Final Year Design Project (FYDP)

Investigating the mechanical properties and thermal resistance of Lime Stabilized Compressed Interlocking Bricks

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List of Acronyms

CISB	Compressed interlocking stabilized brick
ASTM	American Society of Testing Materials
MC	Moisture Content
G_s	Specific Gravity
SDGs	Sustainable Development Goals
CO_2	Corban dioxide
ICEBs	Interlocking Compressed Earth Brick
CSCEBs	Cement-Stabilized Compressed Earth Brick
RC	Reinforced Concrete
FCB	Fired Clay Bricks
LCA	Life Cycle Assessment
DMC	Dimethyl Carbonate
USCS	Unified Soil Classification System
K	Correction Factor
a	Correction Factor
PL	Plastic limit
LL	Liquid limit
L	Effective Length

Chapter 01

1.1 INTRODUCTION

The cement and fired brick industries stand as major contributors to the escalating levels of greenhouse gas emissions, particularly evident in South Asia where coal-fired kilns dominate the manufacturing process (Parvez, Rana et al. 2023). These emissions not only exacerbate global warming but also contribute to air pollution and environmental degradation. Addressing the environmental impact of traditional construction materials becomes imperative, and one promising avenue is the development of Compressed Interlocking Stabilized Bricks (CISB).

Compressed Bricks, as revealed by various studies (Saari, Bakar et al. 2021), demonstrate commendable compressive strength, offering a viable alternative to conventional fired bricks. This is achieved through a thoughtful combination of constituent materials, balancing both strength and economic considerations. A noteworthy study by Asman, Bolong et al. (2020) concluded that the adoption of compressed interlocking bricks results in a substantial reduction of up to 35% in total carbon emissions during building construction compared to the use of fired bricks. This highlights the significant environmental benefits associated with the implementation of CISBs.

In our research project, we emphasize the utilization of naturally occurring lime as the preferred binder. The choice of lime is motivated by its potential to further diminish the carbon footprint of our already eco-conscious bricks. Lime not only provides a sustainable alternative to cement but also offers additional advantages, contributing to the overall green profile of the construction material.

Concrete blocks, while often considered an alternative to fired bricks, still pose environmental challenges. According to (ASTM) C90, nearly 14% of the content in concrete blocks comprises cement, a material associated with high carbon emissions during production (Benhelal, Zahedi et al. 2013). Recognizing this, our project aims to go beyond conventional alternatives and strive for a construction material that minimizes or eliminates cement usage altogether.

The strength requirements of our bricks will be addressed through a combination of soil compression and the interlocking design. This innovative approach not only contributes to the structural integrity of the bricks but also aligns with our commitment to reduce cement usage by using less mortar. Moreover, we envision enhancing the tensile strength of the CISBs by incorporating waste-based natural fibers. This not only strengthens the material but also mitigates the occurrence of shrinkage cracks, enhancing the overall durability of the bricks.

Beyond structural considerations, earthen bricks, such as the CISBs under investigation, present a range of additional benefits. These include improved thermal and acoustic insulation properties. The innate properties of the soil contribute to effective temperature regulation within structures, making them particularly suitable for regions experiencing temperature extremes. Additionally, the ability of these bricks to disintegrate back into the earth after demolition contributes to a net-zero pollution scenario, aligning with sustainable waste management practices.

In essence, our project aims to pioneer an eco-friendly, structurally robust, and economically viable construction material through the strategic use of compressed interlocking stabilized bricks. By harnessing the advantages of naturally occurring lime, minimizing cement usage, and incorporating waste-based natural fibers, we aspire to not only address the environmental impact of traditional construction materials but also contribute to a more sustainable and resilient future for the construction industry.

1.2 SIGNIFICANCE

The significance of this research extends beyond the academic realm to address real-world challenges faced by the construction industry. By exploring Lime Stabilized Compressed Interlocking Bricks, this research endeavours to revolutionize construction practices by providing an eco-friendly alternative to conventional fired bricks and cement blocks.

The potential environmental impact is substantial. The reduction in carbon emissions, estimated at 35% compared to traditional fired bricks (Asman, Bolong et al. 2020), aligns with global efforts to combat climate change. Furthermore, the use of naturally occurring lime as a binder minimizes the ecological footprint, contributing to a sustainable future.

Beyond environmental benefits, this research holds economic and social implications. The cost reduction associated with CISBs, coupled with their ease of construction, has the potential to address issues related to project delays and cancellations due to budget constraints. Particularly in rural areas, where economic considerations play a pivotal role in construction practices, CISBs could pave the way for affordable, fast, and easily deployable housing solutions.

In alignment with the Sustainable Development Goals (SDGs), this research contributes to the goal of providing affordable and clean energy (SDG 7) by exploring the use of renewable energy sources in the brick manufacturing process. Additionally, the recyclability of CISBs and their minimal ecological impact make them conducive to a sustainable and circular economy.

In conclusion, the adoption of Lime Stabilized Compressed Interlocking Bricks has the potential to usher in a new era of sustainable construction, meeting the demand for eco-friendly, structurally sound, and economically viable building materials.

1.3 PROBLEM STATEMENT

Conventional fired bricks and cement blocks pose serious environmental concerns, 1-2 percent of global Corbon dioxide ($CO_{2)}$ emissions and Soot (unburnt carbon) is released due to burning fired bricks (Nath, Lal et al. 2018), the use of cement itself in blocks is a cause of concern. 5-7 percent of the total CO_2 production is due to the cement industry alone (Benhelal, Zahedi et al. 2013). Secondly cost constraints is a major issue in the construction industry that leads to delays and project cancellations. As fossil fuels deplete their cost will increase hence finding solutions that are independent of the combustion process are imperative because both fired bricks and cement industry depend on it. The pace of construction is also a significant issue which is directly related to cost management. The manufacturing process and placing of fired bricks is a lengthy process chiefly dependent on the skill of the mason.

Average temperatures around the globe are increasing at an alarming rate, thus effective insulation is becoming a necessity in structures, as highlighted in (Ylmén et al., 2017). Cement blocks and fired bricks absorb and retain more thermal radiation compared to earthen soil bricks, making the latter a simple and cost-effective remedy especially in economically lagging regions like South Asia and Africa.

1.4 AIMS

The project aims to develop environmentally sustainable, structurally adequate, and thermally efficient Lime Stabilized Compressed Interlocking Bricks

1.5 OBJECTIVES

Environmental sustainability will be ensured in this project because there is no burning process involved, instead compression will be used to give our bricks the desired strength. Compressions is achieved through a hydraulic compressive machine whose power can be sourced from renewable sources like solar or wind power. The use of natural lime as a binder will further reduce environmental impact as no cement will be used in the manufacturing process. Because these are interlocking bricks the need for mortar, and plaster on exterior walls is also reduced, further reducing dependence on cement.

