DEVELOPMENT OF BIO INSPIRED INTERLOCKING COMPRESSED EARTH BRICKS

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This is to certify that the Final Year Project Titled

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has been accepted towards the requirements for the undergraduate degree

in

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Dedication

To our beloved parents, teachers, mentors and colleagues who have stood by our side in rough and tough times, who have taught us to show perseverance in the face of adversity.

ACKNOWLEDGEMENTS

In the name of Allah, the most Beneficent, the most Merciful as well as peace and blessings upon Prophet Muhammad, His servant and final messenger.

We are first and foremost, extremely grateful to Allah Almighty for enabling us to complete our research project and without Whose willingness we could not have imagined to accomplish such an enormous task.

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Abstract

Bricks are one of the most commonly used construction materials employed. This is because of its manufacturing convenience and economy. Having said that, it does have its disadvantages, one of the biggest being its contribution to pollution and low resistance to dynamic loads. This research focused on employing modern techniques to counter the disadvantages and formulate a material that has enhanced strength and eco-friendly. Alongside that, bacteria were utilized for inducing healing property; industrial soil which is rich in bacterial properties was used. For this very purpose a recipe was devised to activate the bacteria in order to produce precipitation when cracks form in the bricks. For the formulation experts in this field were consulted with and various research papers were studied. For the manufacturing of brick, it was found that using high compression effort, with addition of a binding material produces bricks that have the same properties as the kiln produced bricks. This helped in completely bypassing the burning process and producing a brick with zero emission. For the design of the bricks, various literature was consulted in order to come up with a design that has an enhanced resistance to lateral loading. For this very purpose the concept of shear keys was incorporated in the proposed design. This inclusion proved to improve the brick's resistance to lateral loading. After initiating the laboratory testing, COVID-19 was declared a pandemic due to which the country went into a state of lockdown. This left laboratory testing stage incomplete and so the project team regrouped and with consultation with the project supervisor, scope of the project was altered, and numerical modelling of the proposed bricks was included. Numerical modelling was performed on ABAQUS Software, employing micro modelling. The results, discussed later in this paper, showed that the proposed bricks performed well in comparison to the conventional bricks. Average Compressive Strengths of the Proposed Brick was found to be 7.9 MPa which is comparable to Conventional Brick, having 8MPa. It is pertinent to mention that the minimum criteria for load bearing masonry is 5 MPa, which the Proposed Brick comfortably fulfills. Water absorption value in the proposed brick was found to be lower than that of conventional brick, I.e. 15% against 14% for conventional bricks. Thermal Conductivity achieved was also better in the proposed brick, i.e. 0.5 W/m-K against 0.72 W/m-K of conventional bricks. Force-displacement curves from numerical models proved these bricks can resist more lateral loads with far less displacements.

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CHAPTER 1

INTRODUCTION

1.1 General:

There are 1500 billion bricks manufactured annually, with 90% of this quantity manufactured from within our global district. Out of this 90%, Pakistan has the third biggest share in the manufacturing of bricks. Masonry structures account for 62.38% (Sarosh Lodhi 2013) of the total built environment of Pakistan. This dependence on masonry structures can be associated to the fact that bricks are cheaply available and are of good quality due to availability of good quality of clay in abundance in the plains of Punjab and interior Sindh. The bricks available in the market mostly have a standard shape and size, 4.5”x 9”x 3”. Brick in Pakistan are being manufactured in kilns which follow the process of burning fuel which produce harmful by-products in gaseous form, emitted in the atmosphere, mainly carbon dioxide and black carbon. One of the biggest challenges our world faces today is the deteriorating atmosphere, which has an adverse effect on our ecology. Brick manufacturing process is responsible for the high-level emissions of carbon dioxide and black carbon in our environment and has been linked to major health problems. Brick manufacture has a 2.7% share of global Carbon Dioxide emission and 20% share in the emission of Black Carbon globally. This also contributes to the rising global temperatures and recession of polar ice. In a holistic sense, it has a high share in the drive towards the climate change. This study proposes to eliminate the burning process altogether and provide a suitable alternative mechanism for the manufacturing of brick.

The interlocking mechanism introduced provides a lock and key system between the successive layers. This would hold the bricks in place and provide a higher lateral resistance during dynamic loading. Hollow shear keys give the provision of using steel reinforcement or grouting for better interlocking and resistance to lateral and dynamic loading. We aimed to enhance the tensile strength of the bricks so that they perform better in dynamic loading conditions. Records show that conventional bricks have not performed well during earthquakes.

Furthermore, masonry structures have shown to behave poorly during earthquakes. This is because bricks do not have strong resistance to dynamic loads. Therefore, for a country like Pakistan, it is pertinent to come up with a cost-effective solution that would make the manufacturing process environmentally friendly and make masonry structure sturdy and strong; statically and dynamically.

Concept of Self-healing was taken up to make the structure more durable. It is pertinent to note that masonry structures are susceptible to cracks during adverse conditions. One of the factors behind going ahead with this project was to develop a mechanism that would increase the resilience of masonry structures. One way of achieving that goal was to introduce the concept of self-healing. This concept has been applied to various sectors within the civil engineering materials and so we aimed to introduce it here. Various regions based on the bacteria content present in the soil were investigated and the one with the most suitable bacteria content was selected; based on a comparison made between their precipitation potential (healing of cracks).

After getting the results of the laboratory tests, we moved on the numerical modeling phase of our research. We performed the numerical modelling on the Abaqus. We opted for the micro-modelling set-up since that resulted in a more detail-oriented model.

Moving on, due to the unprecedented situational constraint, we could not perform all the proposed laboratory tests, our efforts in executing some of the tasks were hindered. Numerical modeling of the brick and its comparison with the conventional brick were carried out with the limited data available. A comparative study was carried out between the conventional and proposed brick.

1.2 Problem Statement:

According to Pakistan Bureau of Statistics there are a total 19211738 housing units constructed in Pakistan. As of 2018, there are over 7000 kilns in Pakistan which manufacture 25000billion bricks per annum. It is estimated that over 75000 ton of wood and 3120 ton of coal were burnt for brick manufacturing (Turpak 1991). It evident that the manufacturing of conventional bricks is drastically degrading our environment. In 2018 and 2019, Punjab Government decided to shut down all the kilns during the months

October and November to curb the menace of smog which is caused by the pollutants densifying in the air. This had a direct impact on the construction industry.

Conventional bricks behave unstably during earthquakes which is an added danger to the neighboring structures and the people living in them, especially in Pakistan where the residential areas are densely populated. This can be attributed to masonry's weak resistance to shear, which can either cause sliding or diagonal shear failure. history has shown that these structures would get damaged or in worst cases collapse during out of the ordinary circumstances.

This research will development mechanisms and alternatives for existing materials and practices in order to bring an improvement to the structural integrity of masonry structures.

1.3 Research Objectives:

This research aims to find a solution that would cater to the mentioned drawbacks along the lines of making that solution sustainable and adaptable to the current practices being followed here. We aim to come about a solution which is economical, environmentally friendly and convenient for transitioning into for the stakeholders already working in the sector, directly and indirectly.

1.4 Scope and Limitation:

This research started with literature review. From there we developed the composition, shape and dimensions of the bricks on which our test specimen based. From the literature review we also developed a recipe that would activate the bacteria present in the soil.

The next phase comprised of getting the samples prepared. For that we had a customized mold built suitable for the shape and dimensions selected. After getting the mold, we began with our casting and sample preparation. This process included mixing of the constituents, casting and then curing. It was during this phase that COVID-19 outbreak occurred, and the country went into a state of lockdown. Even though the university campus remained closed for physical academic activities, we were in contact with the department offices and we had requested them to perform the test on our behalf.

Upon the outbreak, we revised our scope and we included numerical modelling in the successive phase. This phase was executed while in lockdown. Abaqus software for structural modeling was used.

Another limitation included casting of sample using Compression Testing Machine instead of a hydraulic press with the custom mold. If this facility were made available, our time constraint would have been countered.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The literature review for the research is consisted of four parts. The selection of shape, selection of the materials used, the techniques to stabilize the material, to govern the tests on them and numerical analysis techniques. Materials used were soil, cement, fly ash, water, urea, calcium chloride and LB media. The mixture had to be stabilized chemically and mechanically. Then the mechanical tests were performed on the samples which would give an idea about whether the samples produced lived up to the standards or not. And then the numerical analysis was performed using the results obtained from mechanical tests.

"The previous researches done by people have pose certain advantages of compressed stabilized earth bricks over conventional masonry. They provide compressive strengths comparable to fired clay bricks, durability and thermal conductivity values are within appropriate ranges. They provide ecofriendly and cost-effective solutions to the low or mid income houses. Although the economy is a greater influencing factor here.

The thermal conductivity values are within the acceptable range, they are almost as durable as normal masonry, the compressive strength values are also comparable to their burnt brick counterparts" [1]

2.2 Burnt Bricks

Burnt bricks are often known as Fired Bricks as well. These bricks are baked in furnace kilns which alter their properties altogether.

2.2.1 Production of burnt bricks

Following process is involved while manufacturing fired bricks:

- Preparation of brick earth
- Molding

- Sun drying
- Kiln burning

2.2.1.1 Preparation of brick earth

First, a suitable site is selected where clay soil is found in abundance. Then after site selection, un-soiling of the site is done by eradication of weeds and unwanted vegetation. Once the site is clear of undesired items, then excavation is conducted. Heaps of excavated soils are left in open air for one month of oxidation and excessive salts are removed by rain action.

After this sandy earth and calcareous earth are mixed in right dry proportions and calculated amount of water is added to facilitate the chemical reactions. After mixing, tempering is done by kneading the soil mix manually or by a pug mill. This is done in order to improve plasticity and increase homogeneity.

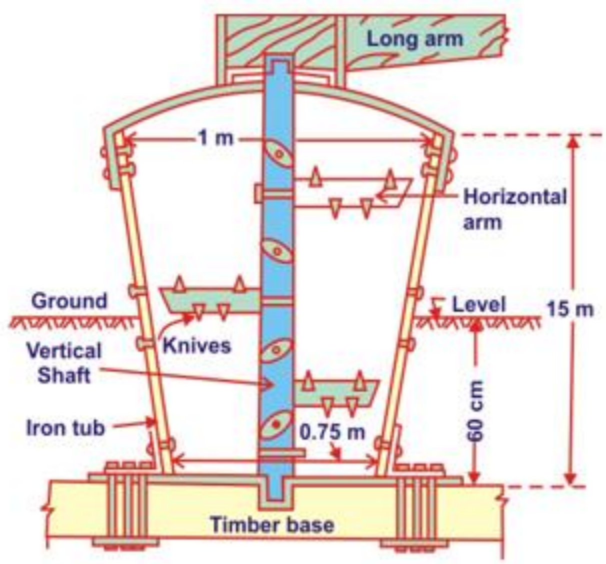


Figure 1. A typical Pug mill.

2.2.1.2 Molding

Molding is done to make the desired shape of brick. A dye or a mold machine is used for this purpose. There are two types of molding:

- Hand molding
- Machine molding

Hand molding is a manual brick shaping technique. It comprises of simple handy tools such as a simple brick mold, rammer and other compressive and shaping tools. It further comprises of ground molding and table molding. In ground molding, brick is shaped using sand and no frog is made on the brick top surface.

In table molding, bricks are molded on stock boards and frogs are impregnated on the brick top surface.

Machine molding, as the name suggests implies the usage of automated machinery for brick molding. It further comprises of plastic or stiff mud process and dry press method.

In stiff mud process, water is added in the soil mix. This moist soil mix is then mixed and further treated in a machine called Pug mill. Addition of water makes the mix more plastic and workable. The raw material is mixed in the mixing chamber of the pug mill. The mixed soil mix is then forced to move out of a mold or a dye of desired shape. The material is continuous just like a long ribbon. This continuous "ribbon" is cut with blade or cutter at desired lengths.

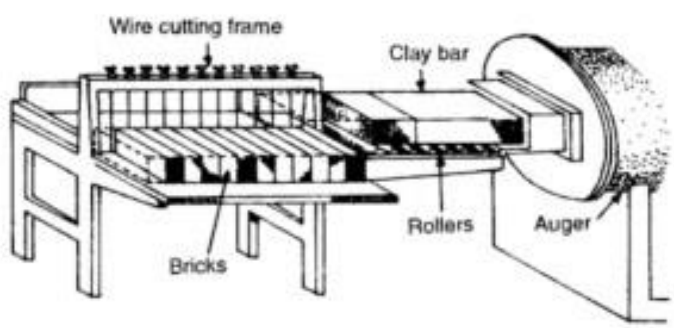


Figure 2. Machine molding

The dry press process is a process in which the soil is mixed with a limited amount of water as compared with the stiff mud process. The mix is then filled in steel molds under the application of high stress. The manufacturing cost of this technique is high, so it is somehow uneconomical.

2.2.1.3 Sun drying

After the molding of the bricks, the bricks are sun dried in an open ground to make the absorbed water evaporated as much as possible. The bricks can also be put near the outer surface of the kiln to provide adequate heat to moist bricks which helps in speedy initial moisture evaporation.

Figure 3. Sun drying

2.2.1.4 Kiln Baking

The temperature inside the furnace kiln lies in the range of 1200-1400 °C. Following stages are followed while burning the bricks in the kiln:

- Dehydration (450-650°C). In this phase the water from the pores is moved out.
- Oxidation (650-900°C). In this phase carbon is eliminated. Ferrous iron is converted or oxidized to ferric compounds. Sulfur is eliminated.
- Vitrification (900-1200°C). In this phase the soil mass is converted into crystalline substance.

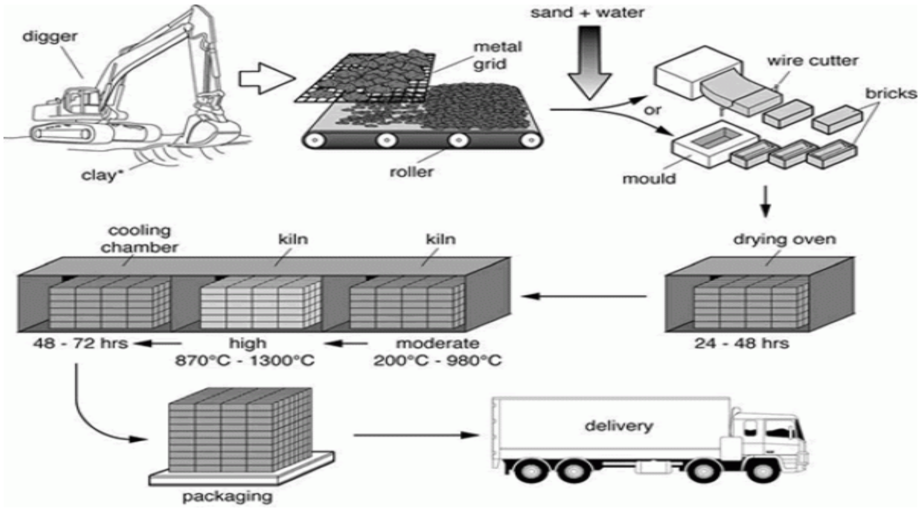


Figure 4. Fire process

2.3 Compressed stabilized earth blocks (CSEBs)

A lot of research has been conducted on the production of compressed earth blocks. Compressed earth blocks research was initiated in order to come up with an economic and sustainable alternate to conventional burnt bricks and other construction materials such as concrete/ cement blocks.

2.3.1 Historical background

If the blocks occupy less than 25% of the surface area then the blocks are termed as "perforated blocks". The history of the interlocking compressed blocks dates to 1950s. The first compressed earth block was made in 1950 using the manual press machine named "CINVA RAM". It was made by an engineer from Chile, Engr. Raul Ramirez. With the passage of time and advancement in science and technology, manual presses were replaced with semi auto presses and fully automated brick pressing machine.

CINVA RAM is a lever operated manual press system. The efficiency of this press is to make one block at one time.

In 1980s, soil stabilization techniques were put into application for enhanced strength and durability characteristics of compressed earth blocks. Cement was used for stabilization purposes.

Interlocks were developed in order to increase the shear strength of brick masonry wall. Initially, the depth of the shear keys was kept as low as 0.25 in to 0.5 in.

2.3.2 Shape and geometry of Bricks

Various shapes, dimensions and geometry of bricks and shear keys have been produced and tested in various countries [2]. The shapes which we came up while doing literature study can be divided into two categories.

