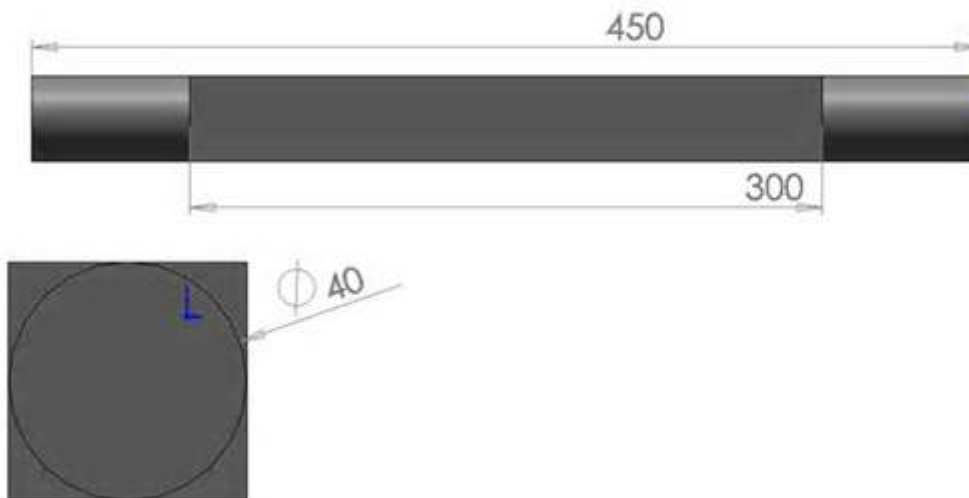


Fig .6.1 Slider's solid work model

b. Link

The link is used to transfer rotational motion (from the handle or lever) into translational motion for the compression plate. The material for this part should be bending resistance material since it is subjected to bending force. All dimensions in these part models are given in mm.

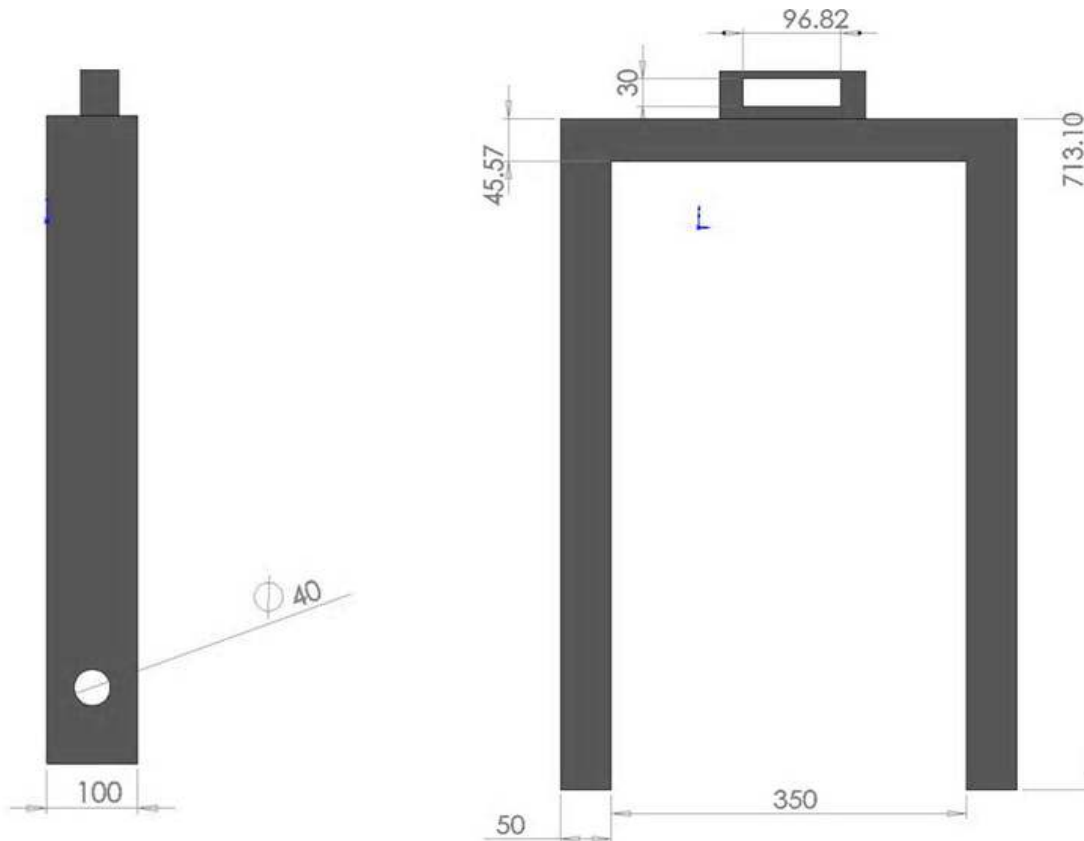


Fig.6.2 Link's solid work model

c. Handle or lever

It is used to drive the link by transfer rotational motion into links by multiple the operator force. Since, it is subjected to bending force; it should be made from bending resistance material.



Fig.6.3 Handle or lever's solid work model

d. Compressive plate

It is a sliding plate used to compress or squeeze (compact) the prepared mixture of mud. Since it is subjected to compressive force, friction and bending forces, it should be made from wear and bending resistance material. And, lubrication is the best way to reduce friction or wear between the plate and body (housing).