Structurally adequate CISBs are a compulsory requirement for use in load bearing structures. Our goal is to use minimal amount of lime as a binder. Yet if a good compressive isn't achieved an incremental percentage of cement will be added, the aim is to achieve a compressive strength between 2000 to 2500 psi. This way our bricks would be comparable to first class Pakistani bricks and will be well suited for load bearing structures. If the target strength was still not achieved or hardly achieved the addition of natural fibers will be another step towards making bricks with enhanced mechanical properties.

There are other advantages of using CISBs like thermal and acoustic insulation, it is achieved firstly because soil is a good insulator of heat. As we compress our bricks its density increases making a more compact medium that will not absorb additional heat. Our Bricks also have voids on the inside. These voids can be filled with reinforcement bars or lean concreate these also act as heat barriers because air is a very good insulator of heat.
The adoption of Compressed Stabilized Earth Blocks (CISBs) promises cost reduction in construction. This is achieved through lower unit prices, uniformity, and simplicity in construction due to an interlocking design. Additionally, CISBs' smooth outer finish eliminates the need for plaster, further reducing costs and effort.

1.6 SUSTAINABLE DEVELOPMENT GOALS (SDGS)

SDG 7 - Affordable and Clean Energy

The research on Lime Stabilized Compressed Interlocking Bricks (CISBs) strongly aligns with SDG 7 by promoting both affordable and clean energy practices within the construction industry.

Clean Energy Production

CISBs significantly contribute to clean energy practices by reducing or eliminating the need for cement in their composition. Cement production is energy-intensive and contributes to a substantial carbon footprint. By utilizing naturally occurring lime as a binder, the research not only minimizes the environmental impact but also aligns with the goal of promoting cleaner energy alternatives in the manufacturing process.

Energy Efficiency in Buildings

The energy-efficient properties of CISBs extend beyond the manufacturing phase. The thermal regulation capabilities of these bricks contribute to reduced energy consumption in buildings. The inherent insulation properties of CISBs create structures that require less artificial heating and cooling, directly addressing the need for energy efficiency, and aligning with the goal of promoting sustainable energy practices.

Affordability and Accessibility

By offering a cost-effective alternative to traditional building materials, CISBs contribute to making sustainable construction practices more accessible. The affordability of CISBs aligns with SDG 7's aim to ensure access to affordable, reliable, sustainable, and modern energy for all. This accessibility fosters a more inclusive approach to sustainable construction, especially in regions where affordability is a significant consideration.

SDG 8 - Decent Work and Economic Growth

The research actively supports SDG 8 by fostering decent work and economic growth, particularly within the construction sector.

Employment Opportunities

The development and adoption of CISBs create employment opportunities in various phases of the construction process. From the production of CISBs to their distribution and use in construction projects, the implementation of this eco-friendly building material has the potential to generate decent work opportunities, aligning with the goal of promoting sustained, inclusive, and sustainable economic growth.

Economic Affordability

The affordability of CISBs not only makes sustainable construction more accessible but also contributes to economic growth. By offering a cost-effective solution, the research promotes economic affordability in the construction industry. This affordability is essential for reducing construction costs, avoiding delays, and fostering economic stability in the long term.

Innovation in Construction

The introduction of CISBs into the construction industry represents an innovative approach to building materials. This innovation contributes to the overall growth and advancement of the construction sector. The adoption of new and sustainable technologies aligns with SDG 8's emphasis on fostering innovation in industries crucial for economic development.

SDG 9 - Industry, Innovation, and Infrastructure

The research on CISBs actively contributes to SDG 9 by advancing industry, innovation, and infrastructure development.

Innovative Building Materials

CISBs represent a groundbreaking innovation in the field of construction materials. The unique composition and manufacturing process of these bricks showcase a commitment to innovative building solutions. This innovation not only advances industry standards but also contributes to the development of sustainable and eco-friendly construction practices.

Sustainable Infrastructure

The adoption of CISBs promotes the development of sustainable infrastructure. By providing an alternative to traditional bricks that is both structurally sound and environmentally friendly, the research contributes to the creation of resilient and sustainable infrastructure. This aligns with SDG 9's goal of building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation.

Reduced Environmental Impact

The sustainable manufacturing practices associated with CISBs directly contribute to the reduction of the construction industry's environmental impact. By minimizing energy-intensive processes and incorporating eco-conscious materials, the research aligns with SDG 9's objective of promoting sustainable industrial practices and infrastructure development.

SDG 11 - Sustainable Cities and Communities

The research on CISBs plays a crucial role in advancing SDG 11 by contributing to the development of sustainable cities and communities.

Eco-Friendly Construction Practices

CISBs embody eco-friendly construction practices, providing a sustainable alternative to traditional building materials. The bricks' characteristics, including thermal efficiency and recyclability, contribute to the creation of environmentally conscious structures. This aligns with SDG 11's goal of making cities inclusive, safe, resilient, and sustainable.

Affordable Housing Solutions

The affordability of CISBs makes them a viable solution for affordable housing, addressing a critical component of sustainable urban development. By offering cost-effective and environmentally friendly building materials, the research contributes to the creation of housing solutions that align with the goal of making cities and human settlements inclusive, safe, and affordable.

Resilient Urbanization

The thermal regulation capabilities of CISBs contribute to the resilience of urban structures. By creating buildings that naturally regulate temperature, the research aligns with SDG 11's objective of building resilient and sustainable cities. The reduced energy consumption and lower environmental impact associated with CISBs further contribute to the development of resilient urbanization practices.

SDG 12 - Responsible Consumption and Production

The research strongly aligns with SDG 12 by promoting responsible consumption and production practices within the construction industry.

Reduction in Cement Usage

A significant aspect of responsible consumption is the reduction in the use of resource-intensive and environmentally impactful materials. The research actively addresses this by minimizing or eliminating the need for cement in the production of CISBs. This reduction aligns with SDG 12's objective of promoting sustainable consumption and production patterns.

Incorporation of Natural Fibers

The addition of waste-based natural fibers in CISBs represents a responsible approach to material usage. By incorporating these fibers, the research not only strengthens the material but also reduces waste, aligning with SDG 12's emphasis on reducing waste generation and promoting efficient resource utilization.