- Shapes with restricted horizontal and transverse movements
- Shapes with restricted transverse and free horizontal movement

2.3.2.1 Shapes with restricted horizontal and transverse movements

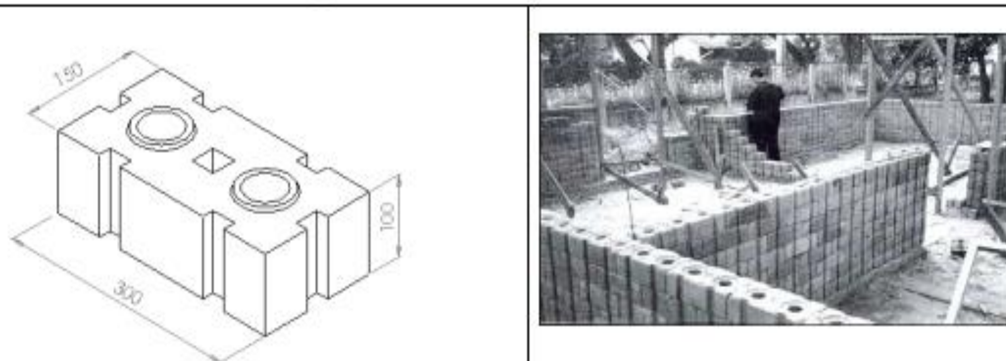
Following paragraphs will give an overview of past brick shapes that offered resistance against horizontal and transverse movements.

2.3.2.1.1 Thai shape blocks

It was developed in the early 1980s in by AIT in Bangkok. They are hollow blocks that can entertain grout and reinforcement for resistance towards out of plane bending.

Grout keys are provided on either sides of the block and through the brick in the form of shear keys as well. The casting of this brick would be perhaps a little difficult, for it requires more delicate mold to ensure proper formation of side grout keys.

The blocks are somehow light weight as well, for they have perforations throughout the brick and side perforations in the form of grout keys are also available, which reduced the weight of the block. This weight reducing eventually makes the handling and usage easy and efficient.



a) Brick length = 300mm, width = 150mm and height = 100mm

b) Wall thickness = 150mm, course height = 100mm

Figure 5. Thai interlocking brick

2.3.2.1.2 Bamba System

The design of this system is quite complex. It comprises of perforations, depressions and protrusions. The block has been designed in such a manner that what is projected in the top surface is totally reversed in the bottom surface to ensure perfect interlock. The accuracy of the bamba brick depends upon:

- Type of soil
- Accuracy of molds and casting techniques
- Proper quantity measures (design mix)
- Accurate and up to standard production and curing

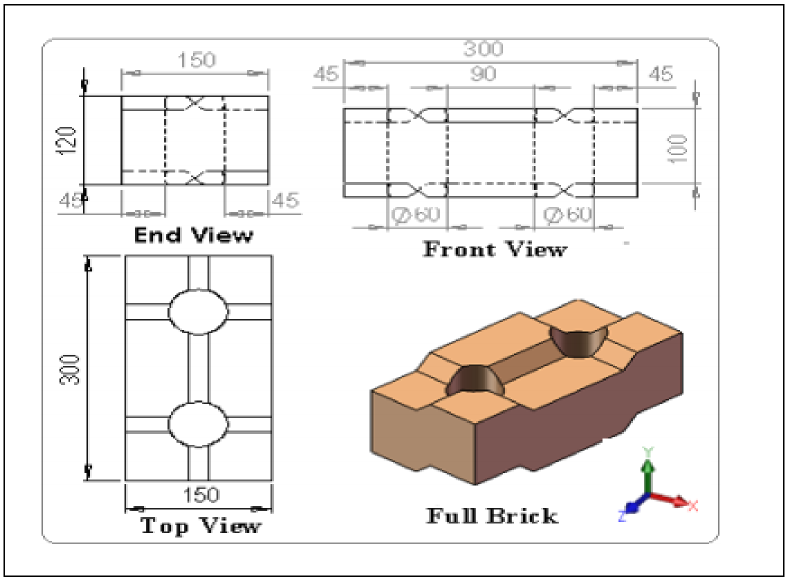


Figure 6. Interlocking model: BAMBA

The system is available in different type of blocks as per utility that is:

- Three quarter at left or three quarter at right
- Beam channel
- Base brick
- Half brick

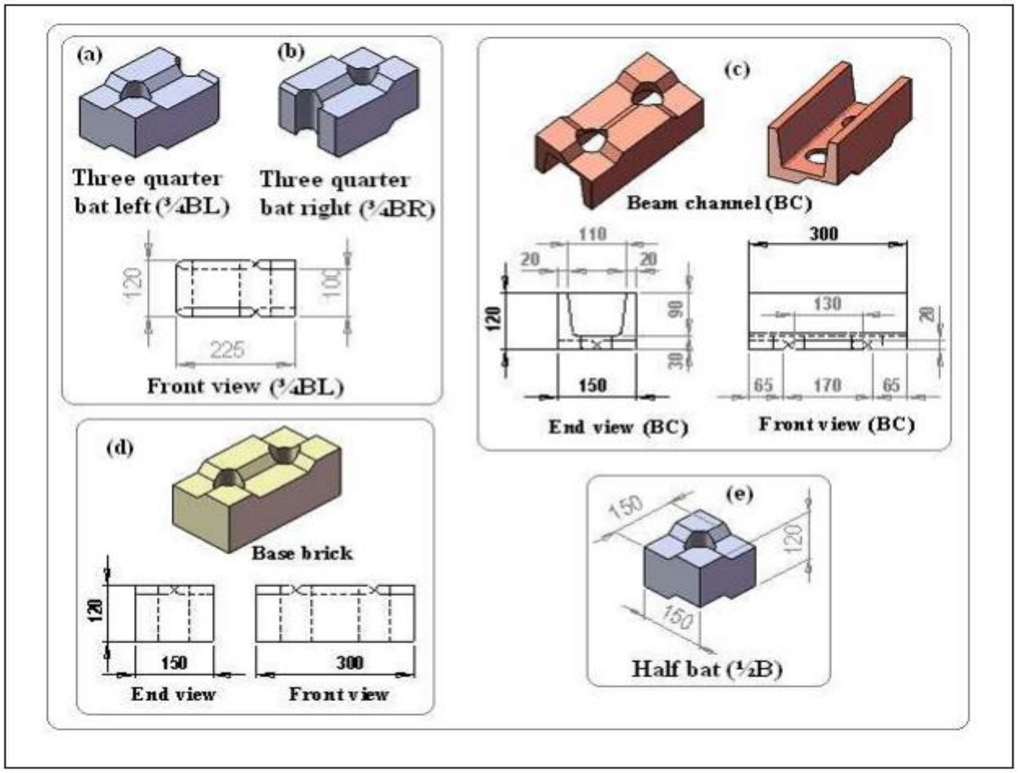


Figure 7. BAMBA interlocking models available in the market

The challenge in producing these bricks is the difficulty in casting such bricks. These bricks demand intense accuracy in lock and key mechanism. The intrusions and protrusions must be made so accurate that they should perfectly fit into one another. One cannot assure perfect or accurate machine precision while casting, so it would not be that much successful in market.

In developing countries where accuracy and precision cannot be guaranteed, this system is not preferred.

2.3.2.1.3 Auram System (India)

It has similarities with the Bamba and Thai systems. It is more or like like a lego block having small thickness protrusions or shear keys. It also has a central grout-reinforcing all through cavity. This cavity can be used to insert grout and reinforcement in the brick wall and make it resist against out of plane bending.

Auram block is heavier than other types of blocks as its weight lies in the range of 9Kg to 10Kg. This is the disadvantage of this type of block system. On one hand the block is dense and solid while on the other hand this block becomes difficult to use and handle because of its massive weight.

So, it is not recommended.

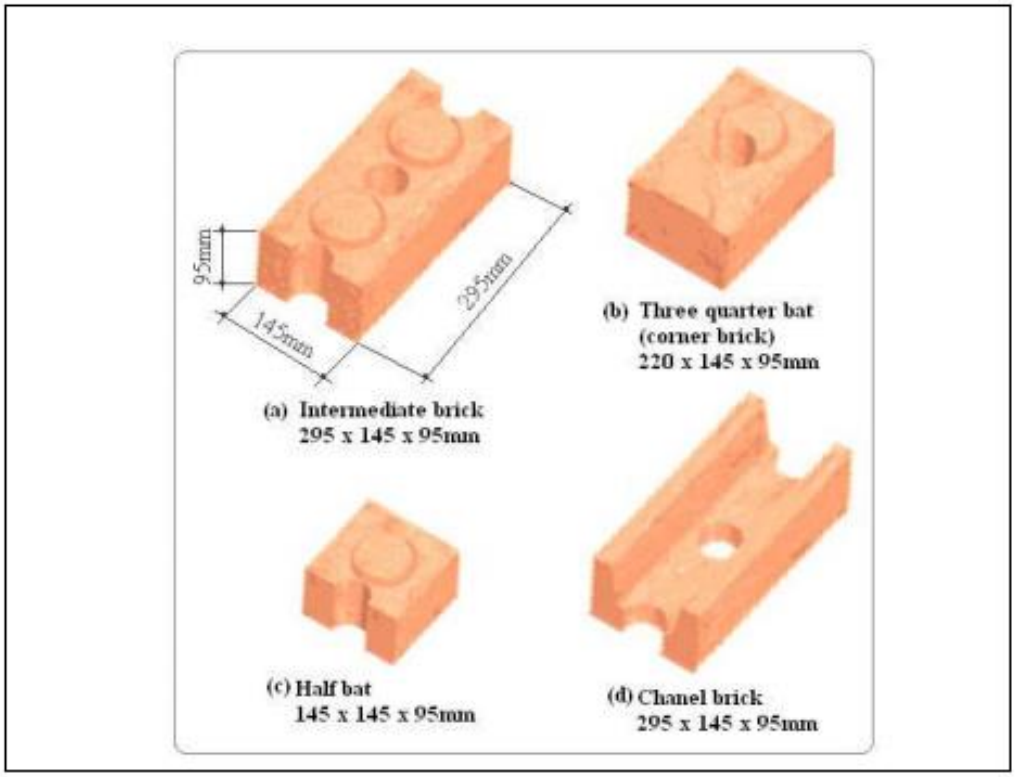


Figure 8. Aurum interlocking bricks

2.3.2.1.4 Tanzanian Interlocking system

Tanzanian Interlocking block (TIB) was made in advancement of the Bamba system. It was casted on the CINVA RAM mechanical press machine. It has similar features as compared to Bamba and the Auram block system. The shear keys or the interlock is in the shape of pyramid. The interlock is hollow through the brick to provide cavity for grout and reinforcement.

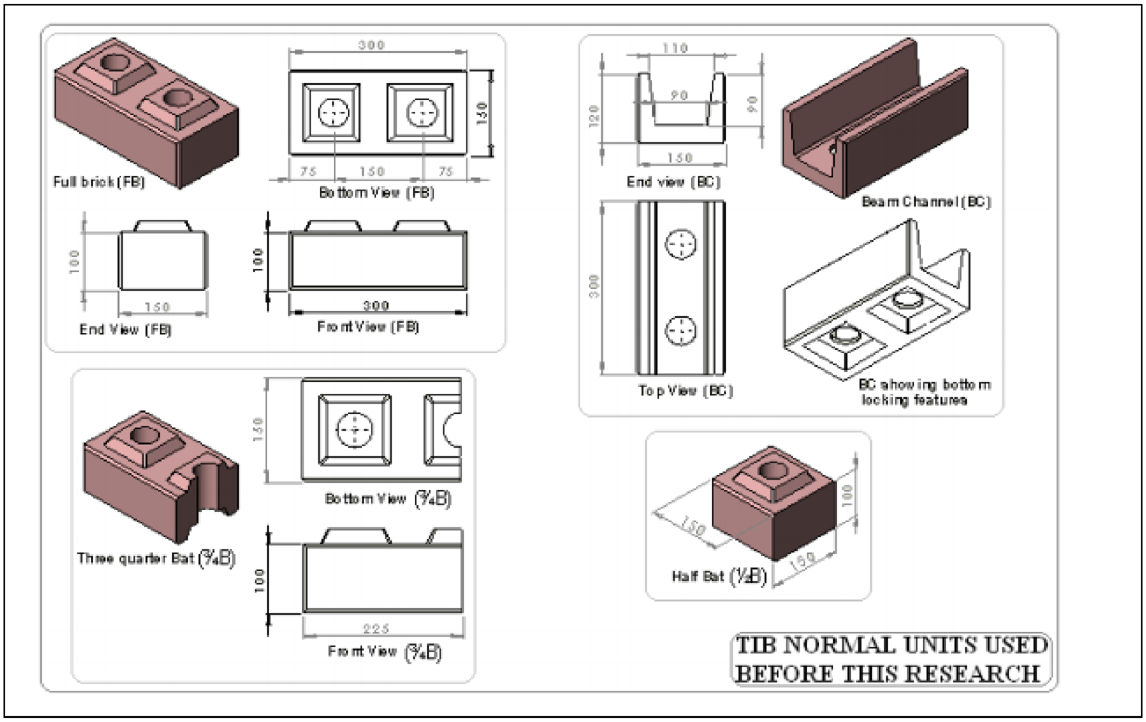


Figure 9. Tanzanian interlocking bricks

The dimensions of the brick are 300 x 150 x 100 mm. The size of the TIB brick is the same as that of Bamba and Auram system. As per the utility, TIB can be shaped into Full brick, three quarter bats, half brick and the beam channel.

This brick can result in thicker walls and hence resulting in greater self-load of the structure.

The shear keys are of sharp edges so it can be easily destroyed during transportation.

2.3.2.2 Shapes with restricted transverse and free horizontal movements

Following paragraphs will give an overview of past brick shapes that offered resistance against transverse movements.

- Solbric system
- Hydraform system

As these shapes provide only transverse restriction, but we require restriction in both direction and out final shape is also based upon those shapes.

2.3.3 Geometry conclusions

As per the shapes discussed in the above paragraphs, we came up with a new shape.

This shape included symmetry in geometry and shape of the brick/block from every side and angle.

In order to make it possible to ensure that the bricks in stack fit perfectly in each other, the shear keys and shear key holes should be located at equal distances from the central axis. And also, a hole was provided in both shear keys to provide reinforcement.

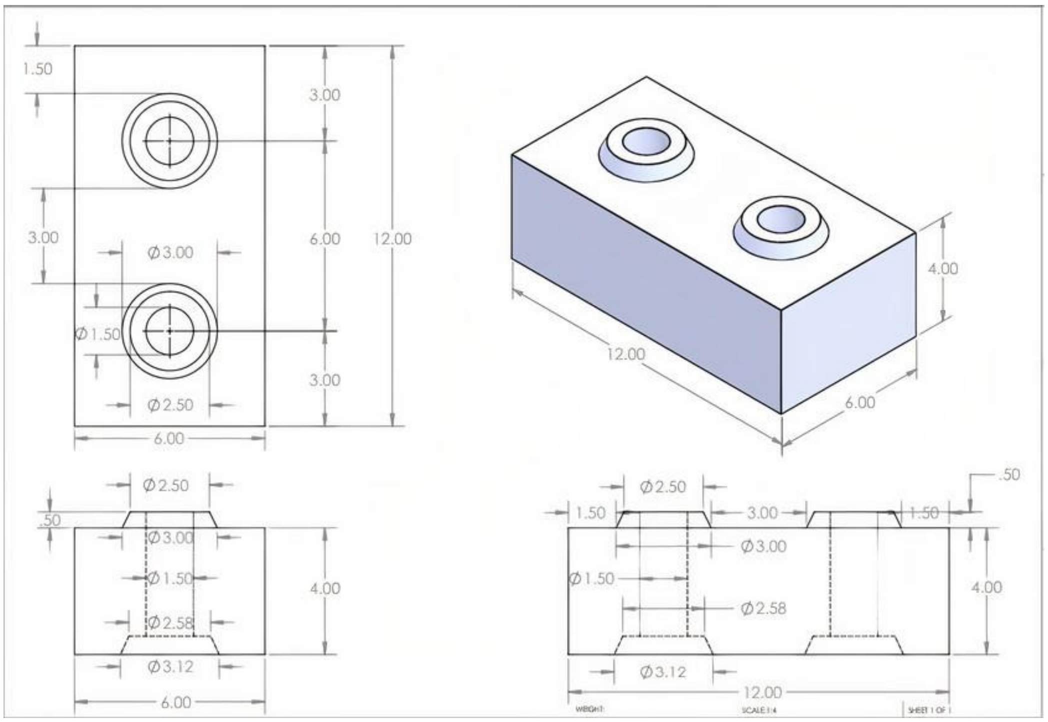


Figure 10. Plan of ICEB

2.4 Unfired Bricks/unbaked bricks

These bricks do not employ the usage of brick kilns. They are either manufactured using sun drying techniques or either using soil stabilizing techniques to enhance the bonding of the soil particles to achieve higher or equivalent strength. These bricks are more ecofriendly and environment protective because of low or minimal carbon emissions [8]. The soil stabilizing techniques will be discussed in detail in the coming paragraphs.