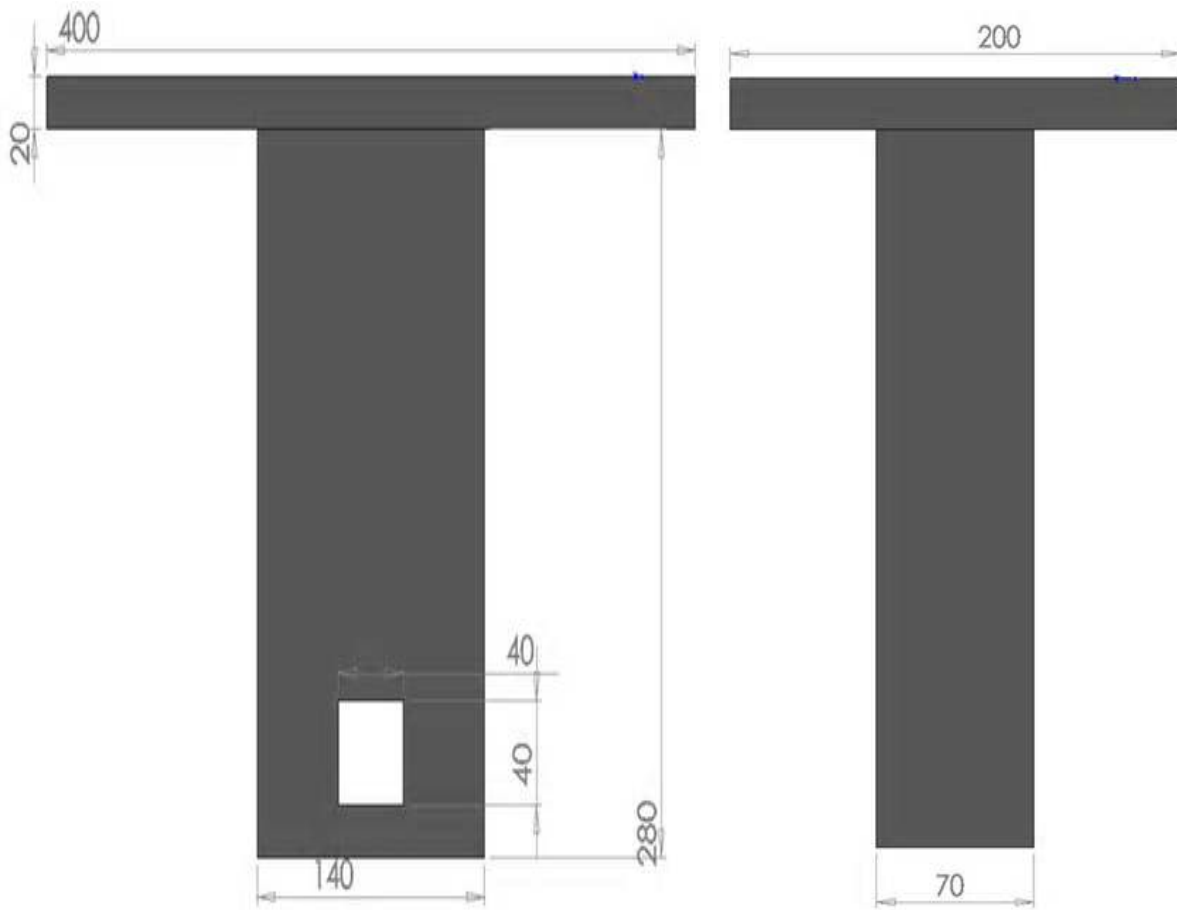


Fig.6.4 Compressive plate's solid work model

e. Lid or cap

It is a cover plate which is used to support the force that comes from combination of lever and the compression plate. Since it is subjected to compression force, it should be made from compressive force resistance material.

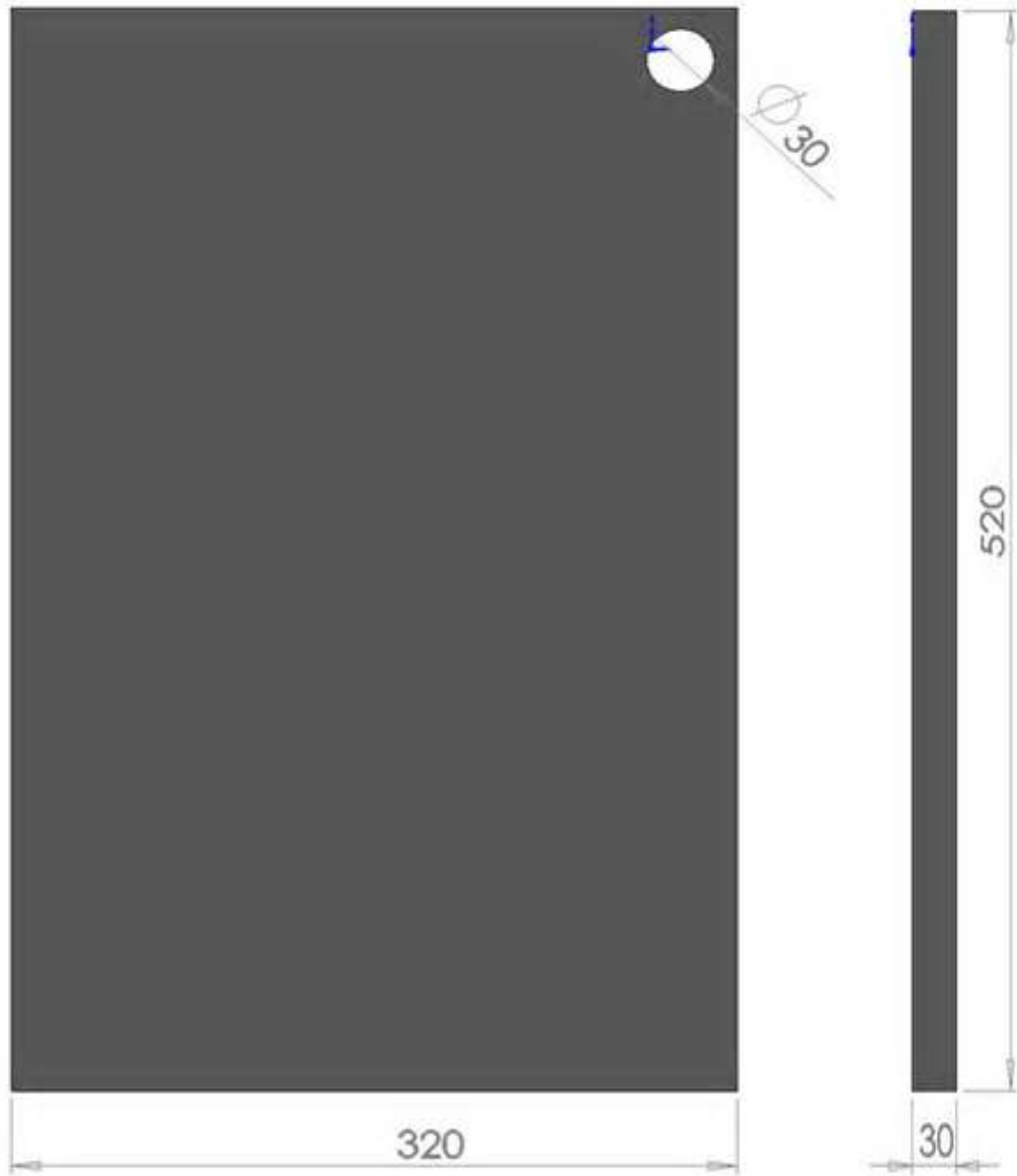


Fig.6.5 Lid or cap's solid work model

Explode view for MOBMM

The exploded view of the above all parts is shown in fig.6.7 to locate the right position of the MOBMM parts during assembling process and its assemble 3D drawing is also shown in fig.6.7.