Recyclability and Environmental Impact

CISBs, with their recyclable and environmentally friendly properties, contribute to responsible consumption. The ability of these bricks to disintegrate back into the earth after demolition creates a net-zero pollution scenario. This aligns with SDG 12's goal of minimizing the environmental impact of consumption and production activities.

SDG 13 - Climate Action

The research on Lime Stabilized Compressed Interlocking Bricks (CISBs) plays a pivotal role in advancing climate action by addressing and mitigating the environmental impact associated with traditional construction materials.

Carbon Emission Reduction

One of the primary contributions to climate action is the substantial reduction in carbon emissions facilitated by the adoption of CISBs. Traditional fired bricks and cement blocks are notorious for their significant carbon footprint, contributing to global warming. CISBs offer a transformative alternative, minimizing or eliminating the need for cement, a material linked to high carbon emissions during production. As a result, the overall carbon emissions in the construction process are markedly reduced, aligning with the urgent need to combat climate change.

Sustainable Manufacturing Practices

The production of CISBs embraces sustainable manufacturing practices. The process involves minimal energy-intensive procedures, especially in comparison to the firing of traditional bricks. The incorporation of naturally occurring lime as a binder further supports sustainable practices, as lime production generally emits fewer greenhouse gases compared to cement. By reducing the reliance on resource-intensive materials and embracing eco-conscious manufacturing, the research promotes sustainable production methods in the construction industry.

Energy Efficiency and Thermal Regulation

CISBs exhibit inherent energy efficiency, contributing to both climate resilience and action. The thermal properties of these bricks, combined with their interlocking design, create structures that naturally regulate temperature. This inherent insulation capability reduces the demand for artificial heating and cooling, thus decreasing the overall energy consumption of buildings. The indirect impact on energy usage contributes to climate action by curbing the demand for energy derived from fossil fuels, a significant source of greenhouse gas emissions.

Promotion of Sustainable Construction Practices

Beyond the immediate benefits of CISBs, the research fosters the broader adoption of sustainable construction practices. By showcasing the feasibility and advantages of eco-friendly building materials, the study contributes to a paradigm shift in the construction industry. This shift, when embraced on a larger scale, not only mitigates the environmental impact of individual projects but also lays the groundwork for a more sustainable and climate-resilient infrastructure globally.

Educational and Advocacy Impact

Moreover, the research has the potential to amplify climate action through education and advocacy. As the findings are disseminated and awareness is raised about the environmental benefits of CISBs, it contributes to a greater understanding of sustainable construction practices. This knowledge dissemination fosters a community of practitioners, policymakers, and the general public who are informed advocates for climate action in the built environment.

In essence, the research on Lime Stabilized Compressed Interlocking Bricks serves as a proactive and tangible response to the climate crisis. By directly addressing carbon emissions, promoting sustainable manufacturing, enhancing energy efficiency, and fostering a broader shift towards eco-friendly construction, the study stands as a catalyst for achieving SDG 13 and building a more resilient and sustainable future in the face of climate challenge.

Chapter 02

2.1 Literature Review

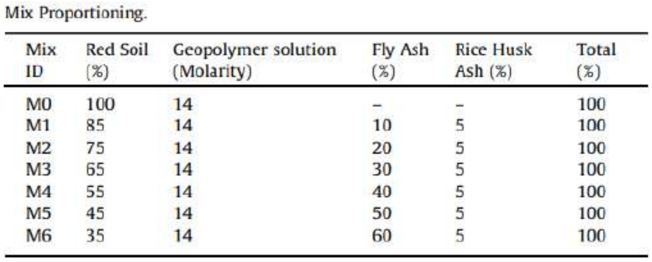
LITERATURE REVIEW

Topic	Findings
Factors of non-uniform properties of interlocking compressed earth brick units	• The laboratory investigation examines the mechanical and physical properties of interlocking compressed earth bricks (ICEBs) to understand the performance and behavior of the masonry structures. • The ICEBs were made from 49% laterite soil, 37% sand, 10% cement, and 4% water. • Four types (wall, beam, column, and half) of ICEBs are tested, with wall bricks showing better properties. • The mechanical properties of ICEB units were significantly impacted by shape, and manufacturing methods with hydraulic compression machines producing higher mechanical properties due to their higher compression rates and vibration, while groove depth, with high depth and low compression rates caused decreased strength.
(Saari, Bakar et al. 2021)	

Topic	Findings
Engineering properties of cement-stabilized compressed earth bricks	• This study examines the engineering properties of cement-stabilized compressed earth brick (CSCEB) samples, focusing on their structure and **durability.** • Eight CSCEB samples, one with zero sand and another with 40% sand content, were mixed with clay soil, with the proportion of ordinary Portland cement varying. • Increasing cement content improves compressive strength, especially with sand. Water absorption decreases with more cement, particularly in samples with sand. • Three-point bending tests show increased bending strength with higher cement and sand content. The minimum cement dosage for producing CSCEB varies, but generally, 7%-10% for no sand and 5% for 40% sand is required, along with mechanical stabilization. Dosage differs for bending strength, especially in the S-0-S sample.
(Dulal, Maharjan et al. 2023)	

<table>
<tr><th>Topic</th><th>Findings</th></tr>
<tr><td>Study on interlocking geo-polymer interlocking earth blocks made with residual rice husk ash and fly ash</td><td>

- Geo-polymer interlocking blocks were created by replacing red soil with residual rice husk ash and fly ash, and a sodium hydroxide solution was used.
- Seven mixes were prepared, varying fly ash content from 10% to 60%, while maintaining rice husk ash at 5%, including a reference mix without mineral admixtures.
- The study found that block M4 with 40% fly ash and 5% rice husk ash, along with a stabilized geopolymer solution, exhibited **superior water resistance** and **high pulse velocity values.**



Mix Proportioning.