2.5 Materials

2.5.2 Raw materials for the brick

2.5.2.1 Soil

For the purpose of making compressed earth bricks, low plastic clay was used as being shown by Zahid Hussain[3]. Soil characteristics given by him are shown below

- Liquid Limit 28.85
- Plastic Limit 16.38
- Plasticity Index 12.5
- Maximum dry density 122.5
- Soil pH 9.7
- Percentage passing sieve no. 200
- Optimum moisture content 13.7 psi
- Remolded Unconfined compression strength 259 psi

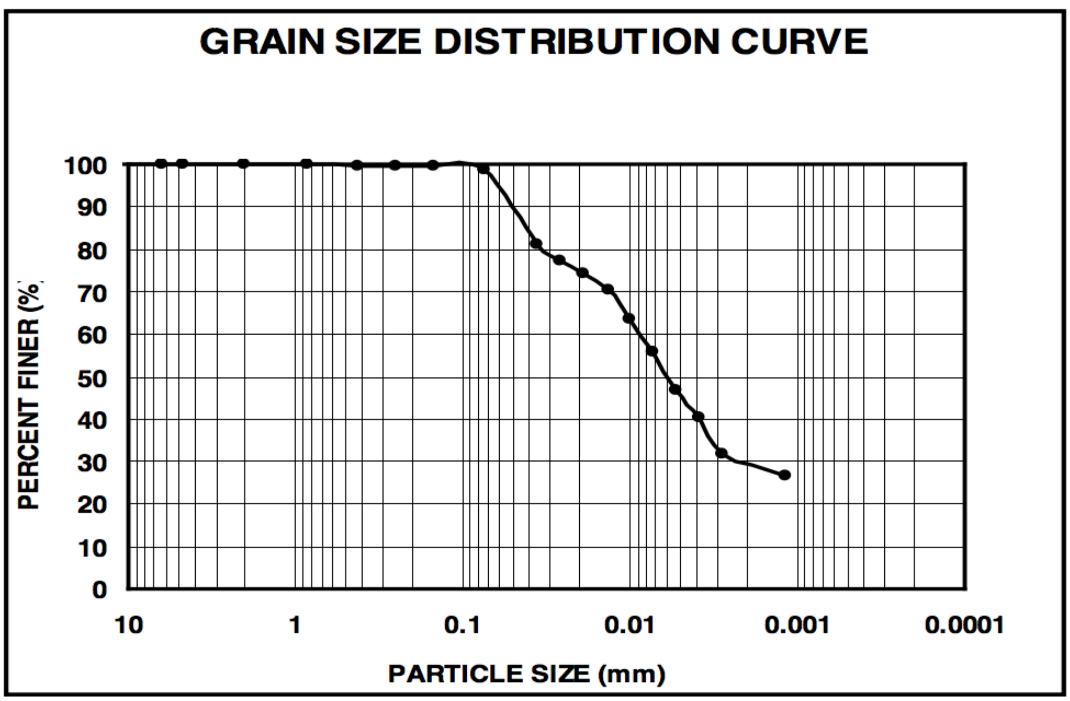


Figure 11. Grain size distribution of Kheshki soil

2.5.2.2 Fly ash

Fly ash is the by-product of coal combustion and in recent years number of coal power plant in Pakistan has increased significantly. So, Pakistan will be producing a huge quantity of fly ash from the power plants. And fly ash has been frequently used in concrete as alternative of Portland Cement. But it has rarely been used for bricks. Joshi and Lohtia [4] reported some of the potential benefits of fly ash for use in clay brick industry which includes use as a fuel because unburnt carbon is present in fly ash the similarity in composition with clay, can replace clay because fly ash has some similarity in composition with clay, due to light weight of fly ash weight of the final product can be reduced, due to the chemical compatibility of fly ash with clays and its inert nature it can reduce shrinkage. Fly ash can also contribute to improvement of compressive strength and increase in frost resistant of bricks. As Pakistan produces 3.5 billion bricks per year, so due to such huge demand, the availability of suitable soil can be reduced. So, it is necessary to find alternate materials which have the potential to replace soil and make buildings more energy efficient[5]. Fly ash has the potential to replace the clay upto 40% in bricks[4]. So, it provides us a huge opportunity to recycle the fly ash in brick industry and minimize impact to the environment. Chemical composition of Fly ash is given at table beneath.

Sr.	Component	Chemical Formulae	Percentage
1	Silica	Sio2	47.6
2	Aluminum Oxide	Al2O3	26.2
3	Ferric Oxide	Fe2O3	9.4
4	Calcium Oxide	CaO	2.4
5	Magnesium oxide	MgO	1.42
6	Sulphur trioxide	SO3	0.86
7	Sodium Oxide	Na2O3	1.1
8	Potassium oxide	K2O	3.02
9	Moisture content	-	-
10	Lost on ignition	-	-

Table 1. Chemical composition of Fly Ash

2.5.2.3 Stabilizer

Portland Cement

For binding purposes, ordinary Portland cement was used. The basic cement properties are described in the paragraphs below. Cement primarily comprises of Lime i.e. Silica (SiO_2) and Calcium Oxide (CaO). These components react in the mix when they are hydrated. Combinations of (C3S) tri-calcium silicate and (C2S) di-calcium silicate are formed as a result of this reaction (Neville, 1995). 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. The reaction among cement and clay is believed to be a three stage mechanism; thus, there is both a long term and a momentary impact. Cement additionally bonds with the sandy skeleton of the soil in the traditional manner. The cement doesn't bond with the all the particles of soil yet assists with framing a stable matrix all through. The impact of adding cement is to improve the dry as well as the wet compressive strength, increment protection from erosion and abrasion. To accomplish great outcomes, it is significant that the cement is well blended in with the soil and bricks are cured appropriately. Chemical composition of Portland concrete is given at table beneath.

Sr.	Component	Chemical formulae	Percentage
1	Silica	Sio2	20-24
2	Aluminum Oxide	Al_2O_3	4-8
3	Ferric Oxide	Fe_2O_3	2-5
4	Calcium Oxide	CaO	60-65
5	Magnesium oxide	MgO	0-5
6	Sulphur trioxide	SO_3	1-3
7	Sodium Oxide	Na_2O	-
8	Potassium oxide	K_2O	-
9	Moisture content	-	-
10	Lost on ignition	-	0.5-3

Table 2. Chemical composition of Portland cement

2.6 Composition

The purpose of this research is to investigate the mechanical and seismic performance of brick made with clay and pulverized fly ash (PFA) and Portland cement as stabilizer. The composition we used soil: fly ash = 70:30 and with 10% stabilizer. This study aims to check the performance of fly ash as replacement of soil as used by [R. Mohamad Nidzam et al.][6]. The previous studies have shown significant benefits of using fly ash as cement replacement.

2.6.1 Water Absorption vs Composition

The use of fly ash as replacement of soil along with cement stabilizer showed significant reduction in water absorption.

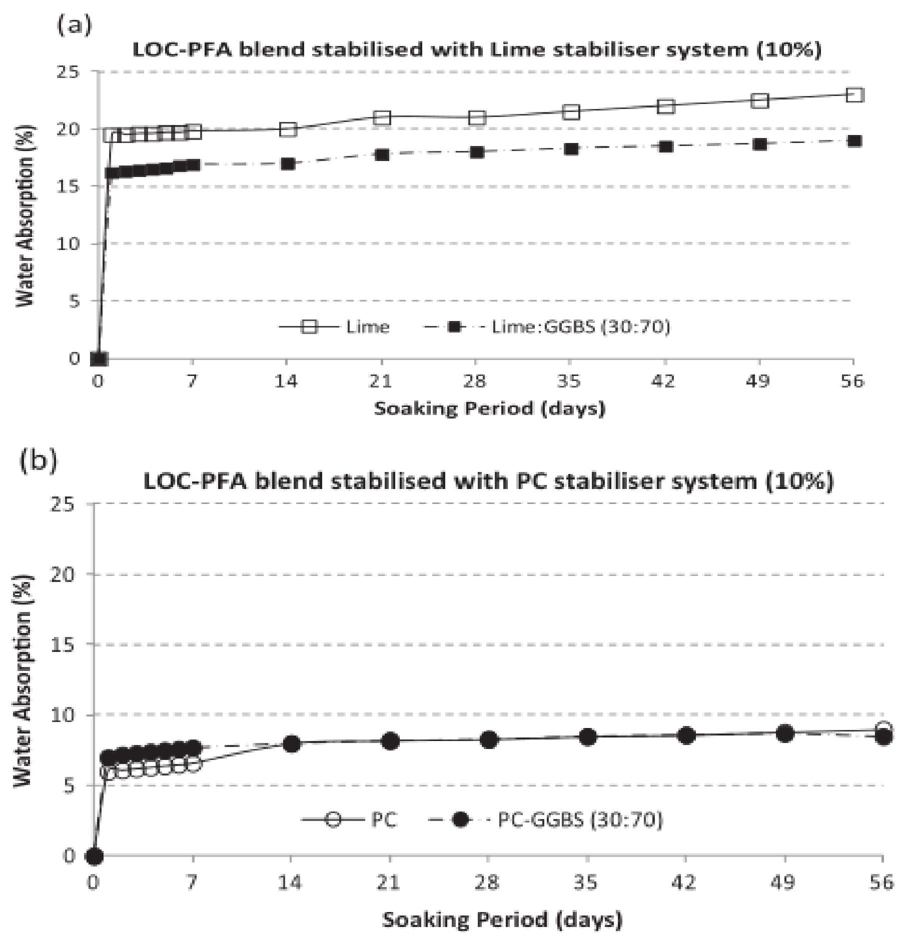


Figure 12. Water absorption of CSEB's stabilized with (a) Lime and (b) PC.

2.7 MICP in ICEB

As it is known, that one of the biggest problems in Interlocked compressed earth bricks is their durability. As their water absorption is much more than the fired bricks. So, the moisture is very harmful for ICEB. And the most useful technique to cater for this problem is Microbially induced calcite precipitation.

2.7.1 Microbially induced calcite precipitation (MICP)

MICP is the procedure in which microorganisms especially bacteria are enriched in the soil and as a part of their essential metabolic activities they deposit calcite crystals [7]. Growth media and essential nutrients are provided for enrichment. And heterogeneous on the bacterial cell walls leads to precipitation of calcite crystals. When these crystals are super saturated, they precipitate inside pore spaces. These calcium chloride crystals act a cloggers in building materials and help in filling the pore spaces and reduction of permeability.

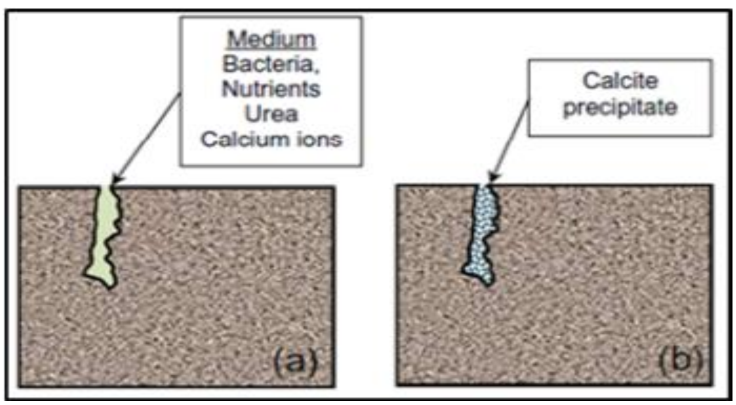


Figure 13. Process of MICP: (a) medium filling the surface pore spaces; (b) calcite precipitation occurs and seals off the pore

2.7.2 Use of bacteria for calcite precipitation

One of the biggest problems of the ICEB is their durability and long-term stability. E.g. Water absorption of these bricks is more than those of conventional bricks. So, one of the possible solutions to overcome these problems can be to use inherent stability of soil. And MICP can be used for inherent stability. Table 2.1 shows summary of previous researches which shows improvement in the water absorption level and durability of bricks and concrete. From the Table 2.1, its can be concluded that improvement in water absorption level and increase in durability for bricks and concrete can be achieved using bacteria[8].

Therefore, it very well may be inferred that by utilizing the microorganisms, it can assist with improving the durability of bricks. Implying that, all the microbes utilized by the past researchers figure out how to experience MICP procedure to deliver calcite precipitation. At that point the calcite will act as protective film covering the surface of bricks which filled all the pore with calcite and forestalled entrance of water. Because of precipitation, the pore connectivity and porosity will be diminished. Subsequently it will lessen the pace of water assimilation in bricks and durability problem can be brought in reasonable limit [9].

Researcher	Type of bacteria	Findings	Remark
Shahrood et al, 2015 *"Surface treatment of concrete bricks using calcium carbonate Precipitation"*[22]	-Dimethyl carbonate (DMC)	-water absorption -compressive strength	-the water absorption of concrete bricks significantly reduce and the compressive strength significantly increase.
D. Bernardi et al, 2014 *"Bio-Bricks: Biologically cemented sandstone bricks"*[23]	-Sporosarcina paseurii	-void ratio and dry density -compressive strength	-the void ratio with MICP treatment shows decreasing in results compared to control specimen.
Abhjit et al, 2013 *"Bacterial Calcification for Enhancing Performance of Low Embodied Energy Soil-Cement Bricks"*[24]	- Bacillus megaterium	-water absorption test -wet compressive strength -porosimetry analysis	-the calcite crystal act as biosealant by filling the pores which leads to reduction in water absorption, porosity, permeability and enhance the strength of the bricks.
Navdeep et al, 2012 *"Improvement in strength properties of ash bricks by bacterial calcite"*[21]	-Bacillus megaterium	-microbiological sand plugging -water absorption and initial rate of water absorption -compressive strength	-the bacteria used was found to be very effective in calcite deposition on the surface of bricks which lead to reduction in permeability, decrease in water absorption leading to enhanced its durability.
Willem et al, 2008 *"Bacterial carbonate precipitation improves the durability of cementitious materials"*[25]	-B. sphaericus	-absorption of bacteria -precipitation of carbonate crystal -water absorption	-there are differences between mortar cubes treated with bacteria and a calcium which show less water absorption compared to untreated specimens.

Figure 14. Summary of bacteria from research

2.7.3 Types of Bacteria based upon source:

Two types of bacteria can be used for MICP process to improve durability based upon the source[10].

1. Exogenous Bacteria

2. Indigenous Bacteria

2.7.3.1 Exogenous Bacteria:

Exo means external. These are the bacteria which are extracted from an external source e.g. soil. Then, they are cultured in suitable growth media and are provided with essential nutrients and reagents for their enrichment. Then they are introduced in the desired soil sample.

2.7.3.2 Indigenous Bacteria:

It is clear from the name that Indigenous bacteria are those bacteria which are already present (inhibited) in the soil sample which is to be used for experimentation and testing. These bacteria are extracted from a soil sample first and then are cultured in a suitable growth media and then are introduced in the same soil sample from which they were extracted along with essential nutrients.

Indigenous bacteria are preferred for use than exogenous bacteria because of the below mentioned factors:

- pH
- Competing bacteria
- Temperature
- Geometric similarity of bacteria
- Fixation and dispersion of bacteria

As Indigenous bacteria are those which are already present in the soil, the environmental conditions for them in that soil are always feasible and they don't need to adjust to it. Conditions like pH, water content, temperature and so on are not an issue for them. The conditions would clearly be favorable for them.

On the other side, exogenous bacteria since originate from an outside source into the new condition, the conditions might or might not possibly be feasible for them. So also, when exogenous bacteria are included into the soil, they need to rival other effectively present bacteria for their sustenance, development and endurance. This renders the odds of their endurance exceptionally low.

So, for our samples we selected indigenous method because of its benefits explained above.

We did not extract bacteria out of soil rather than that we provided growth media and essential nutrient during the production of the brick samples. For the growth media, we used LB broth media and for nutrients we used Urea and CaCO3.

2.8 Finite element modeling of masonry wall

As we know that masonry is stronger in compression but when the masonry structures are subjected to earthquake, there response is not good and biggest damage comes from masonry structures. Various researches have been done to check the behavior of masonry under lateral load. Siddiq (2004) examined the walls with beam column to find out an acceptable load by the wall under lateral load. Satyarno (2008) applied static and cyclic load to masonry and obtained strength of masonry against those loads.

The Finite Element analysis has been broadly used by researchers to analyze Masonry structures, such as Stavridis and Shing (2010) [11] used Finite Element method to determine the behavior of walls made of concrete bricks.

ABAQUS software has been widely used for finite Element modeling and analysis on the Masonry wall. Chen and Zhang (2014) simulated damage behavior of Masonry walls using the Abaqus software. Moghadam (2010) [12] also modelled the Masonry walls using the ABAQUS software.

2.8.1 Modelling techniques used in masonry building elements

Modelling of concrete buildings using finite element method provides successful results. But the same cannot be stated for masonry buildings, where both the elements and the premises used in the modelling of masonry buildings are quite different. In masonry

buildings things are rather different. Modelling the load-bearing wall elements in the structural analysis of masonry buildings is extremely important when finite element

method is used. The solution time may be increased due to the large number of variables and large system rigidity matrix in finite element method which can be used in both

linear and nonlinear analyses. A very important step to overcome this problem was taken by Lourenço (1996) [13] who introduced the homogenization technique. Through homogenization the wall element composed of masonry units and mortar can be represented as a single material. In walls, which are probably the most important components of masonry buildings, the use of

masonry units such as stones, bricks and lightweight concrete blocks along with mortar has various structural characteristics which impedes modelling with the same type of finite element and homogenization. Thus, an acceptable and realistic modelling technique is necessary. Otherwise masonry units and mortar should be separately modelled. In this modelling masonry units and interfacial elements are separately modeled so the number of variables becomes very high (Ural 2009). For masonry modelling several techniques are used. We will discuss some of these techniques in details.