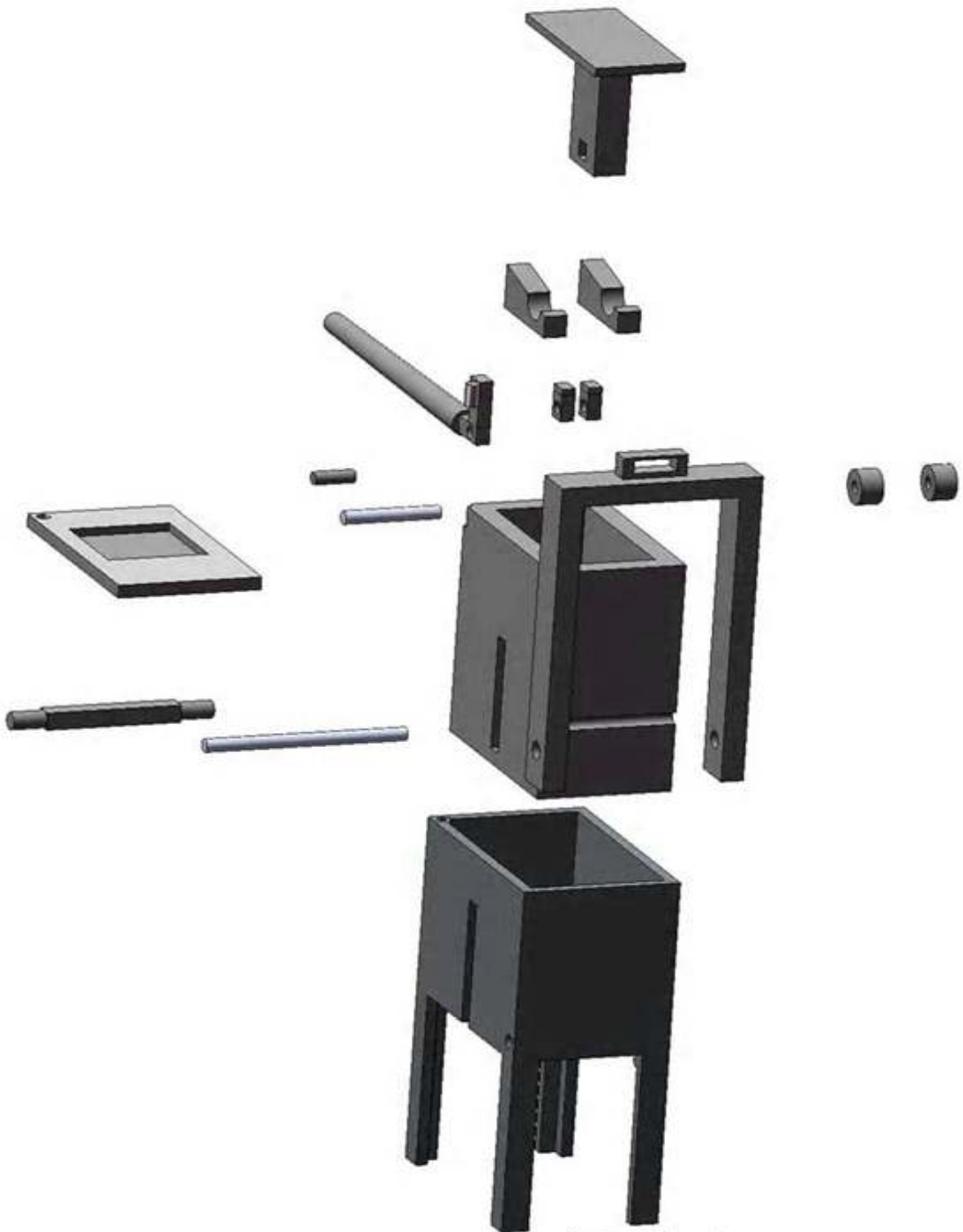


Fig.6.6 Exploded view of the block making machine

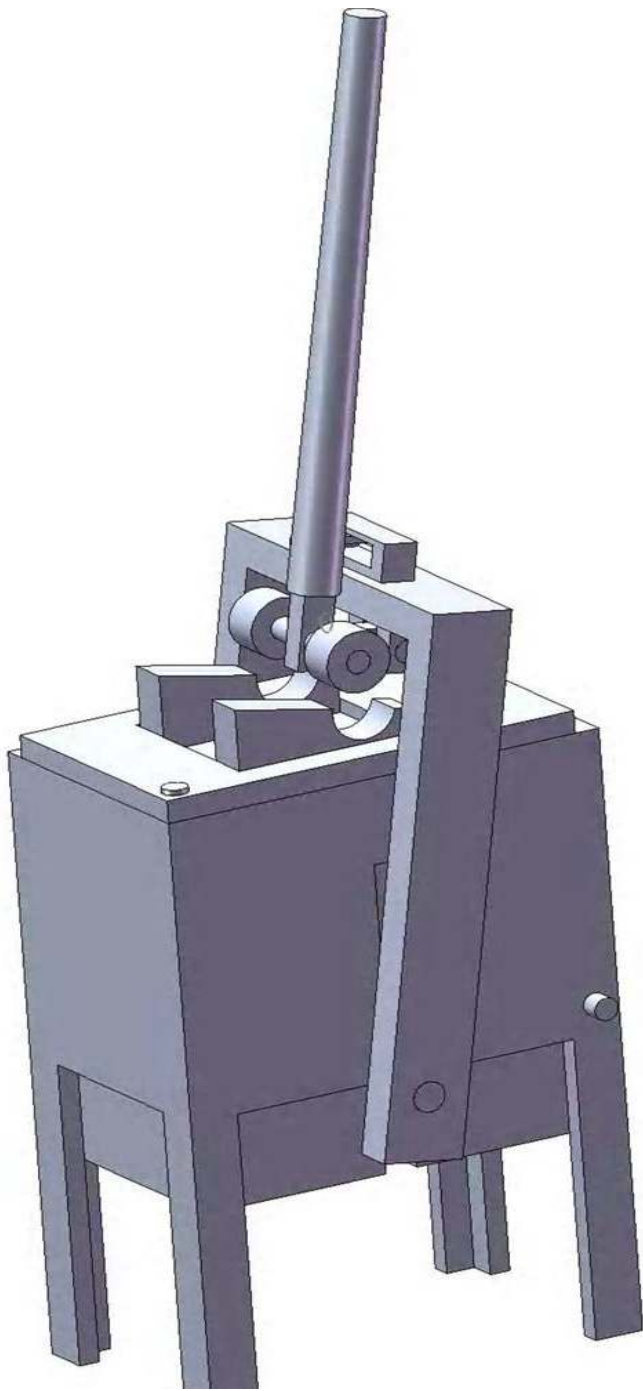


Fig. 6.7 Assembled view of the block making machine

6.2 Part modeling and design using Solid work for manually operating sieve machine

Introduction

This manual operated sieve machine is used for filtering unnecessary parts of the soil and the gravel particles without consuming fuel or electric energy and time. This machine can handle approximately up to 16kg soil at one time. Manually operated sieve machines (MOSM) are designed with simple pulley system which is easily manufactured in local machine shops. Most of this machine parts can be made from local available material and domestic products. In