<table>
<tr><th>Mix ID</th><th>Red Soil (%)</th><th>Geopolymer solution (Molarity)</th><th>Fly Ash (%)</th><th>Rice Husk Ash (%)</th><th>Total (%)</th></tr>
<tr><td>M0</td><td>100</td><td>14</td><td>–</td><td>–</td><td>100</td></tr>
<tr><td>M1</td><td>85</td><td>14</td><td>10</td><td>5</td><td>100</td></tr>
<tr><td>M2</td><td>75</td><td>14</td><td>20</td><td>5</td><td>100</td></tr>
<tr><td>M3</td><td>65</td><td>14</td><td>30</td><td>5</td><td>100</td></tr>
<tr><td>M4</td><td>55</td><td>14</td><td>40</td><td>5</td><td>100</td></tr>
<tr><td>M5</td><td>45</td><td>14</td><td>50</td><td>5</td><td>100</td></tr>
<tr><td>M6</td><td>35</td><td>14</td><td>60</td><td>5</td><td>100</td></tr>
</table>

</td></tr>
<tr><td colspan="2">(Vivek and Mangai 2023)</td></tr>
</table>

Topic	**Findings**
Experimental Study on the Production and Mechanical Behavior of Compressed Lime-Cement-Stabilized Interlock Soil Blocks	• This study examines the physical and mechanical behavior of lime-cement-stabilized compressed interlock soil blocks produced from two types of natural soil. The soil blocks had different index properties and mineral oxide compositions. Lime-cement combination and cement standalone were used as binders. • The initial water absorption rate of lime-cement-stabilized clay soil block decreases by 26.67% and 36.68% with an increase in stabilizer proportion from 2%L + 6%C to 3%L + 8%C and 4%L + 10%C, respectively, meeting the maximum initial rate of 30 g/min/30 in2. • The compressive strength of a medium plasticity clay soil block, stabilized at 3%L + 8%C, 4% L + 10%C, meets the Indian standard's Class 20 block requirement but fails to meet the African standard's minimum dry compressive strength for Class C block.

(Befikadu Zewudie 2023)	

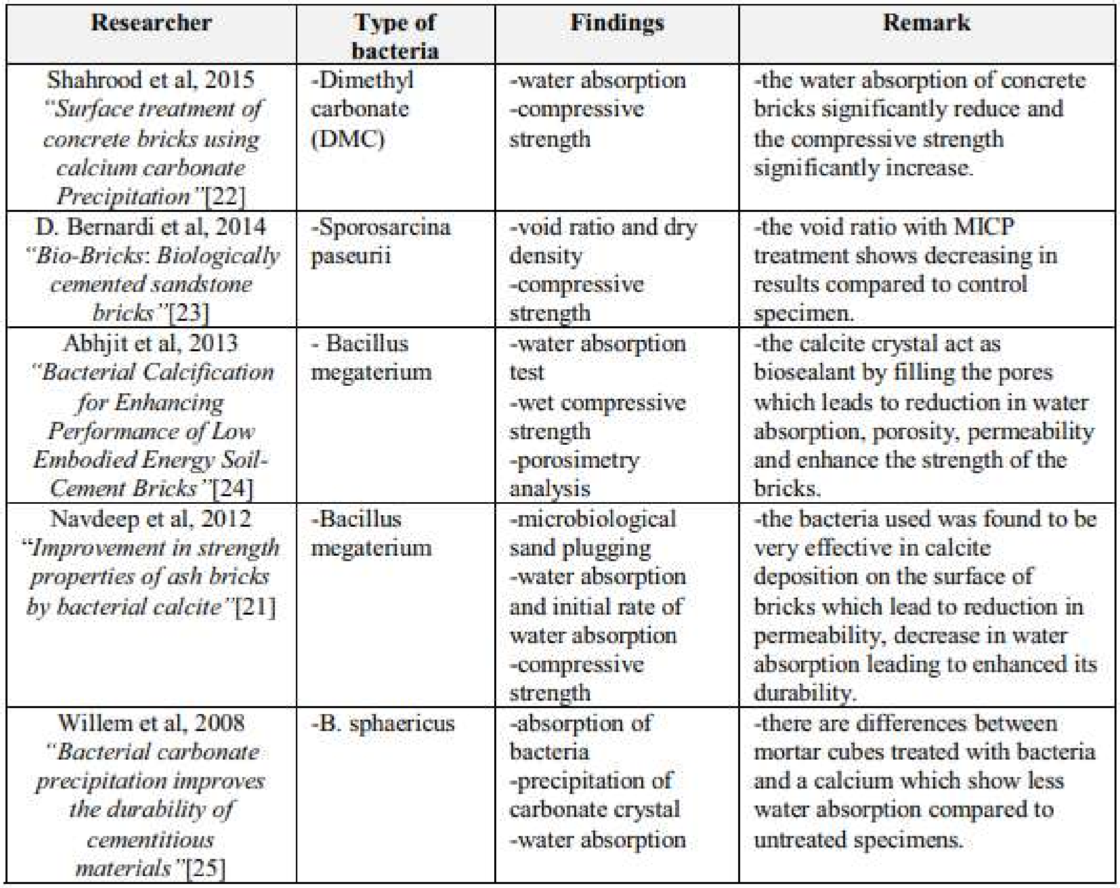
Topic	**Findings**
Interlocking compressed earth bricks as low carbon footprint building material	• This study evaluated the residential building's cradle-to-gate life cycle carbon emissions in Tawau, Sabah, using an interlocking compressed earth brick technology. • Reinforced concrete (RC) structures with traditional construction emit 405.75 kgCO2/m2 of carbon dioxide, while ICEB construction emits 264.50 kgCO2/m2. When compared to the traditional FCB of RC structure, the value for the carbon emission of ICEB as a walling material in building construction is reduced by 35%. • The life cycle assessment (LCA) approach is used in this study. • In this scenario, ICEB may be regarded as green and sustainable materials as the bricks are not burnt, and the construction process also contributes to green building construction. Choosing environmentally friendly materials and sustainable practices will help in minimizing carbon emissions.
(Asman, Bolong et al. 2020)	

Topic	**Findings**

Environmental impact evaluation on interlocking compressed earth brick using life cycle assessment	• This study evaluated the embodied energy environmental impact by using cradle-to-gate life cycle carbon emissions in Sabah, Malaysia. • In this study, the author evaluated the embodied energy of Interlocking compressed earth bricks (ICEB), with their main components are clay, sand, water, cement, transportation, and electricity. Tap water has a negligible impact on energy consumption while cement is the most significant contribution of 0.172KgCO$_2$ per 1Kg of Clay bricks with an embodies energy of 0.202KgCo$_2$ Eq. • Reducing of cement content 10% and 15% gives us the reduction of embodied 27% and 51% respectively. • This study concludes that by reducing cement content in ICEB lead to used less embodied energy.
(Asman, Bolong et al. 2023)	

Topic	**Findings**
A Review on Interlocking Compressed Earth Blocks (ICEB) with Addition of Bacteria	• Interlocking Compressed Earth Blocks (ICEBs) are cement-stabilized soil blocks that enable dry-stacked construction, making wall-building faster and requiring less skilled labour. However, there is room for enhancing their durability, which is influenced by factors like water absorption. High water absorption levels can lead to reduced durability. Various studies have explored eco-friendly methods to improve brick durability, including the introduction of bacteria. • These bacteria induce calcite precipitation, continuously covering cracks and effectively addressing durability issues. This paper reviews ICEBs and their potential for reducing water absorption through the use of bacteria, thus enhancing brick durability.
(Irwan, Zamer et al. 2016)	

Table 1. Various researches works on bacteria.