2.8.1.1 Macro modelling

The interaction between masonry units and mortar is generally neglected when the behavior of the whole building is studied. Such modelling is known as macro modelling (Fig. 1). In macro modelling the analyzed building is studied in partitions of a certain size. Each macro element is either a whole wall or a wall segment in cavity walls with openings. The model is not suitable for small details of the building or the elements. In modelling of masonry buildings some models that reduce the degree of freedom and the time used for calculation using macro elements for the analysis of the behavior of entire building were developed (Brencich and Caliò et al. 2012). Each macro element is either a wall or a wall fragment in cavity walls (Fig. 1(b)).

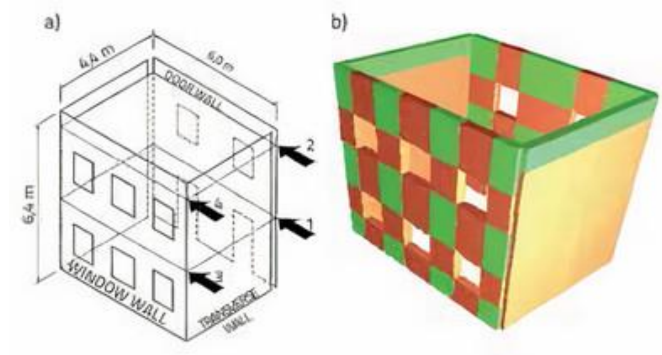


Fig.14. modelling with macro elements

2.8.1.2 Micro modelling

In micro modelling technique, masonry units and the joints and mortar are modelled separately. Interaction joining areas of these elements can be also included in the model. Although modeling of structures with micro modeling technique is a detailed and time taking process, but local behavior of the structures can be investigated wit this technique.

Especially Lourenço (1996) developed a numerical model for micro modelling during his doctoral studies where he uses shear, cracking and failure mechanisms together. Lourenço (1996) defines three methods for modelling masonry walls in his study: macro modelling (Fig. 2(c)), simplified micro modelling (Fig.2(b)) and detailed micro modelling (Fig. 2(a)).

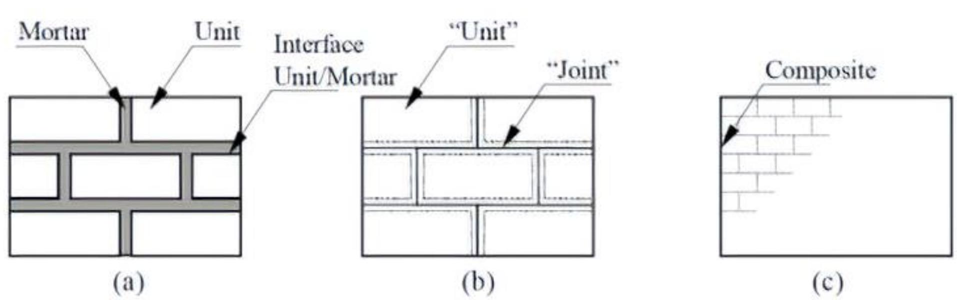


Figure 15. Masonry wall modelling

2.8.1.3 . Selection of modelling technique

Considering the used modelling technique, it might be asserted that macro modelling and equivalent frame modelling are used for modelling of the whole building while micro modelling is merely used for modelling a certain part of the building using present technological facilities. Hence micro modelling is used for modelling the structural elements of masonry buildings especially load-bearing walls.

It has been observed that detailed micro modelling technique is not commonly used in large systems although it is an efficient way for modelling realistic behaviors of masonry walls. Accordingly, research has concentrated on developing various modelling techniques aimed at providing faster solutions for large buildings in lower capacity computers. Simplified micro modelling technique is one of the mentioned methods (Ural 2009). In simplified micro modelling the sizes of the masonry units are enlarged by half the thickness of the mortar neglecting it and the masonry units are separated from each other with average interfacial lines. In detailed micro modelling all the mechanical

properties of bricks and mortar that make up the masonry wall are separately considered.

So, based upon above considerations we have selected simplified micro modelling approach because our brick includes shear key. So, mortar joints are not needed. Also, we have to check the response of shear key against the lateral load. So, we chose micro modelling technique.

The purpose of this part of research is to 1). Perform 3D modelling using ABAQUS.[14] 2). Find out the load vs displacement curve of the model made using ICEB and compare it with the curve of conventional bricks. And then finally compare the results with the results obtained from experimental testing.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

The standard method for manufacturing of interlocking compressed earth bricks is by using a Hydraulic Press machine. This is specially designed machine for manufacturing of compressed bricks in which the brick mix is added in a hopper which after pulverizing it sends it to the compression section where hydraulic force is applied to compress the material and then the brick is removed. But due to non-availability of this machine, we used another approach. A locally manufactured mold was used, in which mix was poured and then compressed in the compression testing machine in NICE Structure Lab.. The pressure on the mix was increased from zero to 1100 PSI. after manufacturing, bricks were placed for curing in air at room temperature and then tested at 7 days 14 days and 21 days intervals. Our original scope of testing involved extensive unit, prism and wallet level testing which was reduced only to unit testing because of COVID-19 situation. Other than this we also performed numerical modelling of our bricks using Abaqus software. The following schematics explain the manufacturing process of interlocking compressed earth ICEBs bricks from start till curing.

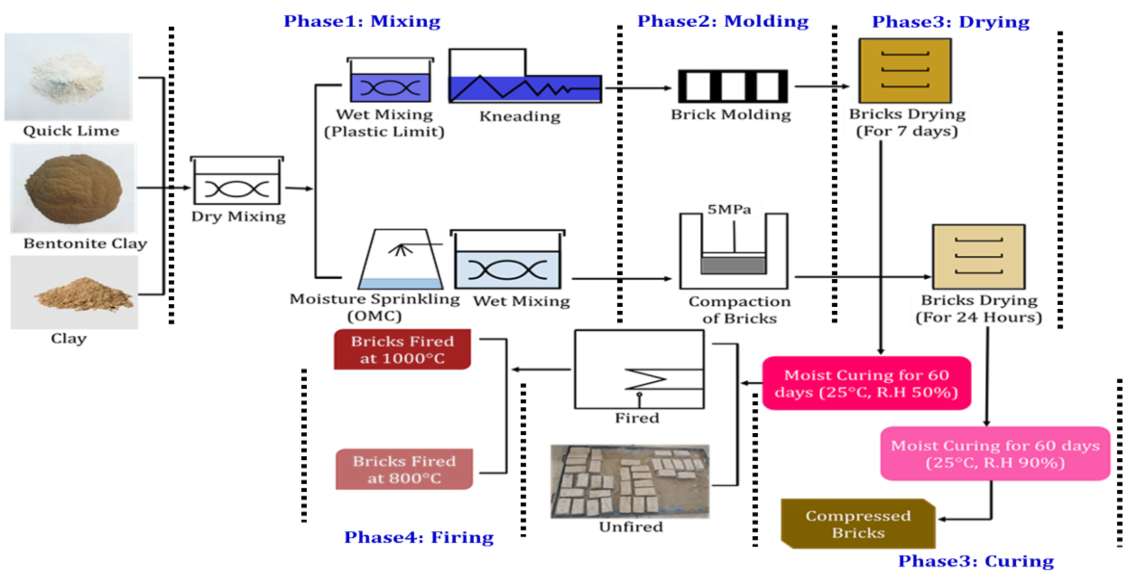


Figure 16. Brick Manufacturing Process

3.2 Methods and Procedures

Since our project includes material structural and numerical aspects, so first material related testing is explained. After that the structural portion comes and at the last, numerical modelling details are discussed in the following paragraphs.

3.3 Material Acquisition and Testing

Material selection and material acquisition was also one of the main parts of this research. In conventional bricks a mixture of clay and water is dried and then fired to get the durable bricks, but our aim was to achieve the durability and sustainability without burning bricks. So, stabilizer should play its role in keeping the bricks intact without the process of burning. Let us discuss both material selection and acquisition/procurement one by one.

3.3.1 Material selection

We can classify our material in two categories. First are those materials which were directly used for the formation of Compressed Earth Bricks and the second are those which were added for activating the indigenous bacteria of the soil and to produce calcite precipitation.

The main constituents of bricks were Soil, Cement, Fly ash and water. All of these are discussed in detail as under:

3.3.1.1 Soil

Soil is the material that is readily available all over the world. Term soil represents different materials with different properties and particle size. Soil is broadly classified as Gravel, Sand, Silt and Clay. All these have different particle size and properties. Apart from clay, silt, sand and gravel soil also contains organic matter and living organisms within it. Both chemical and mechanical properties of soil depend upon the composition of soil (%age of clay, silt, sand and gravel).

For the formation of Compressed Earth Bricks, it was made sure that soil extracted should have no organic content. There are four layers of soil:

1. Organic matter (Leaves etc.)

2. Topsoil (Decomposed Organic matter)
3. Subsoil (Sand, Silt and Clay)
4. Parent Rock (Gravel, Rock)

To get soil suitable for formation Structural compressed Earth Bricks a top 10-12 inches layer of soil was removed to reach to the subsoil level to extract soil containing only clay, silt and sand.

For finalizing the soil for our project, we collected samples from different regions of Pakistan which are Faisalabad, Multan, Bahawalpur, Gujrat, Gujranwala, Lahore, Islamabad, Peshawar, Karachi and Muzaffarabad. There were two main criteria based on which we were shortlisting soil samples. Those are:

1. Soil properties (Low plastic clay)
2. Indigenous bacteria present in soil and capability of soil for the formation of Calcite precipitates.

So, based on above two criteria we chose the soil from industrial area of Islamabad which was having good score for Calcite Precipitation among all soils from the different regions. High calcite precipitation was an indication that this soil contains more resilient indigenous bacteria which can survive in hard conditions.

After finalizing the soil all soil tests were performed on soil of Industrial area Islamabad. The results for the tests are as under:

3.3.1.1.1 Grain size Distribution (Sieve Analysis (ASTM D 422))

Figure 17. Sieves

Sieve Size	Passing %age
1/2"	-
3/8"	100
#4	100
#8	95
#16	95
#30	95
#50	95
#100	85
#200	78

Table 3. Grain Size Distribution for Soil

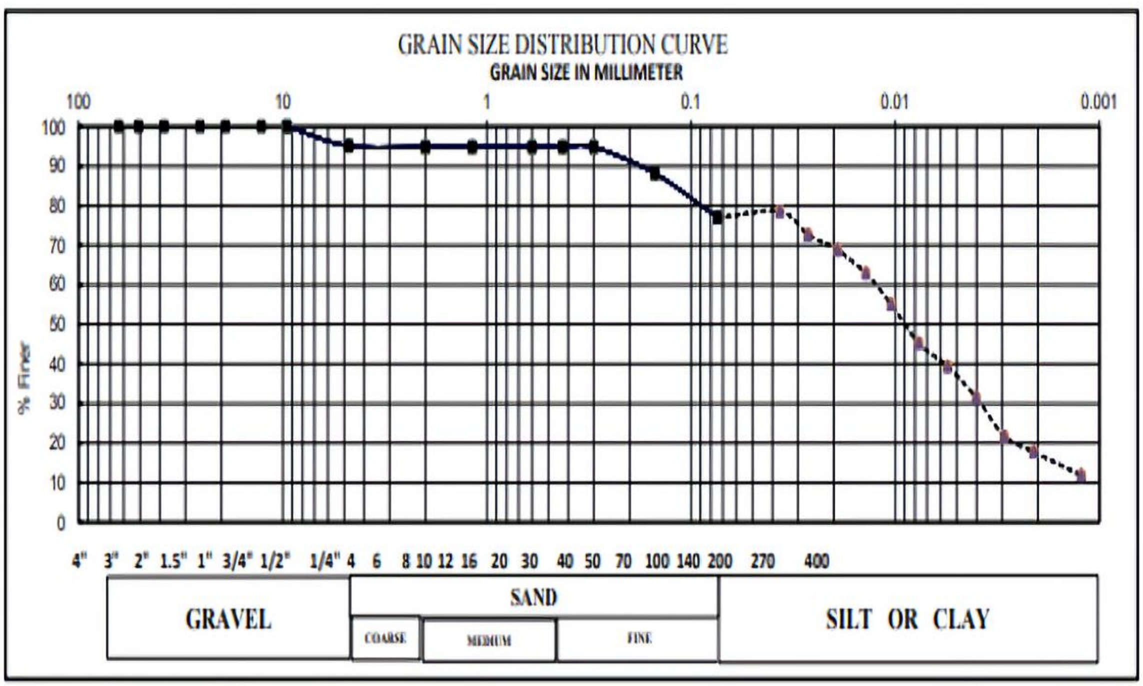


Figure 18. Grain Size Distribution Curve

3.3.1.1.2 ATTERBERG LIMITS (ASTM D 4318)

1. Liquid Limit

Figure 19. Casagrande Apparatus for Liquid Limit Test

No. of Blows (N)	18	27	34
Container No.	D-15	D-17	D-20
Wt. of Container (g)	19.00	18.36	13.91
Wt. of Container + Wet Soil (g)	31.03	29.85	30.25
Wt. of Container + Dry Soil (g)	27.84	26.87	26.07
Wt. of Dry Soil (g)	8.84	8.51	12.16
Wt. of Water (g)	3.19	2.98	4.18
Moisture Content (%)	36.09	35.02	34.38

Table 4. Liquid Limit Test Experimental Data

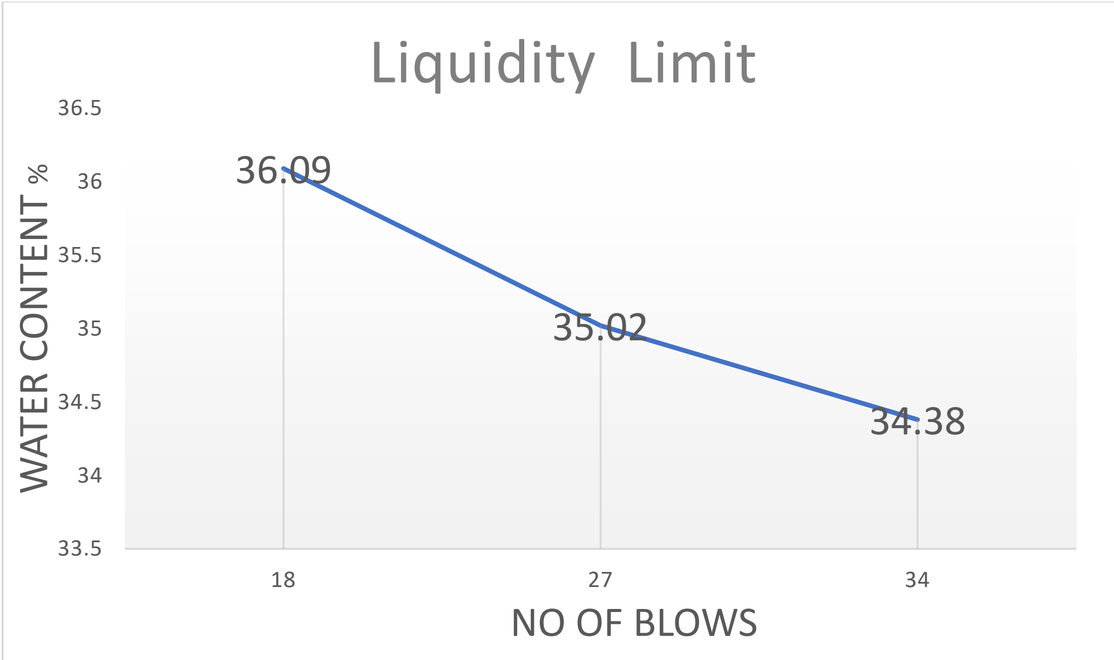


Figure 20. Liquid Limit Graph

Liquid Limit = 35

2. Plastic Limit

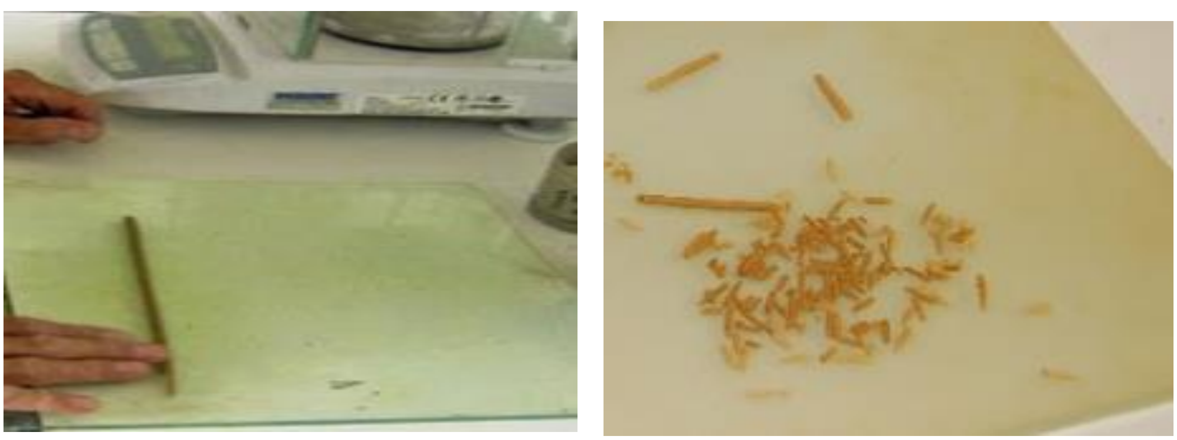


Figure 21. Test for Plastic Limit

Container No.	D-41	D-38
Wt. of Container (g)	10.44	10.44
Wt. of Container and Wet Soil (g)	16.29	16.98
Wt. of Container and Dry Soil (g)	15.20	15.78
Wt. of Dry Soil (g)	4.76	5.34
Wt. of Water (g)	1.09	1.20
MC. (%)	22.90	22.47