general, this manually operated sieving machine is very simple in use, easy in functional and can operate easily. Main parts of manually operating sieving machine's 2-D view and their dimensions are given below (and the assembly drawing is shown in appendix C):

a. Sieve

It is used to screen or filter unnecessary objects or particles from the soil. As it was discussed in chapter 3, the diameter of the sieve hold must not be greater than 2mm (the minimum grain size of the grave texture).

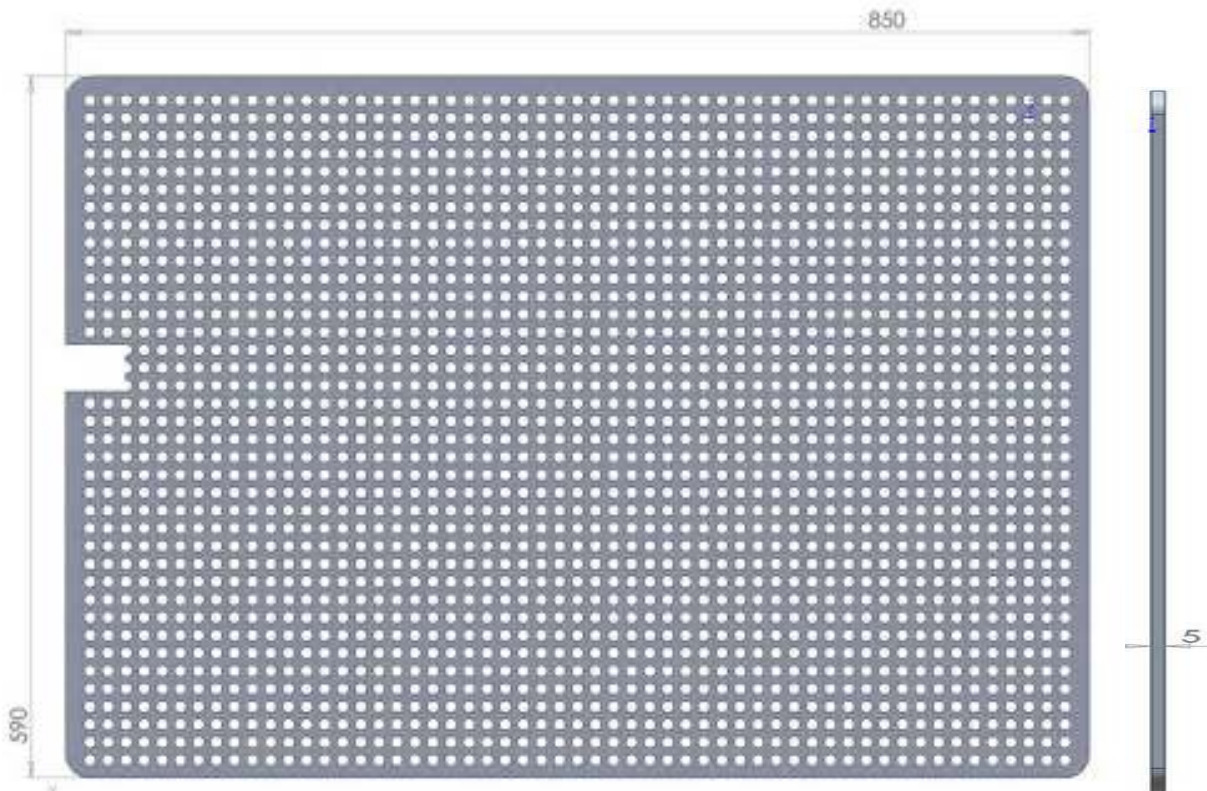


Fig.6.8 Sieve's solid work model

b. Pulleys

The diameter of the driven pulley is two times the diameter of the driving pulley. This is because; the system is wanted to provide a multiplied force or torque for the sieve.