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.

Chapter 03

Methodology

3.1 Introduction

3.2 Mix design

3.3 Materials Properties

  3.3.1 Moisture Content

  3.3.2 Sieve Analysis

  3.3.3 Hydrometer Analysis

  3.3.4 Specific Gravity

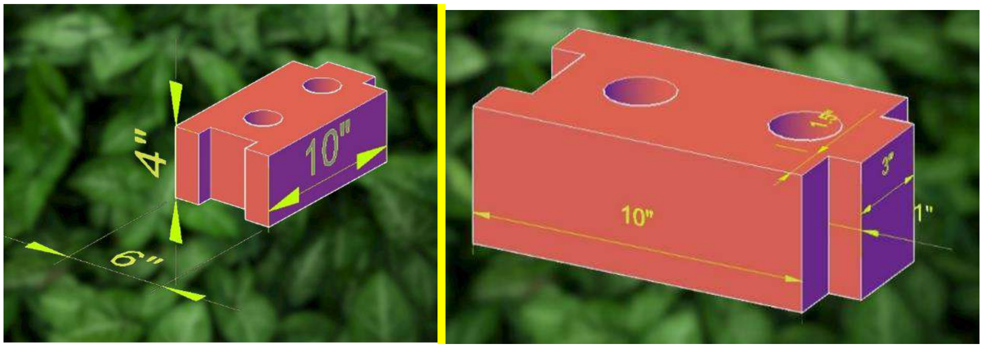
  3.3.5 Plastic Limit

  3.3.6 Liquid Limit

METHODOLOGY

3.1 Introduction

The first step in articulating this research is to decide the shape and size of the CISB. The drawing below is an initial conception. This shape has a simple interlocking design with each brick a bigger in all dimensions than a regular fired brick. Because of the interlocking design and the two holes in the brick that can be lightly reinforced the wall made will be a single brick design. In Figure 3, the piston, base plate, and interlocking mold are shown, while in Figure 4, a wall made up of these interlocked bricks is designed in three dimensions. The brick made in the laboratory is also shown in Figure 4.



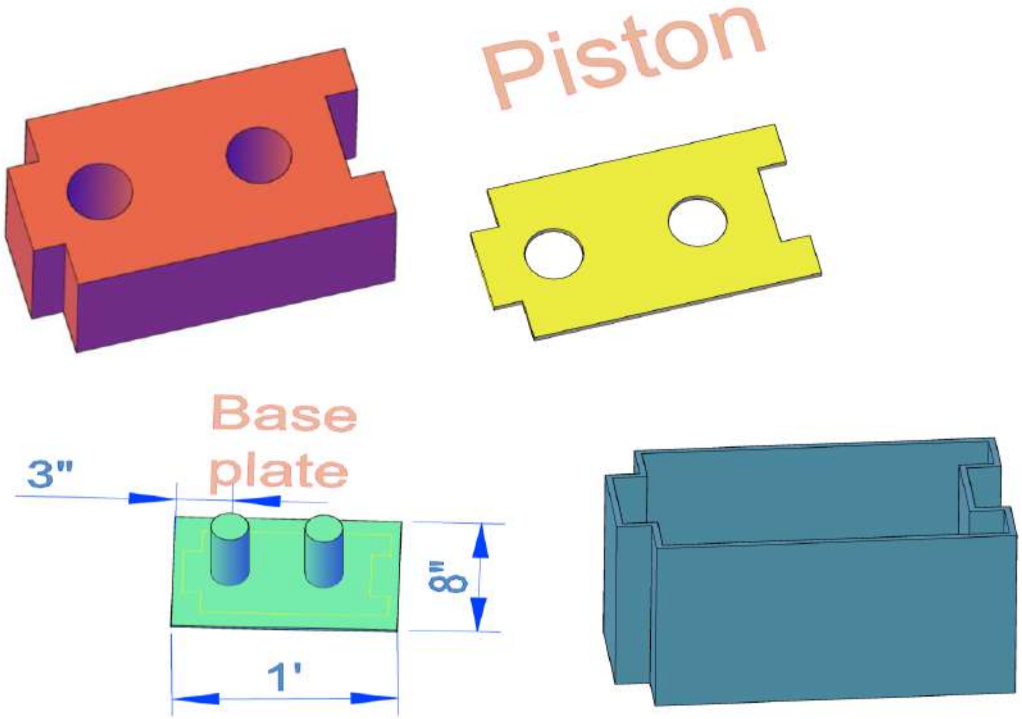


Figure 3

Figure 4

The second step is to make a solid steel mold that corresponds to the shape of the CISB. The first sample prepared will be prepared with only 10% lime giving maximum compressive strength as highlighted in the paper (Malkanthi, Balthazaar et al. 2020). Increasing the percentage of sand also increases strength and reaches the best compressive strength at 40% sand percentage, as explained in the (Dulal, Maharjan et al. 2023) study. The remaining percentage is occupied by soil. Hence an initial mix design with 10% lime, 40% sand and 50% soil has been selected. Using this mix design seven samples will be prepared, and seven tests will be performed: compressive strength test, flexural strength test, water absorption test, density test, geometry test, thermal conductivity test and acoustic insulation test.

3.2 Mix Design

In the systematic exploration of Compressed Interlocking Stabilized Bricks (CISB), a comprehensive process has been devised to delve into material selection, mix design, and an exhaustive series of tests. This research endeavours to optimize the composition, aiming for superior compressive and flexural strengths, water resistance, structural integrity, and thermal and acoustic properties.

The foundational step involves an initial mix design inspired by findings in Malkanthi, Balthazaar et al. (2020) and Dulal, Maharjan et al. (2023). This mix comprises 10% lime, 40% sand, and 50% soil, strategically chosen to maximize compressive strength. The design incorporates an interlocking pattern and reinforced holes to yield a singular brick design.

Utilizing the determined mix design, seven prototypes will be meticulously crafted. These prototypes serve as the canvas for a series of comprehensive tests evaluating their performance under various conditions.

