

**ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE
SLAG AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY
BRICKS FOR CONSTRUCTION**

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ABSTRACT

The proposed research and design project is a final year study, which was carried out between May and November 2025 at Uganda Christian University to determine the applicability of Ground Granulated Blast Furnace Slag (GGBS) as a stabiliser in the production of unfired clay bricks that can be used in the construction process. The poor compressive and high-water absorption of the unfired clay bricks in Namakwekwe, Mbala, Uganda, led to the study.

The study entailed laboratory characterization of the local clay soils, such as, particle size distribution, Atterberg limits, Chemical; composition and specific gravity of the soils after which blending experiments were conducted including addition of GGBS at various proportions. The resulting brick specimens were subject to standard tests which determine compressive strength, water absorption capability, bulk density, efflorescence, and load-bearing capacity as per the international standards e.g. BS 1377:1990, ASTM C67, and EN 1996-2:2006.

It was found out that inclusion of GGBS considerably enhanced the mechanical and serviceability attributes of unfired clay bricks. Best mix ratios gave compressive strengths above the minimum needed of 3.5 MPa, as well as water absorption values decreased to the control range of 12-15%. GGBS led to increased particle interlocking and helped the creation of cementitious gels thus, increasing cohesion and decreasing shrinkage cracking.

DECLARATION

I, Bak Kau Nak, hereby declare that this final year research and design project report is my original work, entitling it “Ground Granulated Blast Furnace Slag to assess the suitability of the material as a stabiliser when manufacturing unfired clay bricks to be used in construction”. It has never been plagiarised, neither has it been presented to any other institution to award a degree or any other academic qualification. All information sources employed in this report have been adequately recognised.

Signature: _____

Name: BAK KAU NAK

Registration Number: M22B32/007

Date: _____

APPROVAL

This is with a certification that the research and design project report entitled Assessing the Suitability of Ground Granulated Blast Furnace Slag as a Stabiliser in the Manufacturing of Unfired Clay Bricks to be used in constructions has been conducted under my supervision by Bak Kau Nak. I do accept this report to submit it to Faculty of Engineering, Design and Technology of Uganda Christian University in part fulfilment of the requirements of awarding the degree of Bachelor of Sciences Civil and Environmental Engineering.

Signature: _____

Date: _____

MR. TOM MORE MWANJE

(ACADEMIC SUPERVISOR)

DEDICATION

The present research and design project report is dedicated to my family because it is their invaluable support and push that made my academic life what it is today. Their instruction and understanding of the importance of education has always motivated me to be excellent.

ACKNOWLEDGEMENT

To start with, I would like to thank the Almighty God who blessed me with the gift of life, wisdom and strength to finish this research project within the necessary time I had.

I would like to express my deepest thanks to my academic supervisor, MR. Tom More Mwanje due to his advice, tolerance and priceless help during the process of this research. His tutelage has played a critical role in the design of direction and quality of this work.

The special recognition goes to the Faculty of Engineering, Design and Technology at Uganda Christian University that offered the environment and resources needed to complete this project at the academic level. I would also like to thank the laboratory workers and my colleagues who provided some technical support and helpful feedback in the course of this experimental stage.

Finally, I would like to mention that I have moral support, encouragement, and understanding of my parents, family, and friends. They have played critical roles in the successful achievement of this research, in their different capacities.

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LIST OF ABBREVIATIONS

GGBS - Ground Granulated Blast Furnace Slag

ASTM - American Society for Testing and Materials

BS - British Standard

CEBs - Compressed Earth Bricks

EN - European Norm

Gs - Specific Gravity

ISSBs - Interlocking Stabilized Soil Bricks

kg - Kilogram

kg/m³ - Kilogram per cubic metre

KN - Kilonewton

LL - Liquid Limit

LSL - Linear Shrinkage Limit

mm - Millimetre

MPa - Mega Pascal

C-A-S-H - Calcium Aluminosilicate Hydrate

% - Percent

PI - Plasticity Index

PL - Plastic Limit

CHAPTER ONE: INTRODUCTION

1.0 BACKGROUND

The developing world such as Uganda is under the growing pressure of using sustainable materials and processes in the construction industry to reduce the environmental effect of the traditional construction processes. Among them is the widespread use of fired clay bricks, which require a lot of energy to burn in the form of bricks and release a lot of greenhouse gases because of the use of wood-fired kilns (Singh et al., 2024). Another option is to use unfired clay bricks, sun-dried rather than kiln-fired, which is a low-cost and ecologically friendly alternative to walling construction and saves energy and carbon emissions (Muheise Araalia and Pavia, 2020).