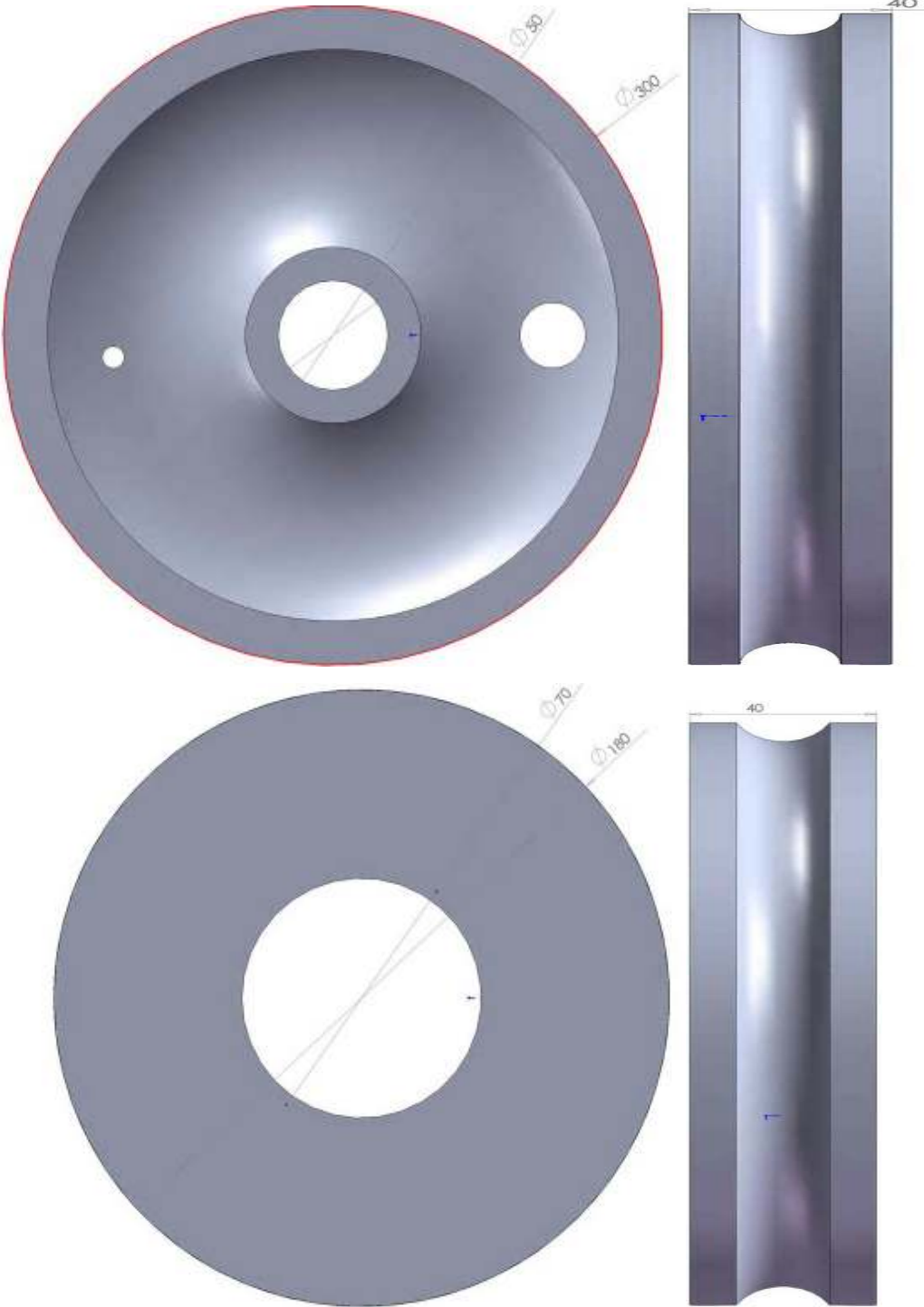


Fig.6.9 Driving and driven pulley’s solid work model

c. Housing

This part is used to supporting and protecting the accessory parts (like pulleys and the sieve) which are mounted parts on it.

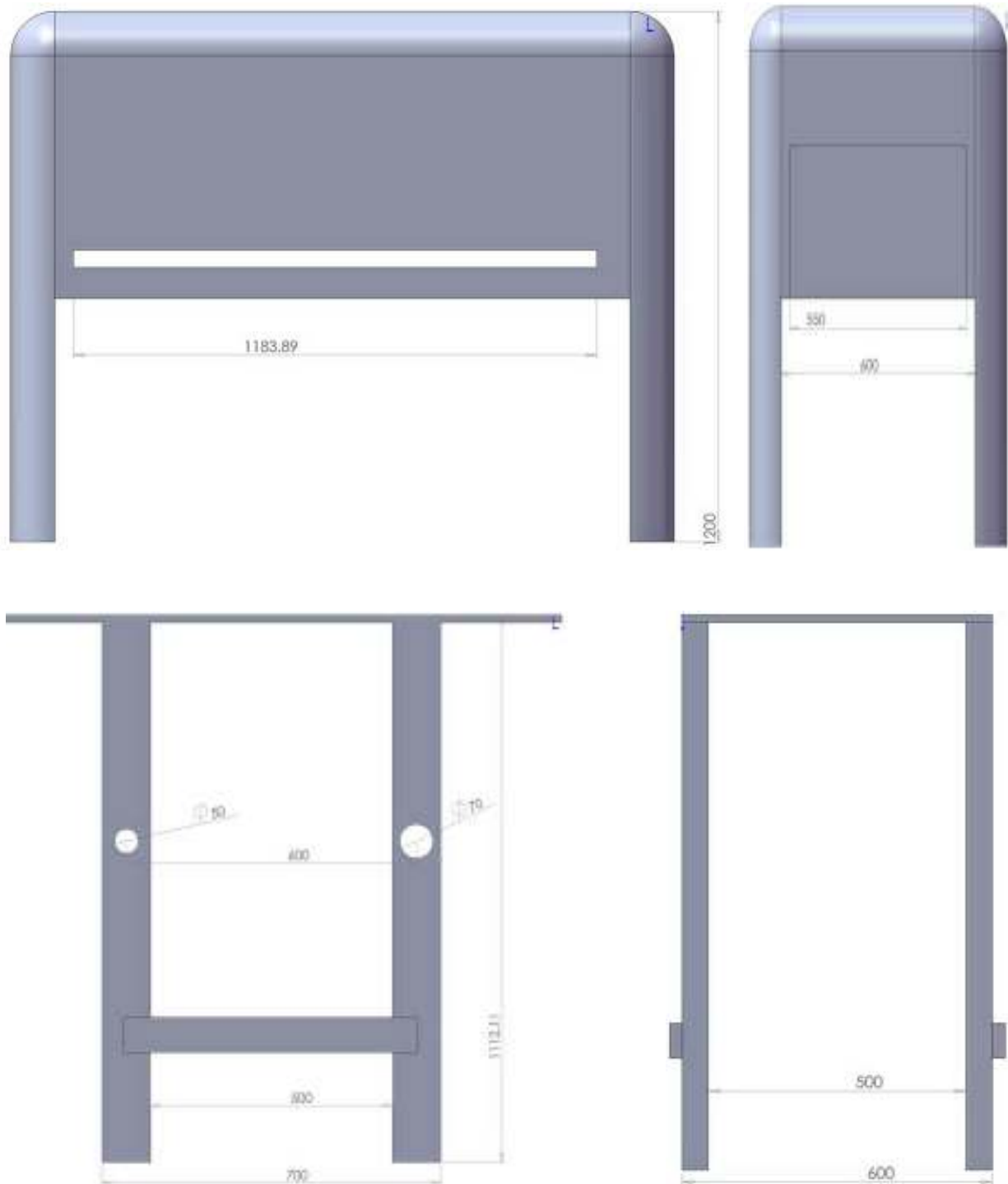


Fig.6.10 Housing's solid work model

d. Handle

It is used to transfer the rotation motion which is produced by the operator in to the driving pulley. These all parts can easily be fabricated in local workshops.