Table 5. Plastic Limit Test Experimental Data

Plastic Limit = 23

Plastic Index = P.L – L.L = 35 -23 = 12

3.3.1.1.3 Optimum Moisture Content

Proctor Test (ASTM D1557-91)

Figure 22. Assembly for Modified Proctor Test

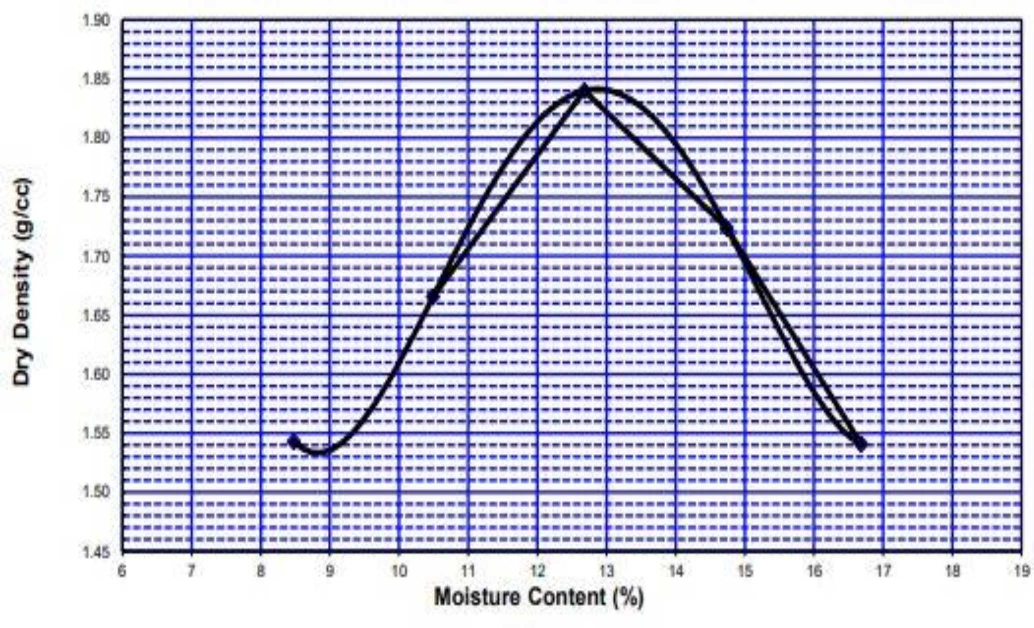


Figure 23. Moisture-Density Relationship

MDD. = 1.841 g/cm3

OMC. = OPC = 12.90 %

3.3.1.2 Cement

As a stabilizer Portland cement was used. It acts as a binder between different materials and provides stability to the mix. Portland Cement comprises of Calcium Oxide and Silica Oxide. When hydrated cement reacts with other materials to form a dicalcium and tricalcium silicate the reaction generates the interlocking crystals which bind the material by providing the stability and increase in compressive strength. The cement although does not bind with all the soil particles but it forms a stable mixture throughout. It also increases the wet compressive strength, dry compressive strength and resistance of soil brick against abrasion and erosion.

The chemical composition of Ordinary Portland Cement (OPC) is given in the following table:

Component	Minimum	Average	Maximum
SiO_2	18	21	24
Fe_2O_3	0.15	2.95	5.75
Al_2O_3	3	5.3	7.55
CaO	58	63	68
MgO	0.021	3.51	7
SO_3	0	2.65	5.3
Na_2O	0	0.375	0.75
K_2O	0.04	0.85	1.66
Equivalent Alkalis	0.03	0.63	1.24
Free Lime	0.03	1.85	3.68

Table 6. Chemical Composition of OPC

Before using Cement lab tests for consistency, initial setting time and final setting time were performed. The results are:

Consistency 29%

Initial Setting time 43 mins

Final Setting time approx. 420 mins (7 hrs.)

3.3.1.3 Fly ash

It is the waste or a by-product which is the result of the burning of pulverized coal in power plants. We replaced 30% of the soil content (90%) with Fly ash. Fly ash is pozzolanic in nature which means when it is in fine form and in contact with water it develops cementitious properties. As it is waste material, so by using it in the bricks it can be utilized without affecting the environment. Fly ash used in our research was brought from the Sahiwal coal power plant.

Composition of Fly ash is as under:

Component	Percentage
Silica (Sio2)	47.6
Aluminum Oxide (Al2O3)	26.2
Ferric Oxide (Fe2O3)	9.4
Calcium Oxide (CaO)	2.4
Magnesium oxide (MgO)	1.42
Sulphur trioxide (SO3)	0.86
Sodium Oxide (Na2O3)	1.1
Potassium oxide (K2O)	3.02

Table 7. Chemical Composition of Fly Ash

Properties of Fly ash that was used are as under:

- Particle size was 19 µm.
- Specific Gravity of Fly ash was 2.35.
- It was Black in Color.
- It increases the durability of the mix.

3.3.1.4 Water

The quantity of water added in a mixture has a major role in the strength and stability of the brick. Water has main role in the hydration process of cement. Total Water required was the sum of the water required by the cement, Fly ash and Soil. Percentage of water was different for bricks without LB media and Bricks with LB media. In the Bricks with LB media a fix quantity of water was replaced by the Solution of LB Media, Calcium Chloride and Urea. This solution was acting as a food for bacteria.

Both tap water and distilled water were used in our research. For preparing media distilled water was used and for mix tap water was used after checking that it ensures that it's:

- Colorless and Odorless.
- Free from any suspended particles.
- Free from Chemicals

- pH is in range of 6-8

It was necessary to ensure above criteria for water to avoid any unnecessary reactions in the mix which can affect strength of the Brick.

Materials which were used to prepare a food or solution to activate the indigenous bacteria are as under:

3.3.1.5 LB Media

Lysogeny Broth which is commonly known as LB media is used for the growth of bacteria. It's nutritionally rich medium composed of several ingredients. It provides the suitable environment to culture the bacteria. When mixed with mineralized solution containing urea and calcium chloride urease producing bacteria can formulate the calcium carbonate crystals as result of reaction taking place between $CaCl_2$, Urea and water in the presence of urease producing bacteria.

Composition of LB Media is given in the following table:

TYPICAL FORMULATION	grams/liter
Beef extract	1
Yeast extract	2
Peptone	5
Sodium Chloride	5

Table 8. Composition of LB Media

The solution was prepared and Autoclaved in the IESE Microbiology Laboratory in the reagent bottles according to the specifications given on the seal pack of LB Media.

Solution of LB media was prepared and autoclaved in the following way:

13 grams of LB powder was dispersed in 1 liter of distilled water in reagent bottle. It was allowed to soak for 10 minutes and then mixed. After that for autoclaving reagent bottles were placed in autoclave chamber at 121 degree centigrade for 15 mins. After cooling down it was ready to use for our research.

3.3.1.6 Calcium Chloride

Calcium Chloride is the salt with white crystalline structure at the room temperature. Its chemical formula is $CaCl_2$. It plays important role for producing Calcite precipitation in the presence of Urease producing bacteria. The Ca^{+2} in the $CaCO_3$ comes from Calcium Chloride ($CaCl_2$) during the reaction in the presence of Urease producing bacteria.

Some properties of $CaCl_2$ are:

- Molar Mass of $CaCl_2$ is 110.98 g/mol.
- Its density is 2.15 g/ml.
- Its melting point is 782 Degree Centigrade and Boiling point is above 1600 Degree centigrade.
- It is soluble in water and the reaction is exothermic.
- It is hygroscopic in nature i.e. it absorbs moisture.

3.3.1.7 Urea

Urea is an organic compound with formula $CO(NH_2)_2$. In the presence of Urease, hydrolysis of Urea produces ammonium and carbonate. In the presence of Urease producing bacteria Ca^{+2} ion from $CaCl_2$ and CO_3^{-2} ion produced as result of hydrolysis of Urea combine to form the Calcium Carbonate i.e. $CaCO_3^{-2}$. The process of formation of Calcium Carbonate due to microbial activity in the presence of LB media and mineralized solution is called Calcite Precipitation.

Some properties of the Urea are:

- Its molecular weight is 60.96 g/mol
- It is white solid substance with melting point of 133 Degree Centigrade.
- Density of Urea is 1.32 g/cm^3.
- Specific Gravity of Urea is 1.34
- It is soluble in water.

Figure 24. (a. Urea, (b). Calcium Chloride

3.3.2 Material Procurement

3.3.2.1 Soil

Soil was excavated in industrial area Islamabad with the help of labors and it was transported to Research Lab in sacks on the vehicle which was permitted by our department NUST Institute of Civil Engineering. After process of drying in sunlight, soil was transported to village near Rawat for pulverization in Brick Manufacturing Factory. After Pulverizing the soil Geotechnical Tests were performed on soil.

3.3.2.2 Cement

Cement was procured from the nearest store in sector G-11, Islamabad in the form of 50 Kg bag on the vehicle permitted by NICE.

3.3.2.3 Fly ash

Fly ash was ordered from Sahiwal and it was received on the railway station which was then transported to our research Lab through rented vehicle in the packed sacks.

3.3.2.4 LB Media, Calcium Chloride and Urea

All the Microbial and chemical material was ordered from the "Musaji Adam & Sons". They delivered all the products on the provided address within the NUST University.

3.4 Brick Shape and Mold

To elect the shape of brick, different papers from the literature were consulted. Different shapes have been used in the past for interlocking bricks as discussed in detail in literature review section. We designed the shape of our brick based on the previous shapes and after consultation with a master's student at NICE. Since one of our objectives was to provide lateral or earthquake resistance to the wall and improve the structural behavior of our brick, therefore inclusion of shear keys was served the purpose. Furthermore, the shape of shear keys was designed as conical in order to avoid the breakage in handling or during manufacturing when brick has not gained its strength. Although inclusion of shear keys improved the lateral strength to a very large extent as compared to normal brick, but the holes were also introduced in the bricks in order to add the feature of steel reinforcement or grout when needed to make much more resilient structurally and an alternative to RCC in future as well.

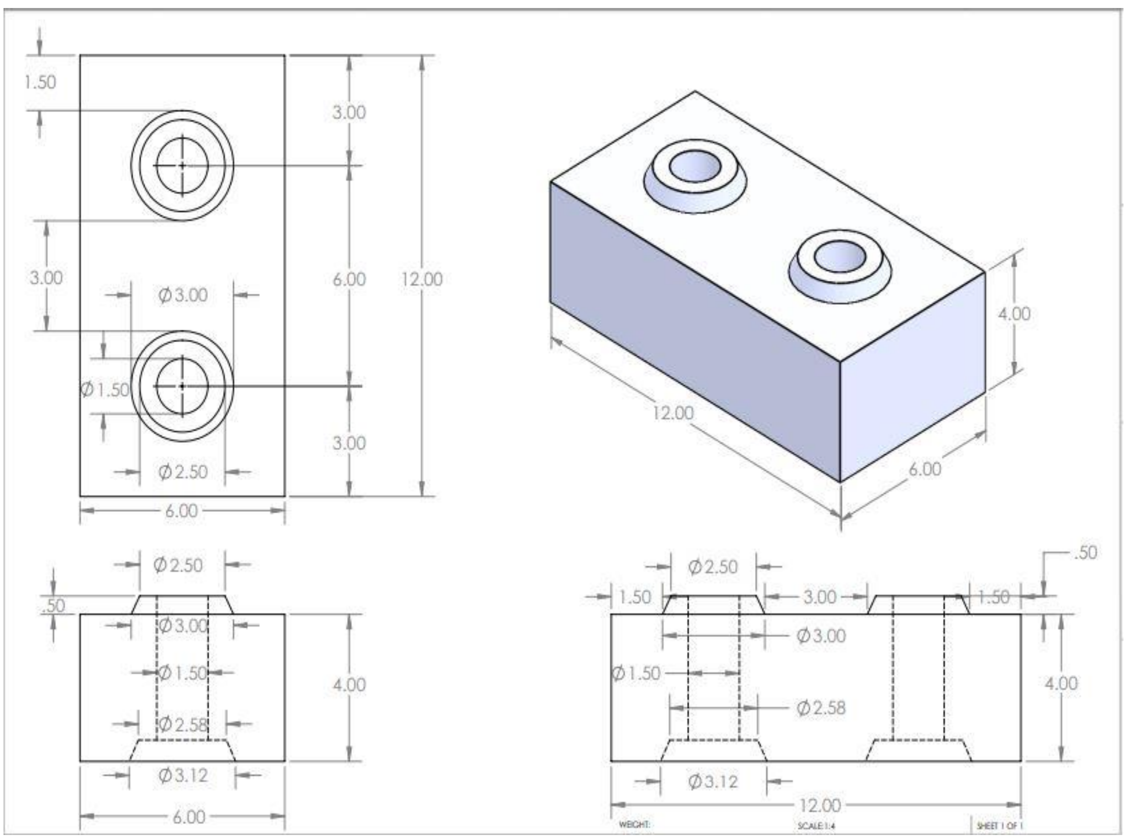


Figure 25. Brick Dimensions

The mold for manufacturing of the bricks was designed and manufactured locally from a Gujrat based vendor. The mold was made of mild steel. It is essentially consisted of five parts

- Top plates
- Bottom plates
- The box plates
- Struts for holes in the brick
- Nuts and bolts for fitting of plates

3.5 Soil pulverization

For the manufacturing of compressed earth bricks, the soil needs to be pulverized first. We outsourced this work. The facility was available at village Dawari near Rawat named Barsal Brick company. The machine used for pulverizing has several parts and soil goes through different processes during pulverization. An important thing before pulverization is that soil must be air dried for at least 10 hrs. and moisture should be well below its Optimum moisture content OMC.

Figure 26. Soil Pulverization

- First soil is poured into a hopper which delivers it to a conveying belt.
- Conveying belt is aligned at some with angle with horizontal. As the soil move on the belt bigger solid pieces are separated and only smaller ones reach crushing unit
- The crushing unit then crushes, breaks lumps and pulverizes the soil into small powdered size particles.
- The crushed soil is passed through this process for once again. The process could be repeated twice or more times depending upon the nature of soil.
- Finally, pulverized soil is then collected in bags.

3.6 Brick job mix preparation

After material acquisition and testing and soil pulverization, the next part was to move on casting the bricks. For that a job mix composition had to be decided. After consulting some literature on the topic and doing some trial testing we came up with the following composition.

- Stabilizer i.e. cement = 10%
- Soil + replacement = 90%

  Out of which
  - Soil is 70%
  - Fly ash is 30%.

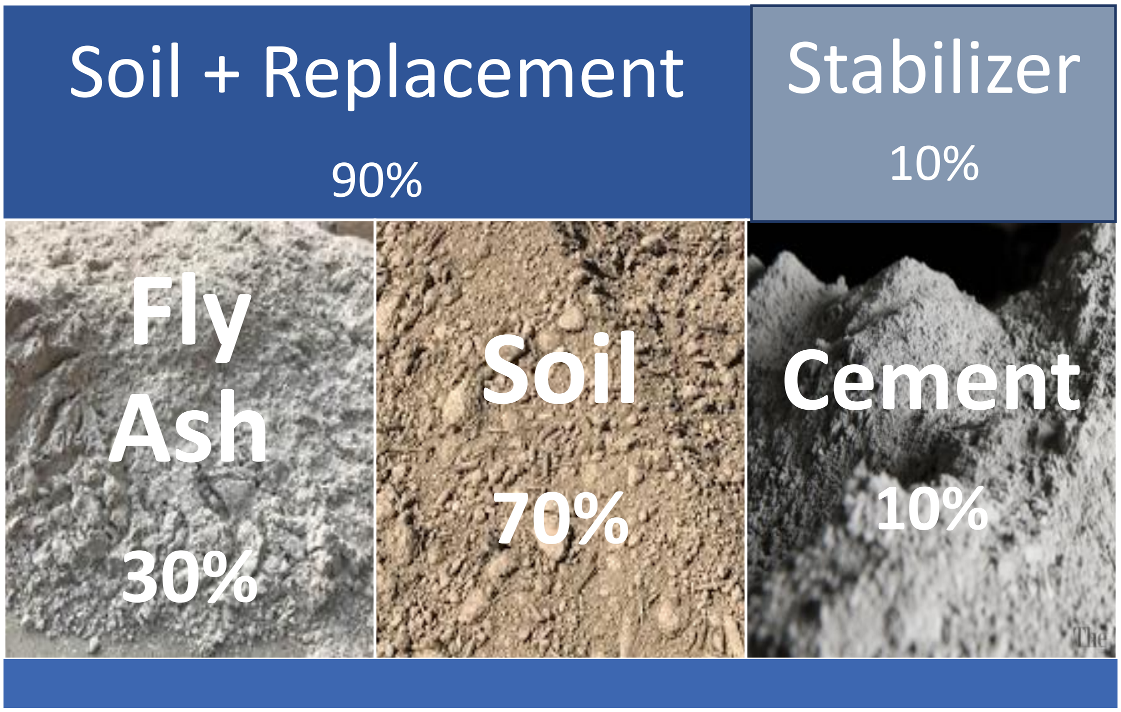


Figure 27. Mix Composition

3.6.1 Dry and wet mix preparation

After finalizing job mix proportions, the mixing of materials was done. The mix was prepared in bathes 45 kg each. First the dry mix was prepared which was 10 % cement i.e. 4.5kg out of remaining 90% , 70% was soil i.e. 28.35 kg and 30% fly ash i.e. 12.15 kg. then water was added according to the optimum moisture content OMC and hydration requirement of cement and fly ash.