The prototypes will undergo a battery of seven tests, each targeting a distinct aspect of their structural and functional attributes. These include Compressive Strength Test, Flexural Strength

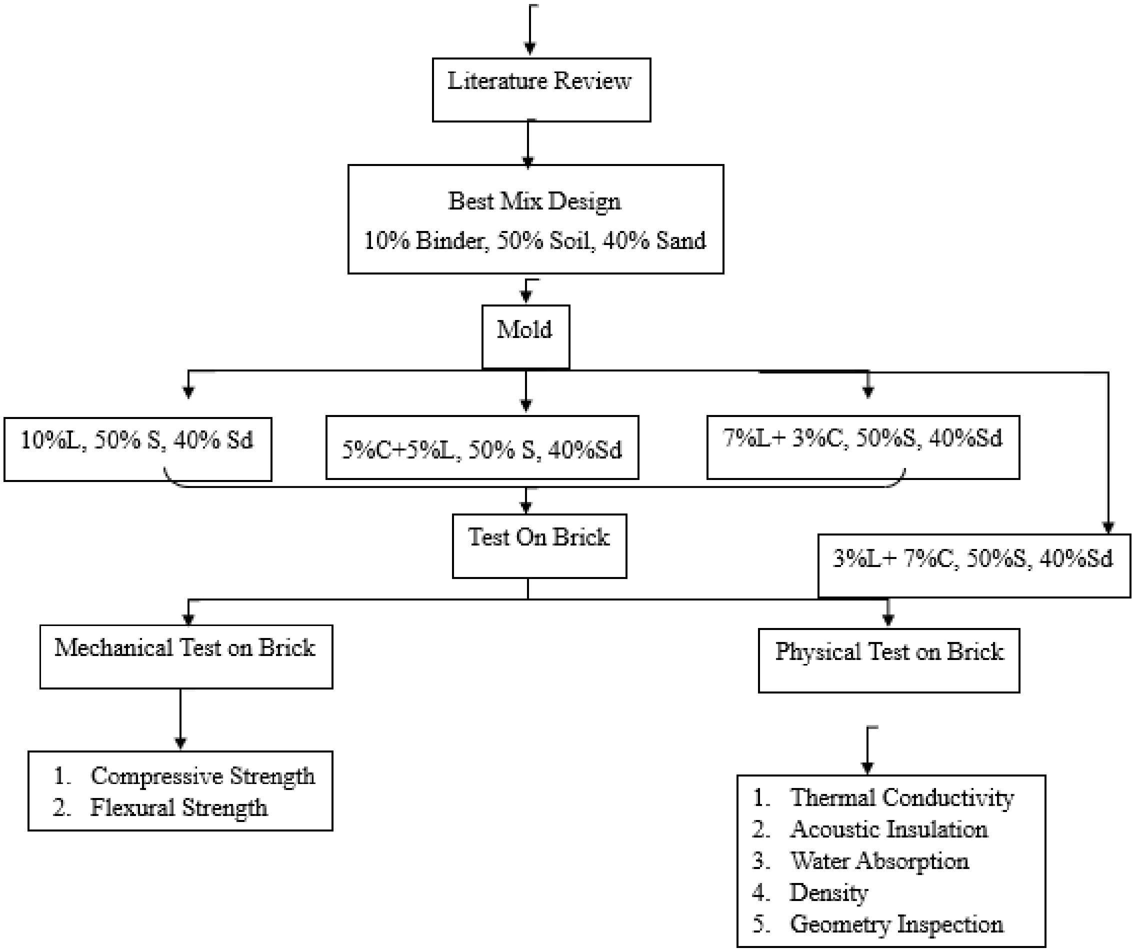
Test, Water Absorption Test, Density Test, Geometry Test, Thermal Conductivity Test, and Acoustic Insulation Test.

Recognizing potential limitations of sole lime as a binder, an additional set of seven samples will be prepared. Each sample varies the lime-cement ratio (7% Lime + 3% Cement, 5% Lime + 5% Cement, and 3% Lime + 7% Cement), drawing insights from Malkanthi, Balthazaar et al. (2020) to enhance overall strength.

In the event of inadequacies in strength and evidence of shrinkage cracks revealed by initial tests, a proactive approach will be adopted. Natural fibers, such as wheat husk, will be incorporated into the most robust sample from the lime-cement series to fortify the material and bolster its durability.

This methodological approach ensures a systematic exploration of the CISB's potential, facilitating continuous refinement based on empirical data. The multi-faceted testing suite guarantees a nuanced understanding of the material's behavior under diverse conditions, paving the way for informed adjustments and innovations in the pursuit of an optimal CISB design.

Flowchart:



3.3 MATERIAL PROPERTIES

3.3.1 Moisture Content

According to the American Society for Testing and Materials (ASTM) D 2216-71 (Testing and Materials 1998), the moisture content of soil is determined using the oven drying method. The determination of moisture content is crucial due to its impact on density, shear strength, buckling, and swelling of the soil. The procedure for moisture content determination involves the use of an empty, clean container, a moist sample, an oven, and a balance.

The procedure is straightforward. Firstly, take an empty, clean container and weigh it as W3. Place some soil sample in the container, weigh it as W1, and then put it in the oven for 24 hours at 110±5°C. After 24 hours, weigh it as W2. To obtain the moisture content, simply divide (W1 - W2) by (W2 - W3) and multiply the result by 100.

The moisture content obtained from our soil sample was **15.54%.** We performed the above procedure three times and then took the average of those results.

3.3.2 Sieve Analysis

To determine the classification of the soil, sieve analysis was performed following the ASTM standard D 422 (ASTM 2007). The apparatus used during sieve analysis included a set of ASTM sieves with Sieve No. 4, 8, 10, 16, 30, 40, 50, 100, 200, and a pan, a measuring balance, a soil pulverizer, a Sieve Shaker, a soft brush, and the soil sample.

Arrange the sieves in order, with the sieve with the largest opening at the top, gradually decreasing in size below. Place the oven-dried pulverized sample on the top sieve and shake it for 5 to 10 minutes. Afterward, calculate the amount of soil retained on each sieve.