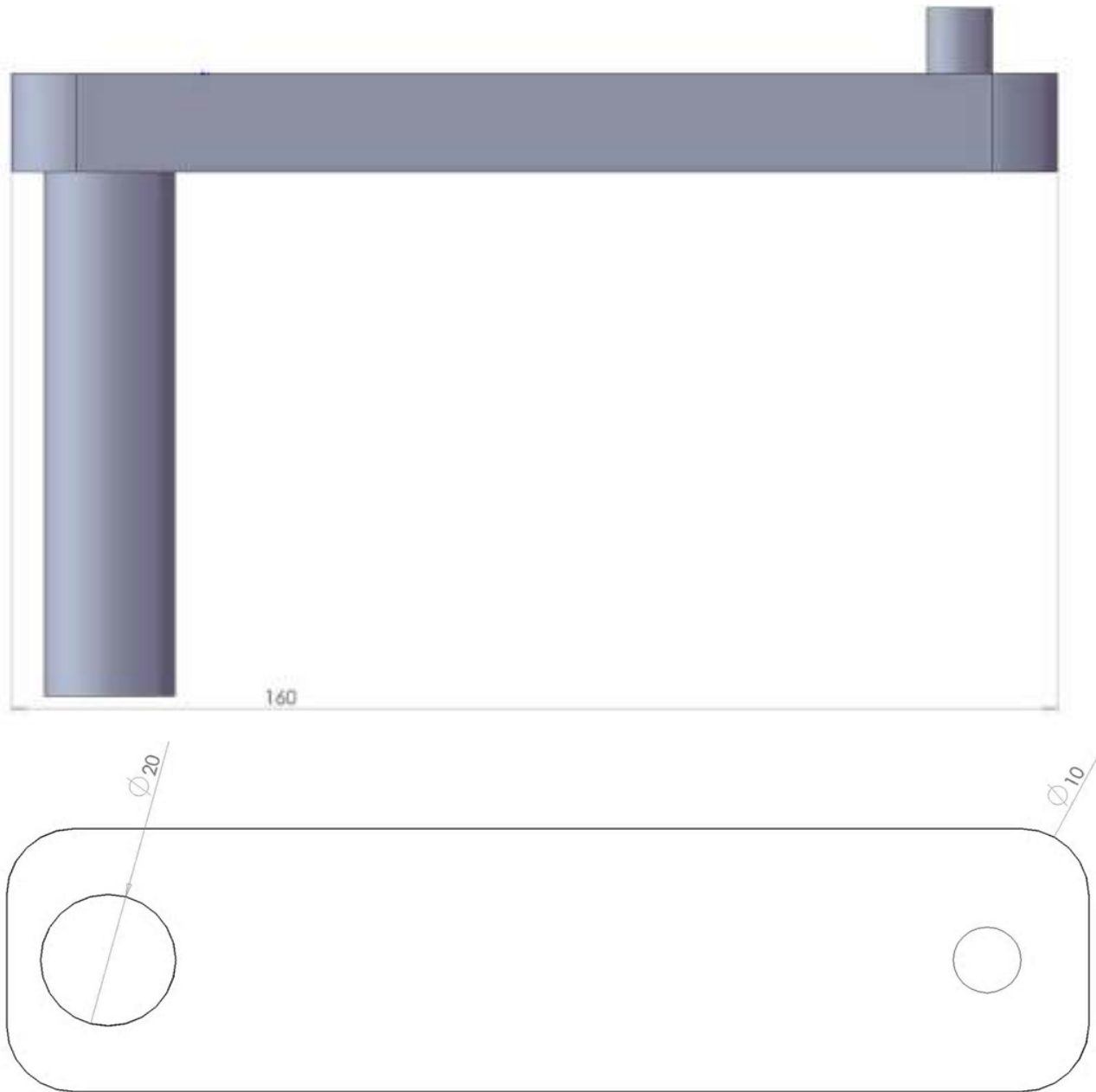


Fig.6.11 Handles' solid work model

Exploded view of MOSM

The exploded view of the above all parts is shown in fig.6.12 to locate the right position of the MOSM parts during assembling process and its assemble 3D drawing is also shown in fig.6.13.