Optimum moisture content was= 12.9 % of soil =12.9%28.35= 3.65kg

Hydration requirement of cement = 30% of 4.5 = 1.35 kg

Hydration requirement of fly ash = 20% of mass of fly ash

Figure 28. Mixer

3.7 Brick casting and Mold Working mechanism

The next step was the casting of bricks using mold and compression testing machine. The procedure for this complete part is explained along with working of mold.

- First, Mold and box plates are cleaned using a piece of cloth and oiled properly so that brick can be removed easily after compression.
- Box plates are then arranged on the bottom plates and bolts are tightened to fix them in position. Vertical struts are then fixed in position for creating holes of reinforcement.
- Brick job mix is poured in the mold. Inner dimensions of the mold are 12x6x7 in. therefor total inner volume was 504 in^3.9 kg of mix was filled in the box.
- Then the top plate is placed at top and mold is placed into the compression testing machine cabin and after saving area and other settings, machine is turned on. The loading rate is set as 7 KN/s
- Then load is applied in two or three cycles because CTM reaches its displacement limit. The top plate is compressed and moved down by 3in and final dimensions of brick are obtained i.e. 12x6x4 in. hence the final density achieved is 1907 Kg/m^3.

- When the compression is completed, the mold is removed from the compression testing machine and after removing top plate, bolts are loosened, and side plates are removed one by one. Then the finished brick is removed from mold and placed for curing.
- After that mold is cleaned again and procedure is repeated.

Figure 29. Compressed Earth Brick Extracted from Mold

3.8 Brick curing

Once the casting was complete total of 70 bricks were casted. The bricks were then placed for air curing at room temperature for certain period. They had to be tested at different time intervals. Some of bricks were cured for 7 days, some for 14 days and other for 28. This is explained later in detail in the structural testing part.

Figure 30. Compressed Earth Bricks left for Curing

3.9 Structural Testing

Originally the scope of structural testing included extensive testing of unit, prism and wallet level along with durability, thermal conductivity and forensic testing for checking the efficiency MICP process quantitatively. Following tables lists the scope of original testing along with number of samples casted for them.

Unit Test	Without bacteria	With bacteria
Dry compressive	6	6
Wet compressive	3	3
Flexure	6	6
Water absorption	3	3
Durability test	2	2
Thermal Conductivity	3	3
Mechanical Healing	3	3
Total	26	26

Table 10. Number of Brick Samples for Unit Test

Prism compression test	Without Bacteria	With Bacteria
Prism flexural bond test	5	5
Prism shear bond test	3	3
Total	13	13

Table 9. Number of Brick Samples for Prism Test

Other than mentioned above, different wallet level testing was also part of the scope. But due the COVID -19 pandemic situation, institutions closed, and we were not able to complete the whole testing. We somehow managed to complete only following three tests. And other than this numerical modelling was added as the part of scope.

Unit Test	Without Bacteria	With Bacteria
Dry compression	3	3
Water absorption	3	3
Thermal conductivity	3	3
Total	9	9

Table 11. Unit Test results

The procedure and details of 3 above mentioned tests is explained below.

3.9.1 Dry Compressive Strength test

Dry compressive strength f_c' of bricks was determined by compression test using compression testing machine as per ASTM C1314. Test was conducted on 3 samples and average value of 3 was taken as compressive strength of bricks.

- First, brick was weighed using electronic balance. The dimensions of the brick were 12x6x4 in.
- Then bottom plate of mold assembly was placed in compression testing machine chamber and brick was placed on it. Also, top plate was placed on the top of brick. This was done to ensure uniform load applied on the brick.
- Strain gauge assembly was also attached with brick mold in order to measure displacement to calculate strain later.
- CTM was turned on and values of dimensions etc. were given as input using the input panel of CTM.

- Loading was applied at the rate of 0.25 MPa/s as per ASTM standards.

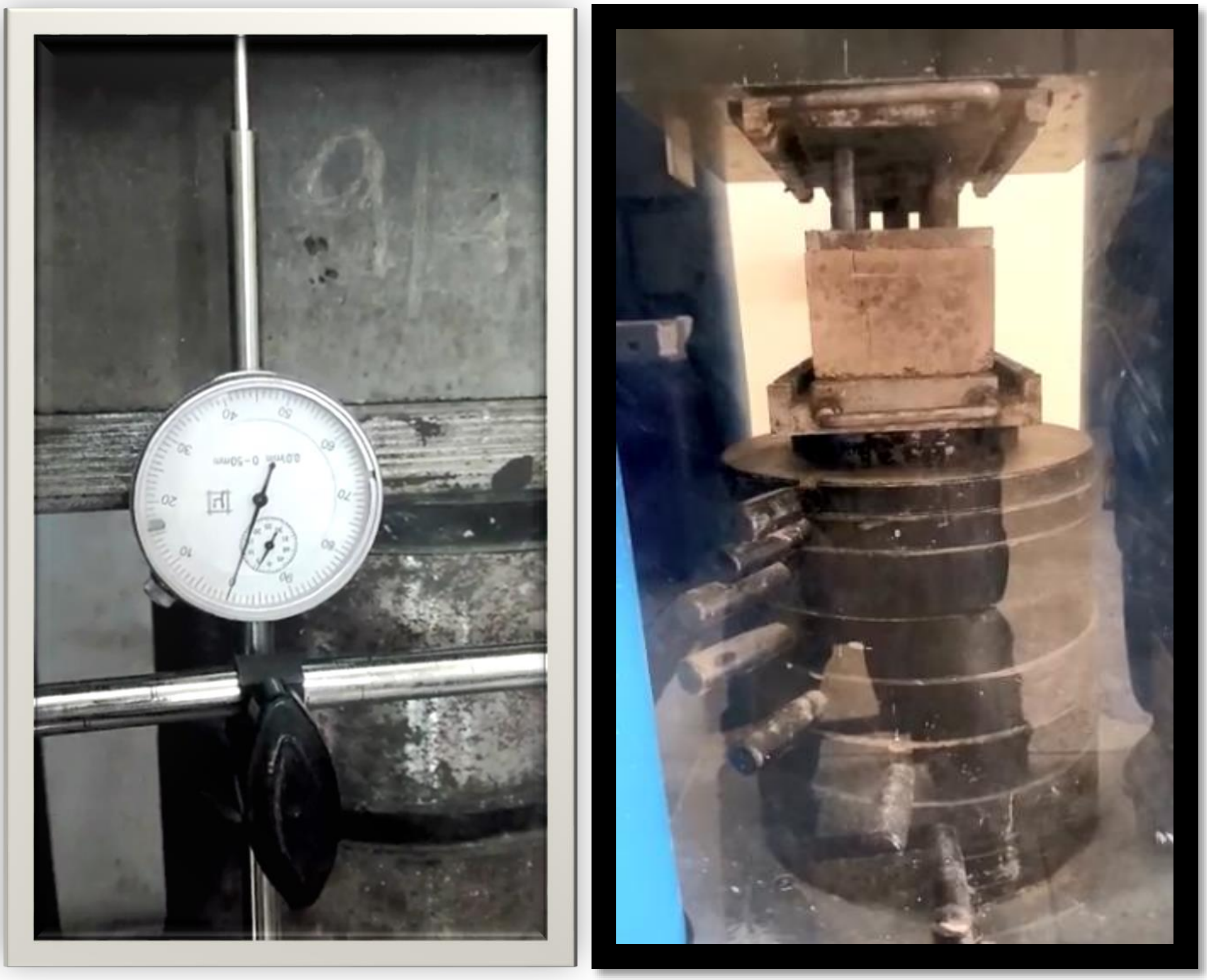


Figure 31. Dry Compressive Strength Test

3.9.2 Water absorption Test

Water absorption test is carried out to determine the maximum amount of moisture a brick can absorb when provided with high moisture conditions. Water absorption is found out as percentage of water by weight of brick. It’s a measure of durability because if the brick absorbs more water, it is susceptible to get damaged by weathering more easily and quickly. The test was carried according to ASTM C-67.

- First the bricks were dried in oven at 100℃ for a period of 24 hours
- After removing from oven, bricks were cooled in room temperature for an hour.

- Bricks were weighed and placed in a container filled with water such that the complete brick is dipped in the water.
- Bricks were placed in water for 24 hours and then removed and weighed again.
- The difference between initial and final weight would give the value of water absorption.

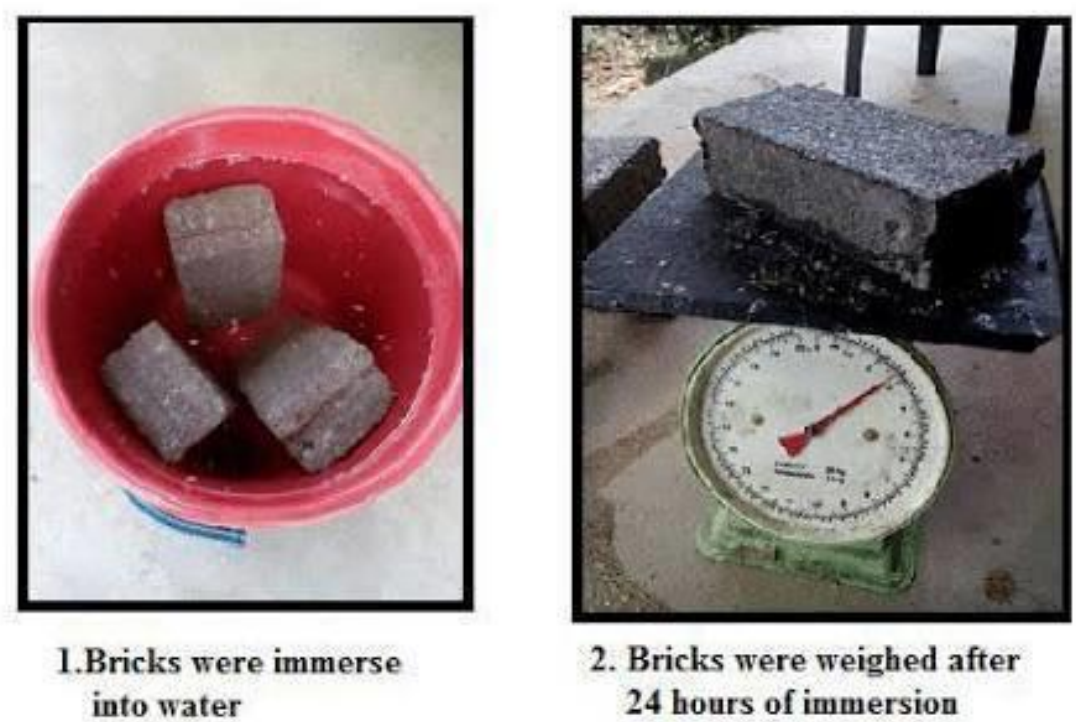


Figure 32. Water Absorption Test

3.9.3 Thermal Conductivity Test

Thermal conductivity of bricks is measured to assess the energy efficiency of the buildings constructed from these bricks. Thermal conductivity of brick was measured according to ASTM C-177-13. The test was performed on three samples and average value was taken as thermal conductivity.

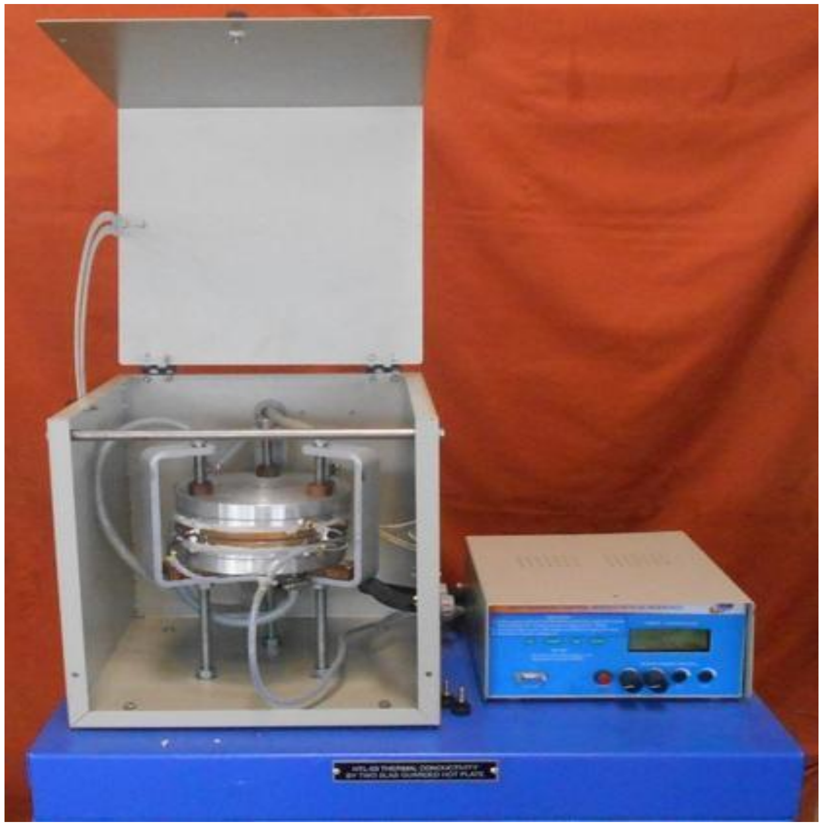


Figure 33. Apparatus for Thermal Conductivity Test

The test apparatus used for this test is called guarded-hot-plate apparatus. The detailed procedure of test is explained in the ASTM. According to which, the brick is first placed inside the chamber. And after turning on the electric supply and setting the original values for given parameters, the thermal conductivity values are noted at different intervals.

This test involves greater care, precision and knowledge of the equipment. Help in this regard was taken from a PHD student at NICE.

3.10 Numerical Modelling

Numerical modelling for both conventional Bricks and ICEB was performed using Abaqus Software. A comparison was drawn between wallet made with conventional bricks and walled made with Interlocking Compressed Earth Bricks using Load vs Displacement Relationship.. Simplified-Micro approach was used for modelling of brick walls.

3.10.1 Numerical modelling with Conventional Bricks:

A brick wallet with dimensions 36” X 36” was modelled using Abaqus standard. For modelling brick wallet first, we created two parts: Full Brick and Half Brick. Density (0.067 lb./in^2), Young Modulus (313500 psi) and Poisson ratio (0.18) were defined in material properties for the bricks. After defining sections and instances bricks were assembled to form the wallet.