Table 2. Sieve Analysis of Soil

Sieve No	Sieve Dia	Mass (gm) Retained	Comm Mass (gm)	Comm%	Passing %
4	4.75	0.35	0.35	0.0294	99.9706
8	2.36	6.66	7.01	0.5896	99.4104
10	2	4.85	11.86	0.9976	99.0024
16	1.18	10.97	22.83	1.9203	98.0797
30	0.595	17.15	39.98	3.3628	96.6372
40	0.42	1.26	41.24	3.4688	96.5312
50	0.297	9.65	50.89	4.2805	95.7195
100	0.149	33.87	84.76	7.1294	92.8706
200	0.074	283.83	368.59	31.0031	68.9969
Pan		820.29	1188.88	100	0
Total Mass (gm)		**1188.88**			

Table 3 Soil Composition	
Gravel, passing 3-in. and retained on No. 4 sieve	0.029439
Sand, passing No. 4 sieve and retained on No. 200 sieve	30.97369
(a) Coarse sand, passing No. 4 sieve and retained on No. 10 sieve	0.968138
(b) Medium sand, passing No. 10 sieve and retained on No. 40 sieve	2.471233
(c) Fine sand, passing No. 40 sieve and retained on No. 200 sieve	27.53432
Particles passing Sieve No 200	68.99687

Hydrometer analysis must be conducted here because **68.99%** of the soil passes through Sieve No. 200.

3.3.3 Hydrometer Analysis

To determine the classification of soil that passes through Sieve No. 200, the analysis can be conducted according to ASTM standards D 421-58 and D 422-63 (Gee and Bauder 1986). The apparatus used in hydrometer analysis includes two 1000 ml graduated glass cylinders, a soil mixer, a dispersing agent (Sodium Hexa Meta Phosphate or Sodium Silicate), a Hydrometer 152H, a measuring balance, a thermometer, and a stopwatch.

The procedure for hydrometer analysis is to take exactly 50 grams of soil sample passing through Sieve No. 200 and mix it with 125 ml of dispersing agent solution. Allow the mixer to stand for one hour and transfer it to the 1000 ml graduated cylinder, ensuring it fills 100%. Take hydrometer analysis readings at intervals of 1, 2, 4, 8, and 30 minutes, as well as 1, 2, 4, 8, and 24 hours, along with temperature readings.

Table 4. Value of Correction factor (a) for specific gravities of soil particles

Specific Gravity (G_s)	**Correction Factor (a)**
2.55	1.02
2.60	1.01
2.65	1.00
2.70	0.99
2.75	0.98

Table 5. Value of L (effective depth) for hydrometer 152H

R	**L(cm)**	**R**	**L(cm)**
0	16.3	30	11.4
1	16.1	32	11.1
2	16.0	34	10.7
4	15.6	36	10.4
6	15.3	38	10.1
8	15.0	40	9.7
10	14.7	42	9.4
12	14.3	44	9.1
14	14.0	46	8.8
16	13.3	48	8.4

Table 6. Hydrometer Analysis of Soil

Test date	30-Nov-23
Hydrometer Number:	H152
Specific Gravity of Soil:	2.5
% Finer of #200 sieve as a percent, F200:	69%
Dispersing Agent:	Sodium Silicate
Weight of Soil Sample:	50
Zero Correction:	5.65
Meniscus Correction:	1

Table 7. Hydrometer Analysis of Soil 1.0

Date	Time	Elapsed Time (min)	Temp	Actual Hydr. Reading (Ra)	Hydro. Correct for Meniscus	L from Table	K from Table
30-Nov-23	9:57AM	0	23.1	52	53	7.6	0.01358
	9:58AM	1	23	52	53	7.6	0.01358
	10:00 AM	3	23.1	51	52	7.8	0.01358
	10:04 AM	7	23.1	51	52	7.8	0.01358
	10:08 AM	15	23.1	50	51	7.9	0.01358
	10:24 AM	30	23.1	49	50	8.1	0.01358
	10:54 AM	60	23.2	48	49	8.3	0.01358
	11:54 AM	120	23.6	48	49	8.3	0.01358
	1:54 PM	240	24.2	47	48	8.4	0.01358
	5:54 PM	480	24.7	46	47	8.6	0.01358
	9:57AM	1440	21.8	47	48	8.4	0.01358

D (mm)	Ct From Table	a From Table	Corr. Hydro. Reading (Rc)	% Finer (P)	Adjusted Finer (Pa)
0	0.7	1.02	47.05	95.982	66.22758
0.0374	0.7	1.02	47.05	95.982	66.22758
0.0219	0.7	1.02	46.05	93.942	64.81998
0.0143	0.7	1.02	46.05	93.942	64.81998
0.0099	0.7	1.02	45.05	91.902	63.41238
0.0071	0.7	1.02	44.37	90.5148	62.455212
0.0051	0.7	1.02	43.37	88.4748	61.047612
0.0036	1	1.02	43.37	88.4748	61.047612
0.0025	1	1.02	42.37	86.4348	59.640012
0.0018	1.3	1.02	41.37	84.3948	58.232412
0.001	0.4	1.02	42.37	86.4348	59.640012

Table 8. F. Soil Classification	**%**
Gravel, passing 3-in. and retained on No. 4 sieve	0.03
Sand, passing No. 4 sieve and retained on No. 200 sieve	31
(a) Coarse sand, passing No. 4 sieve and retained on No. 10 sieve	1
(b) Medium sand, passing No. 10 sieve and retained on No. 40 sieve	2.5
(c) Fine sand, passing No. 40 sieve and retained on No. 200 sieve	27.53
Particles passing Sieve No 200	69
Silt size, 0.074 to 0.005 mm	61.05
Clay size, smaller than 0.005 mm	7.95
Colloids, smaller than 0.001 mm	0