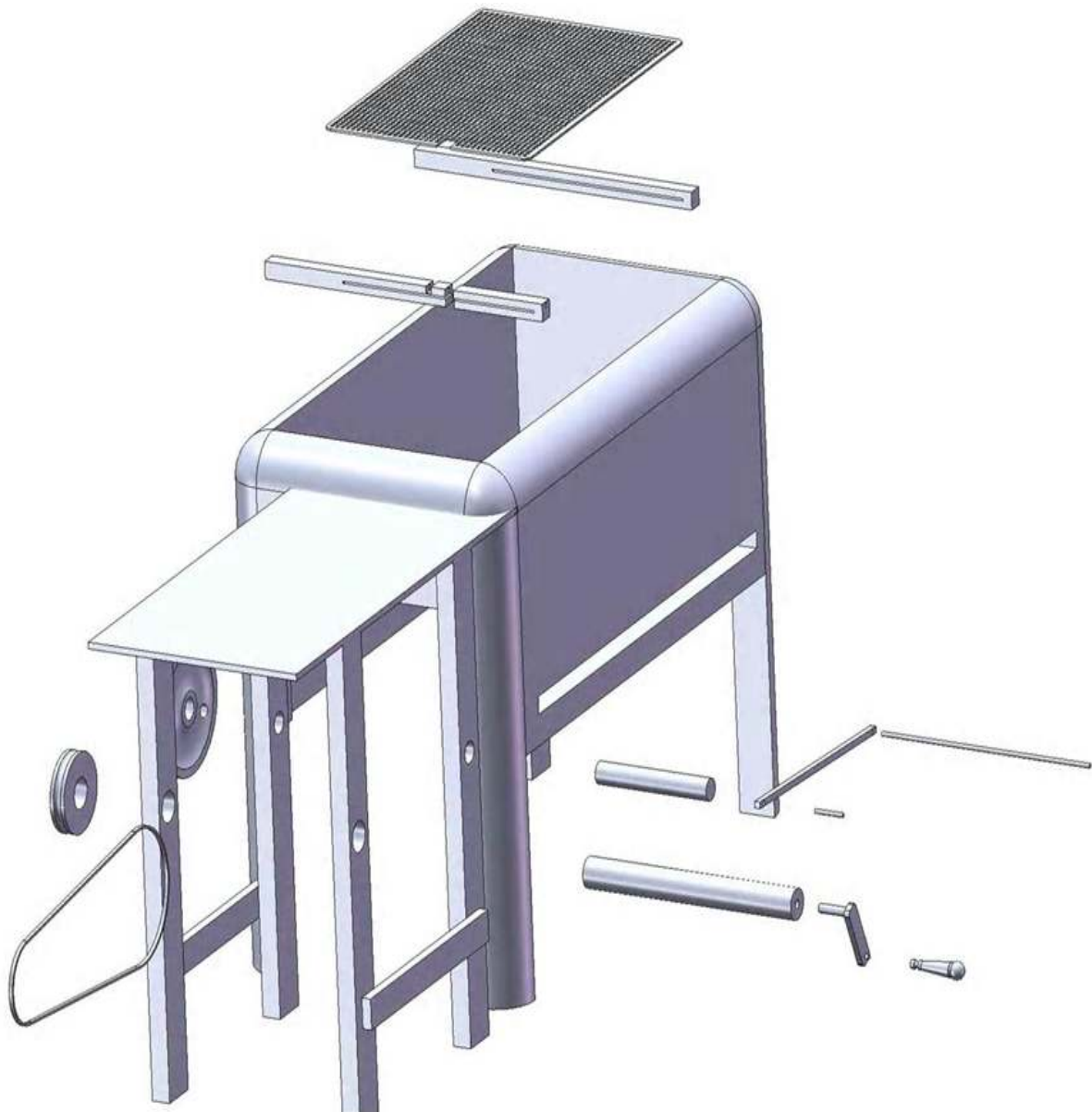


Fig.6.12 Exploded view of the sieving machine's solid work model

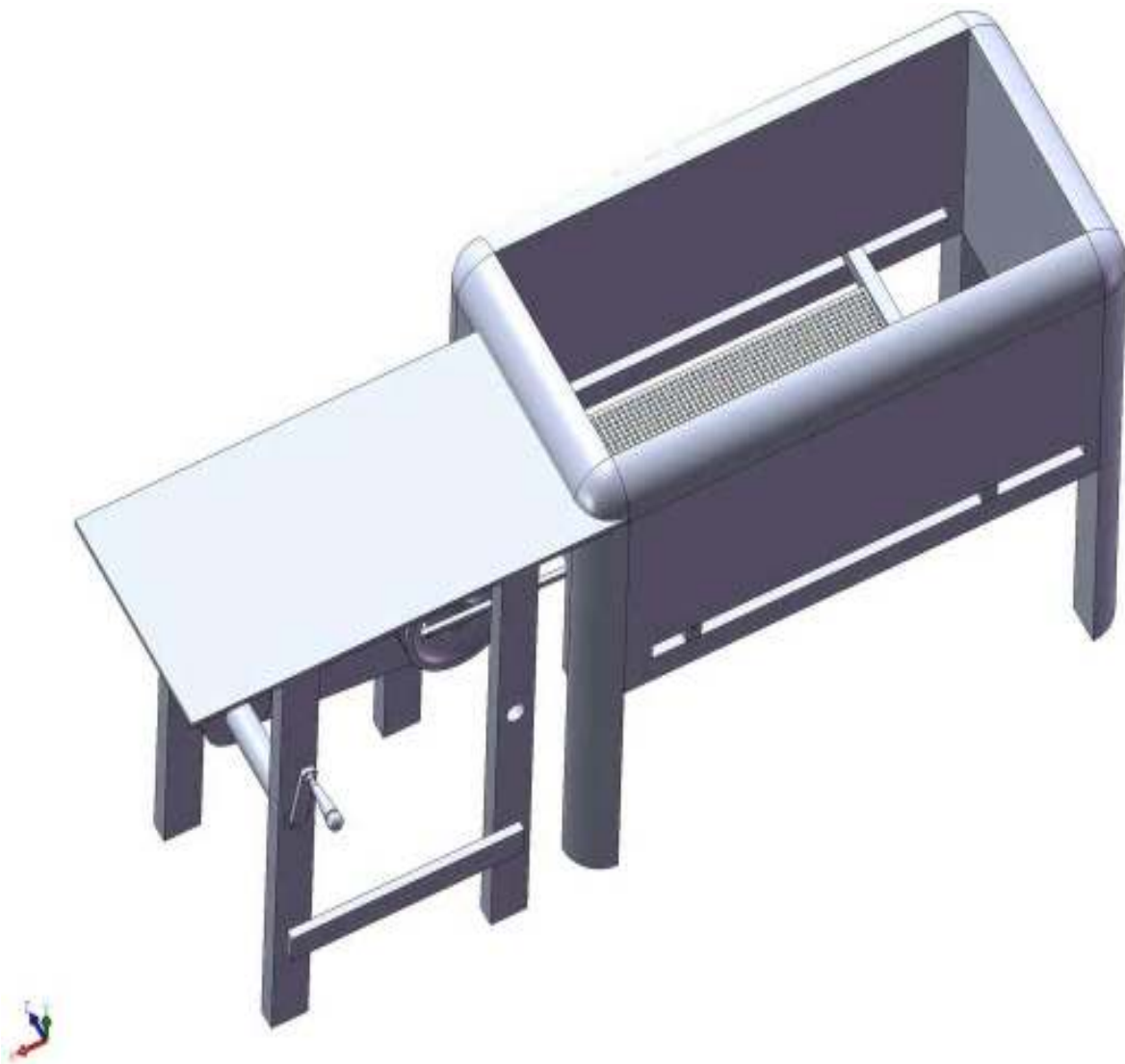


Fig.6.13 Assembled view of the sieving machine's solid work model

CHAPTER 7

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. Production of stabilized soil block using cement and straw fiber as a stabilizer fulfills a number of objectives which are necessary to attain a durable structure from locally available soil. Some of these are: better mechanical property (better compressive strength), and better cohesion between particles (reducing porosity which reduces changes in volume due to moisture fluctuations).
2. Increase in cement content results in an increase in the compressive strength value of blocks. For instance, by increasing the cement content from 2% to 5 % yields 58.3 % increment in compressive strength of the block. Increase in straw fiber content results in an increase in the compressive strength value of blocks. For instance, by increasing the straw fiber content from 3% to 6 % yields 6.33 % increment in compressive strength of the block. That value is not large compared to the cement value. However, it has significant effect on young's modulus or stiffness. When the amount of straw fiber increases, its stiffness decreases.
3. Increase in cement content could be a more effective method of increasing compressive strength values than increase in straw fiber. In addition, the strength reached by a block is much more sensitive to variations in the cement content than the straw content.
4. The amount of water added in the soil-cement mixture needs to be carefully controlled. There needs to be sufficient moisture for the cement to fully hydrate but excess water would reduce the final strength and increase porosity.
5. The moisture absorption capacity of the block could be significantly correlated to its durability. Increase in the cement content of blocks results in a reduction of its water absorption capacity. An increment of the cement content from 2% to 5% results into a reduction in water absorption of 14%.
6. From literature the recommended soil composition for compressed earth block production is 40 - 75% for sand, and 25-60% for fine texture (silt and clay). In this research, soil which is taken from Yeka area of Addis Ababa with a composition of sand 59.5 % and fine (silt and clay) 34.8% is used as a raw material for stabilized earth block production.

7. This thesis assists in solving the country housing problems with economical and environmentally friendly way by introducing earth block production technology. To aid this technology, two manually operated machines are proposed for easy and fast block production system. Their solid work model is presented with their corresponding dimensions and simulation.

7.2 Recommendations

- Suitable soil which is used for stabilized earth block production selection using laboratory tests may be expensive for small-scale production. Simple field test methods and trial block production should be produced and be made available.
- Stabilized earth block production technology is not common in Ethiopia. This technology opens ways for small-scale entrepreneurs who do not require high investments and skills. The accessory which is used in earth block production can be manufactured in local work shop by small business groups (entrepreneurs).