As the demand of affordable housing and infrastructure grows in Uganda, there is an urgent need to explore the possibility of using GGBS to enhance unfired clay bricks properties in the country since they are limited in mechanical strength and can easily degrade due to water and, therefore, stabilization is necessary to be used in the broad scope of application (Reddy et al., 2018).

The utilization of Ground Granulated Blast Furnace Slag as a sustainable technology in geopolymer and cement-replacement technologies has been encouraged worldwide. Ground Granulated Blast Furnace Slag (GGBS) is a by-product of the steel manufacturing process that has been known to have cementitious characteristics when used in several construction works (Neville, 2012). GGBS is obtained by the rapid cooling of molten slag that is generated during the iron ore extraction in a blast furnace and granulated slag is produced with the help of water or air (Patel et al., 2023). This granulated slag is then dried then ground in ball mills or vertical

roller mills to fine powder to form GGBS. Amorphous silica and alumina are found in the final product and have latent hydraulic and pozzolanic activity (Chen et al., 2023). These chemical characteristics enable GGBS to generate calcium silicate hydrate (C-S-H) and calcium alumino-silicate hydrate (C-A-S-H) in the presence of water and calcium hydroxide and eventually enhance compressive strength, durability, and water resistance of construction materials, such as unfired bricks (El-Sayed and Hassan, 2024).

GGBS is becoming more available in the framework of Uganda because of the development of local steel and cement production industries (Lutaaya et al., 2022). Although Uganda does not have large-scale iron blast furnaces, a number of steel industries in the country like Jinja, Tororo and Namanve produce slag as one of the by-products of electric arc furnaces and mini-blast furnaces. These are like Roofings Rolling Mills, Steel Rolling Mills Ltd and Pramukh Steel Ltd among others. Part of this slag is reworkable into GGBS by use of available grinding facilities at the local cement plants.

Considering the industrial activity in Eastern Uganda and the current attempts to introduce sustainable construction material, the GGBS can be sourced realistically to produce both small and large scale of unfired clay bricks.

Recent studies demonstrate good outcomes: in bricks, a compressive strength of 3.5-24 MPa and water absorption of 4-7% with 25-30 percent replacement of cement with GGBS showed compliance with the requirements of a brick (Chen et al., 2023). Similar improvements like increased water resistance and mechanical durability of concrete are also described in other studies that use industrial by-products, including GGBS (El-Sayed and Hassan, 2024). Regardless of these developments,

concerns on the most appropriate proportions of mixes, performance in humid climates over the long term, and adjustment to local soils remain.

The purpose of this research is to determine the effect of the different concentrations of GGBS on the structural and durability properties of unfired clay bricks. The research aims to fill the gap between the theoretical advantages of compressive strength, water absorption, and resistance to erosion and practical application of the same to aid in the development of low-cost, sustainable bricks to match the construction requirements of Uganda.

1.1 PROBLEM STATEMENT

In Mbala District Namakwekwe, both fired and unfired clay bricks are also very common when it comes to the building of low-cost houses. Nonetheless, unfired bricks that are produced on-site tend to be weak, highly porous, and they quickly degrade during wet seasons because of their low compressive strength and large water absorption capacity (Muheise Aaralia and Pavia, 2020). Conversely, fired bricks are stronger, but their manufacturing is energy-consuming, and it requires burning biomass fuels, e.g., wood, which increases deforestation and greenhouse emissions (Lutaaya et al., 2022).

BS 3921:1985 states that a minimum compressive strength of 5 MPa of standard fired clay bricks should be used in general purpose and that EN 1996-2:2006 suggests that a unit of masonry should not have a water absorption rate exceeding 16% to maintain structural integrity and durability particularly in humid conditions. Nevertheless, research indicates that locally manufactured unfired clay bricks in Uganda usually have compressive strengths of 1.5-3.5 MPa and water absorption rates tend to be greater than 20% and are not suitable to be used as structural material in the long

term without stabilization (Muheise Araalia & Pavia, 2020). This is a critical void in performance that underscores the immediate need to have affordable and sustainable processes like GGBS stabilization to improve the mechanical and durability characteristics of locally made bricks.

Reddy and Jagadish (2018) showed that the addition of fly ash into clay bricks remarkably increased compressive strength and durability. In the same manner, Chen et al. (2023) found that Ground Granulated Blast Furnace Slag (GGBS) mixed with fired brick matrices produced compressive strengths up to 24 MPa and water absorption less than 7 per cent, which is within international brick standards. Amakye et al. (2021) also indicated the potential use of steel industry waste materials, including slag, in the soil stabilization and masonry industries in Uganda. Nevertheless, in spite of these results, there is scanty research work done in Uganda to evaluate how locally obtained GGBS might be effectively applied to stabilize unfired clay bricks especially within the tropical climate of the country, local soil properties, and informal construction procedures.