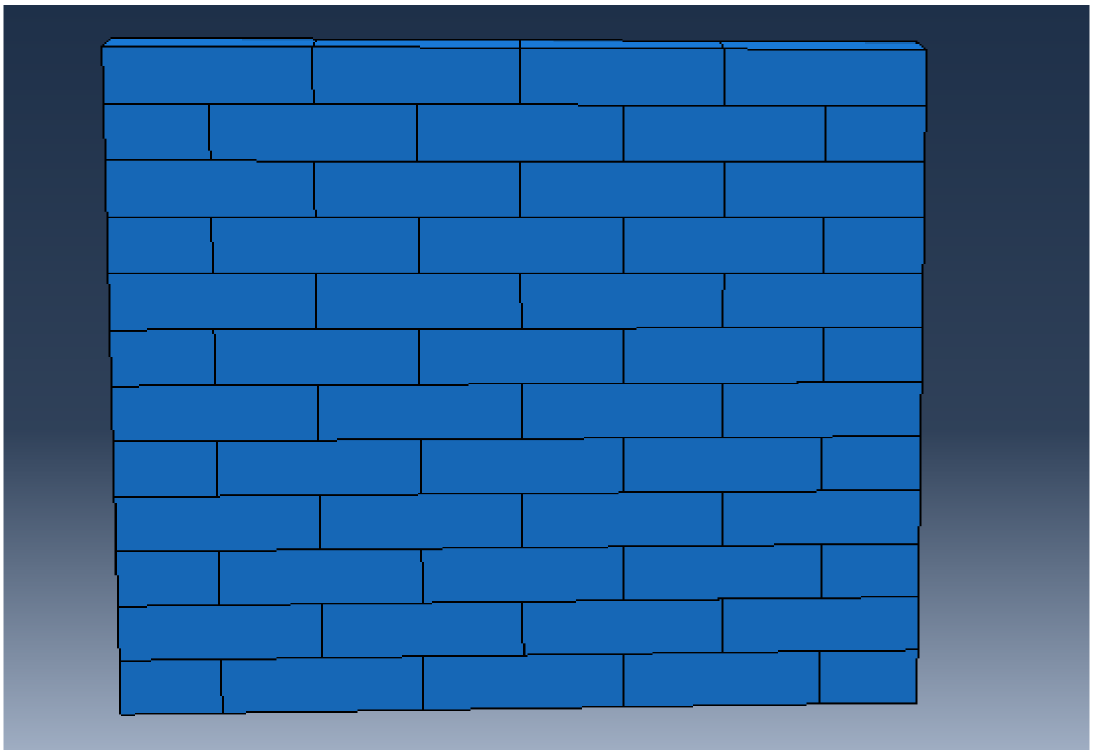


Figure 34. Conventional Brick Wallet Model

3.10.2 Interaction between Bricks:

Four types of interactions were defined between the bricks which are mentioned as under:

1. **Tangential Behavior**
   - Friction Coefficient = 0.78
2. **Normal Behavior**
   - Hard Contact

3. **Cohesive Behavior**
   - Knn = 470 Psi
   - Kss = 205 Psi
   - Ktt = 205 Psi
4. **Damage**
   - Initiation: Normal = 40 lbs. shear 1= 100 lbs. Shear 2 = 100 lbs.
   - Evolution: Total Plastic Displacement = 0.08 in
   - Stabilization: Viscosity Coefficient = 0.0002

3.10.3 Boundary Conditions and Loadings

Bottom of wallet was Fixed. From top only in-plane out of plane movement was allowed. Deformation in other direction was restricted. Top pressure of 43.5 psi was applied and in-plane displacement of 4 in was applied to observe the behavior of wallet.

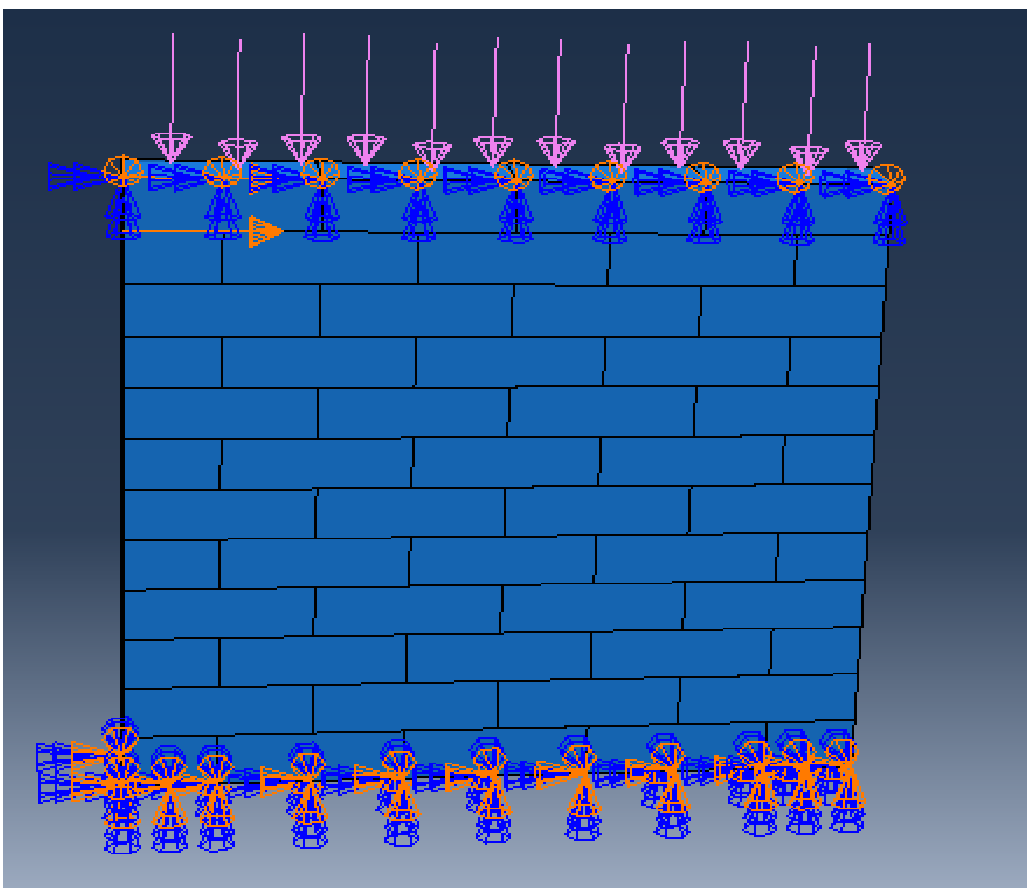


Figure 35. Conventional Brick Wallet under Loading

3.10.4 Numerical modelling with ICEBs

In order to draw the comparison between the conventional and newly designed bricks, model size was kept the same as 36"x36" wallet. These basic material properties were provided for analysis of wallet.

Density = 1907 kg/m^3

Young's modulus = 387800 psi

Poison's ratio = 0.165

3.10.5 Interaction and Boundary Conditions

Interaction between bricks was defined as general interaction "all with self". Because the main purpose was to compare interlocking brick without mortar with that of conventional brick with mortar. The brick has shear keys which are provided to resist lateral loading and improve over structural properties of brick as compared to conventional brick. That's why no other material was defined for binding of bricks with each other as in case of conventional bricks.

Only one contact was defined which was normal hard contact.

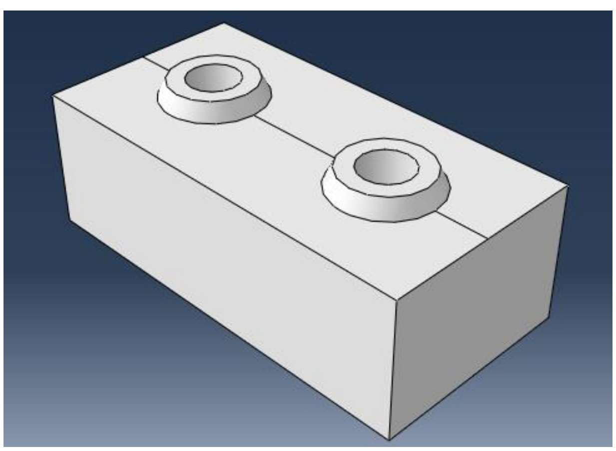


Figure 36. Compressed Earth Brick modelled in Abaqus

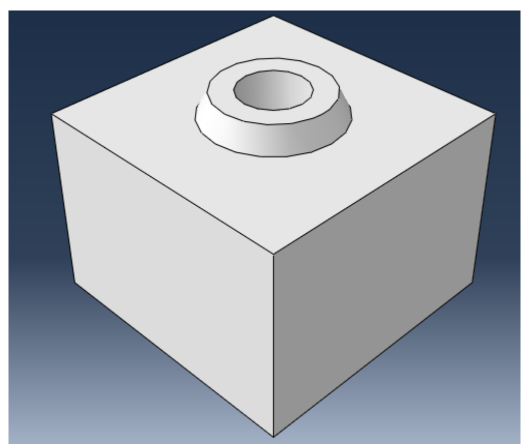


Figure 37. Half Compressed Earth Brick Modelled in Abaqus

Boubdary condtions and loadings etc of ICEB wallet was kept similar to the conventional in order to draw a fair comparison between them.

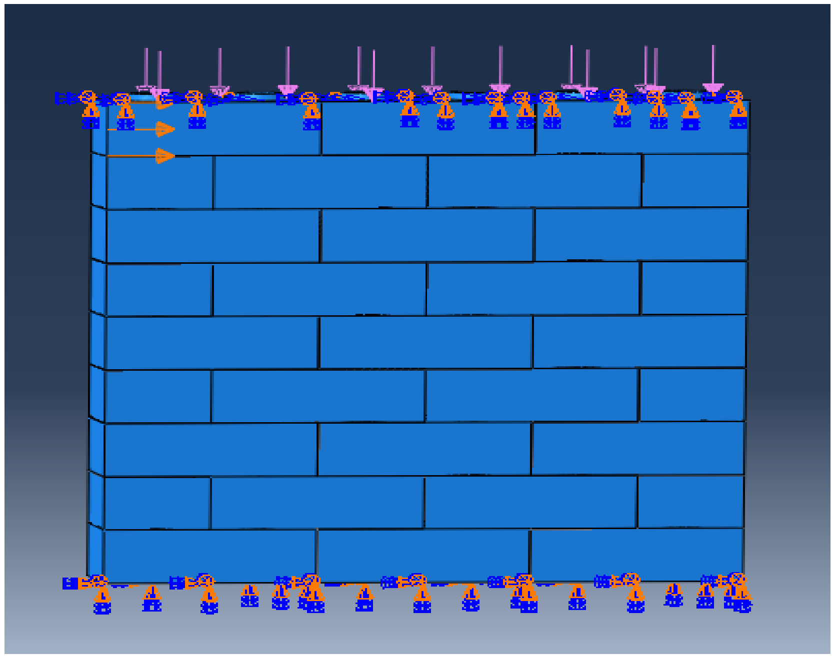


Figure 38. Compressed Earth Brick Wallet Model under Loading

CHAPTER 4

TEST RESULTS

4.1 Mechanical Test results

4.1.1 Dry Compression Test on Bricks:

For the full brick units, the value we obtained from dry compression test was **5 MPa** for ICEB without bacterial enrichment and **7.9 MPa** for samples with bacterial enrichment. And the threshold value required for load bearing masonry is **5 MPa**. So, our samples fulfill the minimum required criteria. Also, with the increase in quantity of stabilizer the strength of bricks will increase subsequently.

But we used minimum quantity of stabilizer because if we increase the quantity of stabilizer from 10% the cost of bricks will increase. The other contributor to the reduced strength was the unavailability of hydraulic press and we casted our samples in mold using compression testing machine due to which several samples were damaged during the de-molding of samples. Also, the size of our brick sample was bigger than that of the conventional bricks which led to reduce compressive strength of our samples.

Additionally, to get clear idea about the compressive strength we have to increase number of test sample, because coefficient of variation for compressive strength is too high that test on only 3 samples would not depict the actual strength of brick samples, to cater this issue we casted 9 samples for this test but we were not able to perform test on all of the samples due to Covid-19 situation.

The comparison of compressive strengths of the tested samples in given in the following figure:

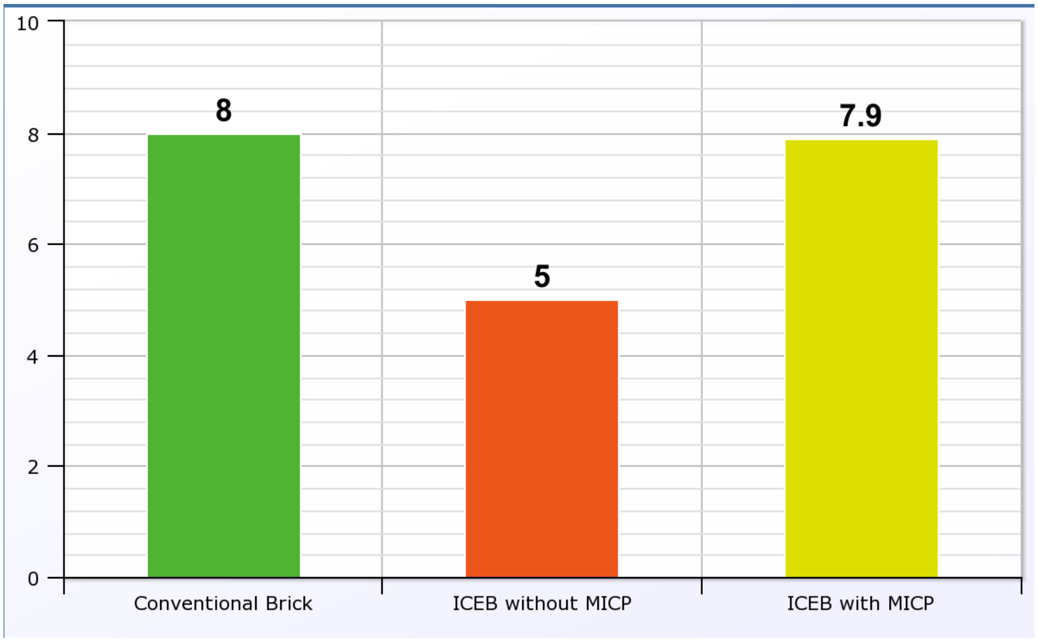


Figure 39. Comparison of Compressive strength

4.1.2. Water Absorption Test on the bricks

The value we obtained from water absorption test was **18.55%** for ICEB without bacterial enrichment and **15%** for samples with bacterial enrichment. The value of water absorption in case of samples with bacterial enrichment was comparable to that of the conventional bricks. Initially, in brick samples without bacterial enrichment, the value was high because of the use of fly ash, whose particles have high surface area and has larger particles, which led to the pore's creation in samples and increased water absorption.

But with bacterial enrichment, those pores were filled with calcite precipitation, which reduced the water absorption value. Water absorption test is a good measure of the durability of brick samples. This implies that our brick has the capability to stand the wear and tear of the harsh weather.

The comparison of water absorption of the tested samples in given in the following figure:

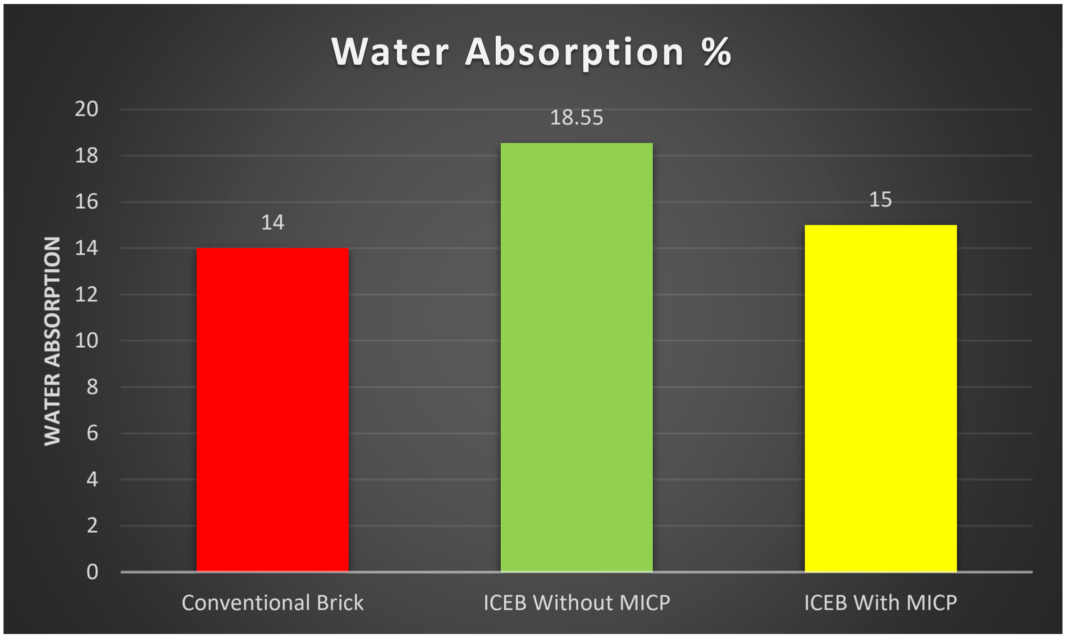


Figure 40. Comparison of Water absorption

4.1.3. Thermal conductivity of the bricks

The value of thermal conductivity for ICEB without bacterial enrichment is **0.3 W/m-K** which is far less than that of conventional bricks whose value is **0.72 W/m-K**. But in case of ICEB with bacterial enrichment, the value of thermal conductivity has increased to **0.5 W/m-K**, but it is also less than the value of conventional bricks. So, uses of these bricks in place of conventional bricks can lead to high energy efficiency in structures.