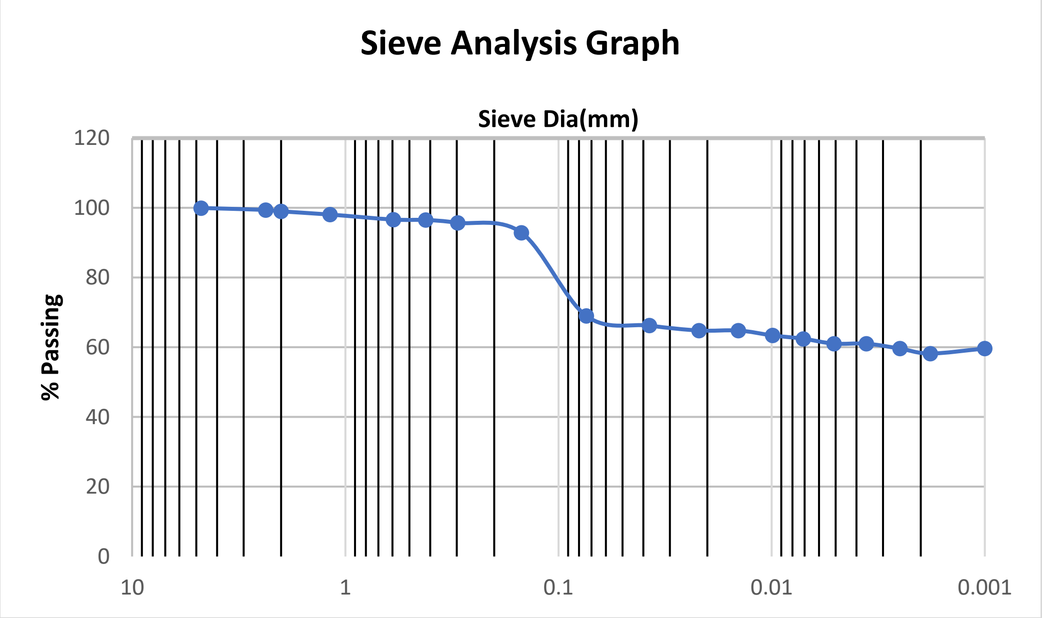


Figure:1

According to ASTM 2487 (Soil and Rock 2017), it is based on the Unified Soil Classification System (USCS), in which the given sample is classified as **CL-ML Sandy Silty Clay with Gravel**.

3.3.4 Specific Gravity

To determine the specific gravity of soil is crucial because other important parameters of soil can be derived from it. Specific gravity is the ratio of the weight of a given volume of material to the weight of an equal volume of water.

According to ASTM standard D 854-58 (AASHTO 2006), the specific gravity of soil is determined through a specific procedure explained here. A volumetric flask of 250ml, a balance, thermometer, and soil pulverizer are used in this process.

The procedure for determining specific gravity is as follows:

- Weigh the empty volumetric flask as W1.
- Add 50 to 100 grams of pulverized soil sample to the volumetric flask and weigh it as W2.
- Add distilled water to the volumetric flask until a specific mark, which is at the neck of the volumetric flask, is reached. Remove any voids and, after cooling, measure their mass as W3.
- Empty the flask, add distilled water to it, and record the weight as W4. Also, measure its temperature.

Table 9. Specific Gravity of Soil		
Flask (W1)	W_1	280.14gm
Flask + Soil (W2)	W_2	330.37gm
Flask + Soil + Water (W3)	W_3	1304.01gm
Flask + water (W4)	W_4	1274.76gm
SG= $(W_2-W_1)/[(W_4-W_1)-(W_3-W_2)xK]$		**2.5**

Table 10. for the value of correction factor (K)

Temp (ºC)	Density of Water (g/ml)	Correction Factor (K)
18	0.9986	1.0004
19	0.9984	1.0002
20	0.9982	1.0000
21	0.9980	0.9998
22	0.9978	0.9996

23	0.9975	0.9993
24	0.9973	0.9991
25	0.9970	0.9989
26	0.9968	.09986
27	0.9965	0.9983
28	0.9962	0.9980
29	0.9959	0.9977
30	0.9956	0.9974

Table 11. Specific Gravity of different type of Soil

Gravel	2.65 – 2.86
Sand	2.63 – 2.67
Silt	2.65 – 2.68
Clay	2.67 – 2.9
Organic Soil	Less than 2

The Specific Gravity of the soil used is **2.5**.

3.3.5 Liquid Limit

To determine the liquid limit (the amount of moisture content at which soil transitions from a plastic to a liquid state), ASTM standards D 423-66 (Kollaros 2016) and D 424-59 (Afrin 2017) must be followed when using a Casagrande-type mechanical liquid limit device.

The apparatus used to ascertain the liquid limit includes a penetrometer, penetration cone assembly, container, gauge plate, balance, stopwatch, mixing bowl, wash bottle, humidifier, spatula, and worksheet.

Take a 200g soil sample and mix it with 50–70ml of water until a homogeneous paste with a uniform color is obtained.

Push the soil paste into the metal cup to prevent air from entering during the process. Remove excess paste and flatten it using a spatula.

Place the cup under the penetrometer and lower the cone until it is just above the soil paste. Release the spindle for 5 seconds and record the reading.

The initial reading should be close to 15mm. Take a representative sample of 10g and weigh it before and after drying.

Repeat the process by adding some water to the remaining sample and record readings until reaching 25mm or greater, taking 3 to 4 readings.

The moisture content corresponding to 20mm will be the liquid limit of the soil sample; in this case, the liquid limit is **27.19%**.

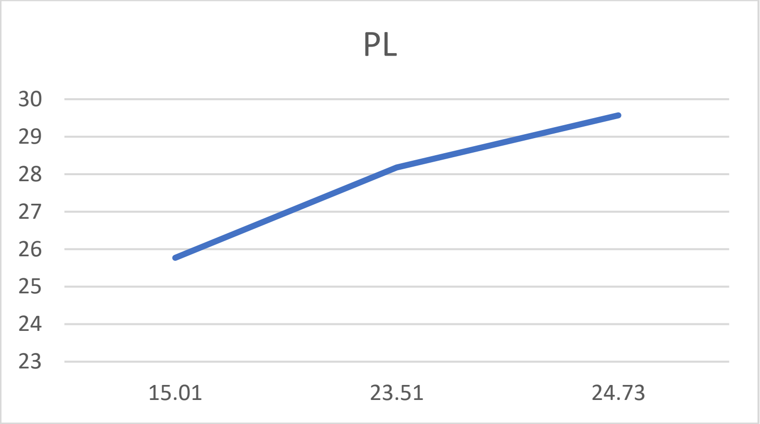


Figure:2

Table 12. Moisture Content of Soil		
Trials	**Moisture Content (%)**	**Penetration (mm)**
1	25.77	15.01
2	28.18	23.51
3	29.57	24.73
The moisture content at 20mm penetration is 27.19%.		

3.3.6 Plastic Limit

To determine the plastic limit of a soil sample, ASTM standards D 423-66 (Kollaros 2016) and D 424-59 (Afrin 2017) are followed.

Take 20 grams of soil (oven-dried) and mix it with water to form a plastic ball shape. Take 8 grams of the plasticized soil and roll it to make it crumble with a diameter of 3mm. Collect the crumbled sample and place it in the oven, ensuring to measure its weight before and after heating. Repeat this process three to four times and calculate the average. In this case, the average moisture content of the crumbled soil sample was **21.14%.**

Chapter 04

4.1 Conclusion

4.1 CONCLUSION

In the end we conclude that our compressed interlocking stabilized bricks are economically viable, environmentally friendly, and cater to easy and simple construction processes. In rural areas these bricks can enable cheap, fast, and easy-to-make houses complementing the economy and social growth. Which is a key demand of the SDGs. Lastly CISBs are recyclable and have minimal adverse ecological impact which is a key aspect of sustainable future growth.

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