Consequently, the current research paper offers to determine the appropriateness of Ground Granulated Blast Furnace Slag (GGBS) as a stabilizing material when manufacturing unfired clay bricks. This is aimed at determining an ideal mix design, which enhances compressive strength, water absorption resistance, and erosion resistance, using locally available clay soils in Mbala District. The proposed research will offer a feasible and replicable solution to manufacturing structurally sound and environmentally friendly walling units, thus building affordable and sustainable construction in Uganda, and make an example of industrial wastes.

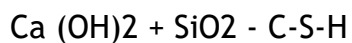
1.2 JUSTIFICATION

The research only fills a burning need in the construction industry of Uganda: it is necessary to identify low-cost building materials that can be used sustainably and would work successfully in the local environment. Even though unfired clay brick has some interesting advantages like less energy consumption, carbon emissions, than the kiln-fired one does, it lacks mechanical strength and easily gets damaged by water unless properly stabilized (Patel et al., 2023). This introduces a distinct technological divide especially in areas such as Namakwekwe in Mbala District whereby the soils in the area are different and construction activities are informal.

Ground Granulated Blast Furnace Slag (GGBS) is a promising locally available treatment because of its latent hydraulic and pozzolanic properties that allow it to create cementitious compounds in combination with moisture and active minerals in clay (Amakye et al., 2021). The main reactions that may take place on incorporation of GGBS into a clay matrix can be as follows:

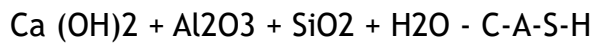
Latent Hydraulic Reaction

GGBS is added to water and calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form Calcium Silicate Hydrate (C-S-H), which is the form of cementitious systems that forms the major source of strength.



Pozzolanic Reaction

Alumina (Al₂O₃) and silica (SiO₂) were also present in GGBS and reacts with Ca(OH)₂ and water to form Calcium Alumino-Silicate Hydrate (C-A-S-H):



Such hydrates increase significantly the compressive strength as well as the water resistance of the bricks with time (El-Sayed & Hassan, 2024). Although these reactions are only initiated by natural alkaline minerals in clay in unfired states, in certain regions with moisture-rich curing conditions such as in Eastern Uganda, these reactions can occur to an adequate extent.

1.3 SIGNIFICANCE

The Uganda construction sector is experiencing growing demand of cheaper and more sustainable and environmentally friendly building materials due to the growing rate of urbanization and the necessity to curb environmental pollution caused by fired bricks (UBOS, 2023). The use of traditional fired bricks production in Uganda has been a major contributor to deforestation caused by overuse of firewood, which causes soil erosion and carbon emission (NEMA, 2020). The paper is meaningful because it discusses the advantages of using Ground Granulated Blast Furnace Slag (GGBS) as an additive to unfired clay bricks to ensure sustainable construction.

The use of GGBS as an industrial byproduct of the iron making process is also in line with the world to use waste materials in construction processes, which will lower landfill waste and save the natural resources (Neville, 2011). GGBS has demonstrated the ability to strengthen and make building materials more durable and environmentally friendly (BSI, 2015). Nevertheless, the usage in the production of unfired clay bricks is under-researched, especially in the country of Uganda.

The study is relevant to the body of knowledge since it presents data about the best utilization of GGBS on clay soils of Namakwekwe and Nabumali as a supporting factor in the production of low-cost, eco-friendly bricks that can be used in sustainable housing. In addition, the use of unfired brick technology is also encouraged to cut down on the use of energy and greenhouse gases, which is in line with the sustainable development targets of Vision 2040 that are to be implemented in Uganda (National Planning Authority, 2020).

The research will have an implication to the local brick manufacturers, policymakers, and construction industry by providing the alternative to fired bricks, improving the environmental effects, and increasing the material performance in the building use.

1.4 RESEARCH OBJECTIVES

1.4.1 MAIN OBJECTIVE

To determine the suitability of Ground Granulated Blast Furnace Slag as a stabilizer in production of unfired clay bricks to be used for construction.

1.4.2 SPECIFIC OBJECTIVES

1. To determine the physical and chemical characteristics of the clay soils in Namakwekwe and Nabumali that can be used to make unfired bricks.
2. To determine the optimum amount of Ground Granulated Blast Furnace Slag that can be added to the local clay soils of Namakwekwe for manufacturing unfired clay bricks
3. To determine the effect of Ground Granulated Blast Furnace Slag on the physical and chemical properties of the unfired clay bricks, including the

impact of drying time and humidity conditions on the performance of stabilised unfired bricks.