- Training people in community about the earth block production technology and the technique and working principle of the manually operated machine is needed. In addition, operation manual for the soil testing and compressed earth blocks production should be organized.
- Promoting stabilized earth block through advertising and pilot housing, so that many people could have better knowledge about this technology.

Future work

- Further detailed fieldwork to identify the most suitable soils for stabilized earth block in each part of the country (Ethiopia).
- Life span study for the stabilized earth blocks
- The precise amount of water for best durable stabilized block and the proportion of water amount and block size.

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APPENDIXES

APPENDIX A

Compressive strength test result of stabilized earth blocks

Table A.1 Compression strength, strain and young's modulus result for category 1 samples

Samples	Area(cm ²)	Max.force(kN)	Max.Compressive strength (Mpa)	strain(ε)	Young's modulus (Mpa)
E	278.1	26.84	0.97	0.081	12.05
C2	284.2	65.05	2.31	0.093	24.83
C5	287.0	158.34	5.52	0.094	58.72
S3	278.1	48.62	1.75	0.135	12.96
C2S3	283.5	101.56	3.58	0.143	25.03
C2S6	285.6	107.34	3.75	0.207	18.11

Table A.2 Compression strength, strain and young's modulus result for category 2 samples

Samples	Area(cm ²)	Max.force(kN)	Max.Compressive strength (Mpa)	strain(ε)	Young's modulus (Mpa)
E	278.1	23.51	0.85	0.073	11.64
C2	284.9	72.81	2.55	0.097	26.28
C5	285.6	152.52	5.34	0.107	49.90
S3	278.1	44.21	1.59	0.126	12.62
C2S3	282.2	104.01	3.68	0.152	24.21
C2S6	284.9	113.17	3.97	0.214	18.55

Table A.3 Average compression strength, strain and young's modulus results

Samples	Average Max.Compressive strength (Mpa)	Average strain(ε)	Average Young's modulus (Mpa)
E	0.914	0.077	11.84
C2	2.43	0.095	25.57
C5	5.43	0.101	54.31
S3	1.67	0.130	12.79
C2S3	3.63	0.147	24.62
C2S6	3.86	0.210	18.33

APPENDIX B

Volume change or shrinkage value

Table B.1 Change of volume (shrinkage) in drying process for category 1 samples

Samples	Length (cm)	Width (cm)	Thickness (cm)	Area(cm ²)	Brick's Volume(cm ³)	Volume change or shrinkage(cm ³)
E	20.6	13.5	8.6	278.1	2391.6	254.4
C2	20.8	13.7	8.7	284.9	2479.2	166.8
C5	20.7	13.8	8.8	285.6	2513.8	132.2
S3	20.6	13.5	8.7	278.1	2419.5	226.5
C2S3	20.6	13.7	8.8	282.2	2483.5	162.4
C2S6	20.8	13.7	8.8	284.9	2507.6	138.3

Table B.2 Change of volume (shrinkage) in drying process for category 2 samples

Samples	Length (cm)	Width (cm)	Thickness (cm)	Area(cm ²)	Brick's Volume(cm ³)	Volume change or shrinkage(cm ³)
E	20.4	13.6	8.6	278.1	2385.9	321.3
C2	20.6	13.8	8.7	284.2	2473.2	172.8
C5	20.8	13.8	8.8	287.0	2525.9	120.1
S3	20.6	13.5	8.7	278.1	2419.5	226.5
C2S3	20.7	13.7	8.8	283.5	2495.5	150.4
C2S6	20.7	13.8	8.8	285.6	2513.8	132.2

Table B.3 Average change of volume (shrinkage) in drying process

Samples	Average shrinkage(cm ³)	Percentage shrinkage (%)
E	287.8	10.8
C2	169.8	6.4
C5	126.2	4.7
S3	226.5	8.5
C2S3	156.4	5.9
C2S6	135.25	5.1

APPENDIX C

Photos



Fig.C.1 Stabilized earth blocks' photos



Fig.C.2 Compressive strength test and testing machine photos