The comparison of thermal conductivity of the tested samples in given in the following figure:

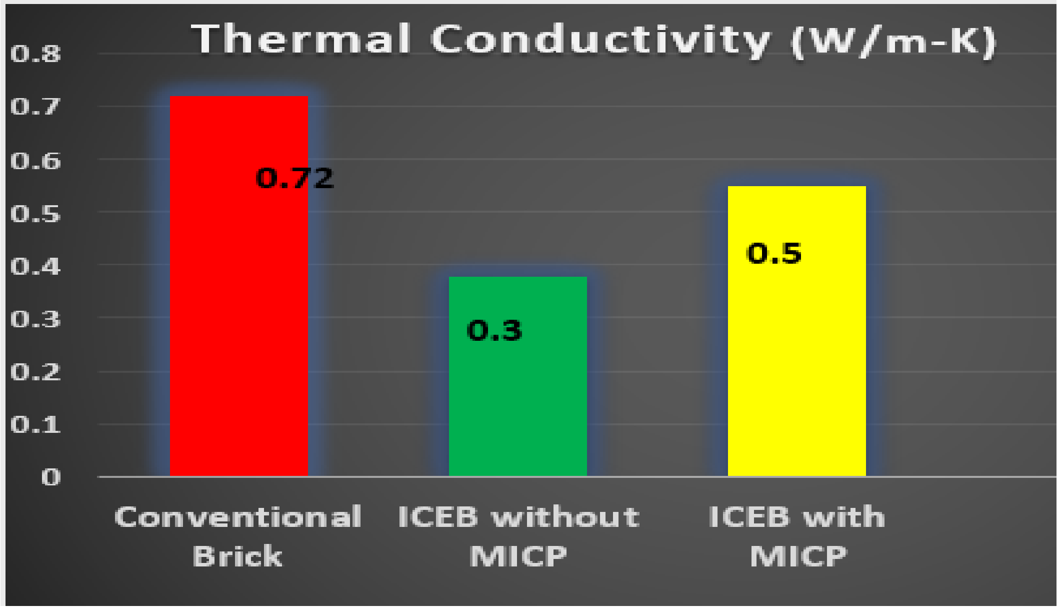


Figure 41. Comparison of Thermal Conductivity

4.2 Numerical Modelling results

4.2.1 Deformed shape

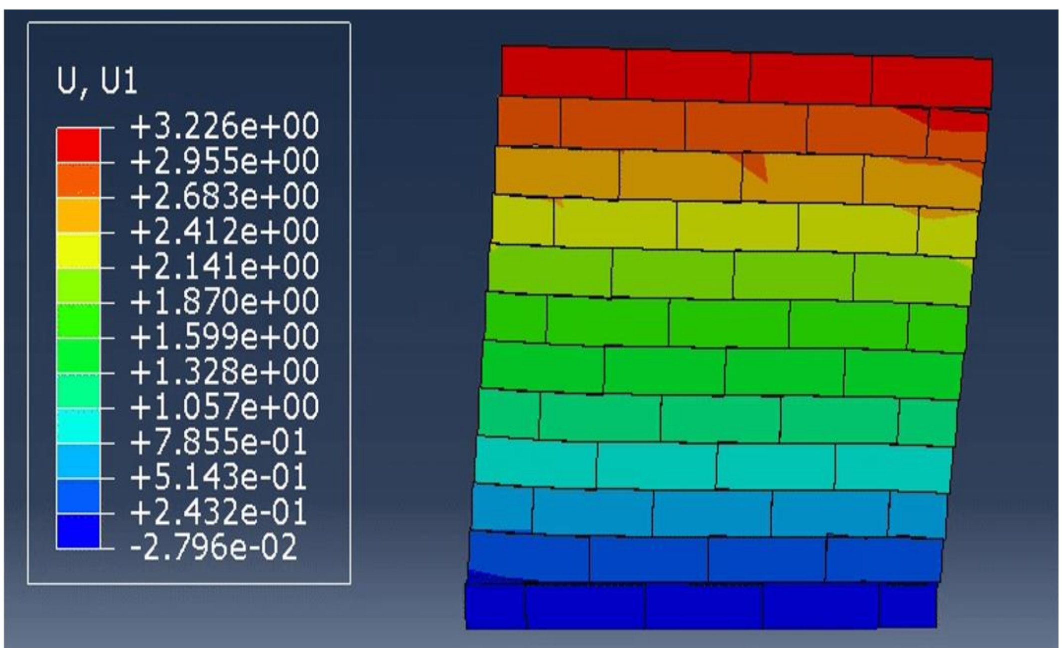


Figure 42. Deformed shape of Conventional Brick Model

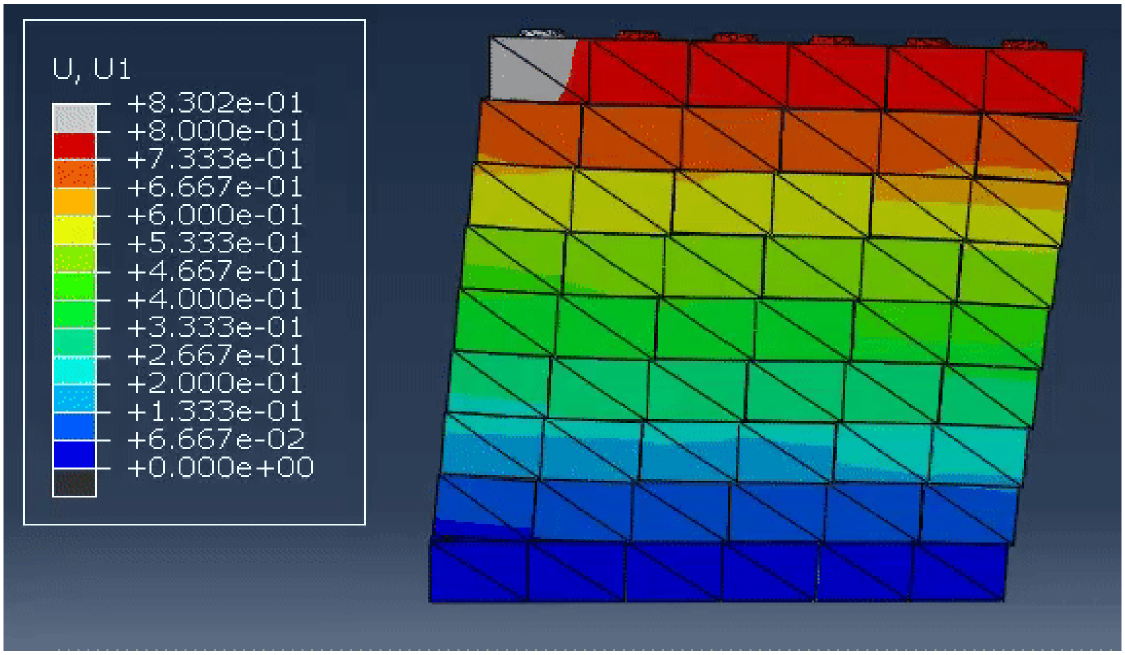


Figure 43. Deformed shape of Bio inspired ICEB

The response of masonry to the in-plane load can be observed in the form of colors in Figures above. The deformation is maximum at the top where in-plane load/displacement was applied. The deformation also propagated to other layers which resulted in the breaking of bond and cracks started appearing in the wallet. Bonds in both horizontal and vertical directions were weakened, and layers started to open. Cracks which initiated are in diagonal pattern which is very obvious in the case of masonry wallet.

It can be observed that wallet is also trying to rotate about the right bottom corner of the second last layer of bricks. As bottom layer is fixed so due to moment greater than the strength of bond at the second layer the bond between last and second last layer of bricks started to break and wallet rotated in clockwise about the bottom right corner of second layer of bricks. In real life this type of failure of masonry wall is called rocking failure which is common in walls with greater height.

The figures above shows the results of deformed shapes of wallets made up of conventional and newly designed ICEBs. The table at the left of figures is showing deforrmation values in inches along wth a color code. It is very clear from the maximum deformation values for conventional brick wallet is 3.226in which is far more than deformation values of ICEBs which is 0.830in. this proves lateral resistance of ICEBs with shear key is much better than that of conventional brick.

4.2.2 Force Displacement Curve

Following figures show the force displacement curve for conventional and Bio Inspired ICEBs.

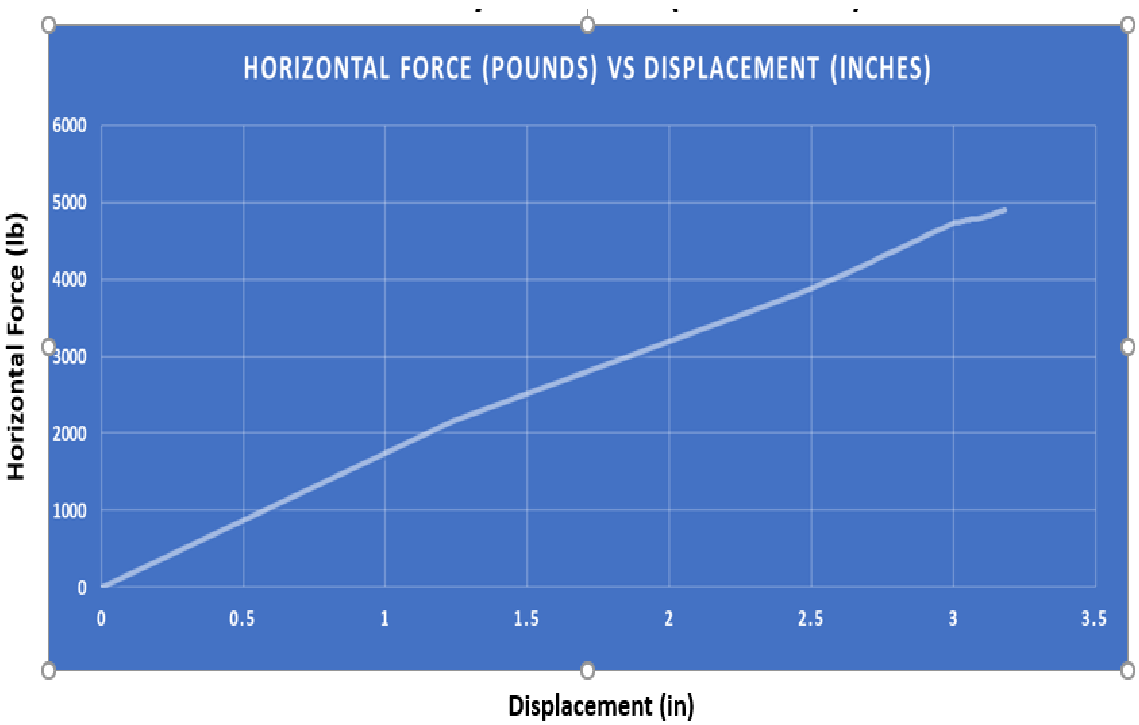


Figure 44. Force displacement curve for conventional brick wallet

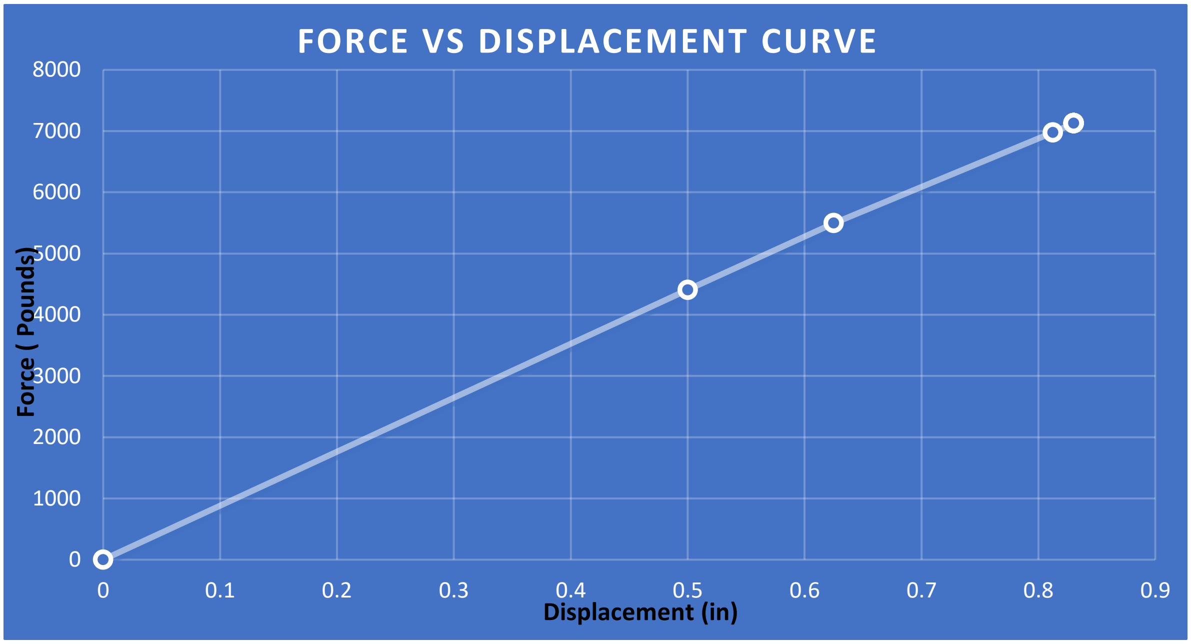


Figure 45. Force displacement curve for Bio Inspired ICEBs

In the above grsphs, on y-axis is the recation force produced in the bricks as a reesult of applied force. greater values of reaction force shows means that brick has greater capacity to take loads and stresses. As we can see in case of conventional bricks, maximum value of reacion force is 5000lb against the displacement values of 3.226in. The value of reaction force for ICEBs is greater than 7000lb against the displacement of 0.830 in.

it can be deduced from the above resultss that the structural performance of ICEBs is much better than the conventional bricks. Because the displacement value has been reduced to 25.77% of the value of conventional bricks along with 42% increse in value of reaction froce as compared to that of conventional bricks. These values could be further reduced further and coud become comparable to RCC by adding reinforcemnt in shear-key-holes.

CHAPTER 5

CONCLUSIONSAND RECOMMENDATIONS

5.1 Conclusions

- XRD results show that soil from Gujrat and industrial area of Islamabad region has more potential for the calcite precipitation which is an indication of the presence of indigenous bacteria and hence can be utilized for the purpose of formation of bricks with self-healing properties.

- Average Compressive Strength of Proposed Brick was 7.9 MPa which is comparable to Conventional Brick's 8MPa. It is pertinent to mention that the minimum criteria for load bearing masonry is 5 MPa, which the Proposed Brick fulfills.

- Water absorption value was 15% compared with 14% for conventional bricks. Which shows that these bricks are sustainable as burnt bricks. And provide better resistance to extreme conditions.

- Thermal Conductivity achieved was 0.5 W/m-K against 0.72 W/m-K of conventional bricks. These bricks have much less conductivity which shows that the buildings can be made more energy efficient using these Interlocking Compressed Earth Bricks.

- Force-displacement curves from numerical models proved that these bricks could resist more lateral loads with far less displacements. So, Interlocked bricks will act better under earthquake and other lateral loads as they have more lateral resistance than the conventional bricks

- Zero emission manufacturing process, so production of bricks has no direct contribution towards deterioration of environment.

- For the purpose of Self-Healing, utilization of existing bacteria instead of injecting new one showed promising results. Sufficient precipitation was witnessed using XRD test. For the very purpose, appropriate feed is needed to activate the bacteria.

- From the results shown by Bio-Inspired Interlocking Compressed Earth Bricks we can conclude that earth can be used as construction material without any burning process in kilns and only utilizing mechanical and chemical stabilization of the bricks which do not have any hazardous effect on the environment.

5.2 Challenges Faced

- Mold assembly is intricate. It took too long handling the mold assembly for casting of bricks. Due to that and its weight, samples were damaged while handling it.
- Mold assembly needs to be strong enough to sustain the pressures up to 600psi. During our casting stage, we faced an issue where the top plate of the assemble started undergoing bending. Rectifying this resulted in more time delays. This made it cumbersome to work with during the complete casting process.
- Surfaces of mold required oiling which reduces the compressive strength. This process is necessary in order to extract the brick sample from the mold without causing any damage to it. Further, applying the oil after every round of casting increases the inefficiency.
- The shape of brick required care while handling. Especially during demolding, it had to be placed and demolded very carefully in order to avoid any damage to the shear keys. Shear keys are a very delicate feature of this brick which is quite weak when initially compressed. Cylinders used for making the shear keys need to handle carefully and delicately during the extraction of brick. Slight carelessness could lead to complete damage of the shear key.
- Soil pulverizing is a labor-intensive process and is necessary in order to have proper mixing with lime and cement. However, when it is done mechanically, it’s an efficient process though incurs an additional cost.

5.3 Recommendations

- Hydraulic press should be used for manufacturing of ICEBs. One of biggest challenge for during the manufacturing process is compressing the brick in the mold. For this very purpose, using a hydraulic press would result in fast tracking the manufacturing process, increasing efficiency of the whole process.

- The mold of machine should be made of stainless steel with pulverizer and hopper attached. This would help in better handling of the bricks and increasing the efficiency. This would help in avoidance of brick material developing a strong contact bond with the mold walls and adhering to it. Using a pulverizer and hopper would speed up the process of mixing and loading of material into the mold.
- Lab experimental investigations of prism and wallets of these bricks should be performed. This would provide real life statistics and behavior properties for the proposed bricks, when utilized in real life scenarios.
- Detailed unit testing should be performed in laboratory so that a more detailed comparison between the conventional and proposed bricks can be done.
- Numerical models could be verified by modelling in other software such as Ansys. this would help in further analysis of the properties of this brick. This would help in providing strong basis for the results founds.

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