1.5 RESEARCH QUESTIONS

1. Which major physical and chemical characteristics of clay soils at Namakwekwe and Nabumali affect their usage in the production of unfired bricks?
2. What are the physical and chemical characteristics of unfired clay bricks when Ground Granulated Blast Furnace Slag is added?
3. How much Ground Granulated Blast Furnace Slag should be used to produce the optimum performance in unfired clay bricks manufactured using local clay soils?

1.6 GEOGRAPHICAL SCOPE

This research will be carried out in Namakwekwe in the Mbala District in the East of Uganda. High clay content of the soil, informal brick-making industries, and the increasing residential developments are some of the characteristics of the area that require low-cost building materials. Their closeness to nearby steel plants and cement industries including the ones found in Tororo, Jinja, and Namanve makes the access to GGBS realistic to be used in experiments (Lutaaya et al., 2022).

1.6.1 Time Scope

The time frame of the study is five months with the time spent on collecting soil and GGBS samples, then running laboratory tests, moulding and curing bricks during up to 28 days, and mechanical testing. It is anticipated that the research would be done during the period of August 2025 through November 2025.

CHAPTER TWO: LITERATURE REVIEW.

2.1. Introduction

The tension between sustainability and performance is underscored in the literature on the topic of unfired clay bricks. Although unfired bricks are environmentally friendly, they have limited mechanical capabilities which have limited their application. Researchers have thus discussed stabilizers that can improve strength as well as durability without affecting the eco-friendliness. Ground Granulated Blast Furnace Slag (GGBS) is one of the by products of the steel industry that are also a candidate because of their pozzolanic reactivity, cost-effectiveness, and the use of industrial wastes. This review summarizes research on clay soils, GGBS characteristics and performance of stabilized unfired bricks, whilst placing the study in the wider context of sustainable construction.

Researchers are working on how to stabilize clay or soil matrices with industrial by-products or chemical additives to enable the production of bricks curing in ambient or mild conditions instead of fire (Jones & Wilson, 2019). Ground Granulated Blast Furnace Slag (GGBS) is one of such promising additives.

GGBS is a by-product of steel/iron industry. GGBS when finely ground and activated (say, by lime or alkali) contains latent hydraulic or pozzolanic properties that may react with aluminosilicate phases to form binding gels (e.g. C-S-H) (Thomas, 2007). The general hypothesis of the given direction of research is as follows: GGBS when activated accordingly can serve as a stabilizer in the clay or soil matrices and enhance the engineering characteristics of unfired bricks to the level that may be permitted to be used (Lee et al., 2020).

2.2 Physical Characteristics of Clay Soils to make bricks.

2.2.1 Clay Soils for Brick Making

The clay soils are not homogeneous; their ability to make bricks is based on the mineralogy, particle size, and plasticity. In some areas like Namakwekwe the soils are usually excessive silt with little sand and the soils usually shrink and do not cure properly. According to literature, the variability of clay, which is determined by climatic conditions, topography, and land use: it must be stabilized to produce consistency in performance. Hence, clay is a resource, and it has an issue, that is, it is plentiful and, at the same time, does not possess the qualities of durability of unfired masonry properties.

2.2.2 Clay Soils- Physical Properties.

2.2.2.1 Particle Size Distribution

Balance between workability and cohesion depends on the size of the particles. A soil that contains fines is easily moulded but cracks upon drying whereas a sandy soil does not crack and does not cohesion. Both durability and moldability are guaranteed by the ideal blend (20-30% clay, 30-50% silt, 20-30% sand). The poor gradation can be countered by the use of stabilizers such as GGBS, which fill the spaces and form a denser matrix, which leads to minimization of shrinkage and increased interlocking of particles.

2.2.2.2 Atterberg Limits

Atterberg limits, i.e. liquid limit, plastic limit and plasticity index are imperative signs of soil behaviour. The index of plasticity between 15-35 is the ideal index in the production of bricks. Excessive shrinkage is indicated by high PI values and poor

cohesion is indicated by low PI values. GGBS replaces these limits with minimized plasticity hence limiting shrinkage cracking as well as enhancing moldability. This change is not the numbers only, but it represents an essential change in the reaction of soil to moisture and stress.

2.2.3.3 Moisture Content of Natural Clay Soils.

Natural Moisture Content (NMC) is the quantity of water that is found in a given sample of soil in its natural form before any drying or other form of treatment occurred. It is given as percentage of the mass of dry soil and is a key parameter of the behaviour of clay soils that are used in making of the bricks. Soils that have high natural moisture content are usually associated with a low load-bearing capacity and high shrinkage potential whereas soils that have very low moisture content can be hard to shape.

NMC has direct effects in brick production as it affects compaction, drying behaviour, and shrinkage. The soils with medium moisture content (5-15%) are usually regarded to be appropriate in moulding as they provide the best balance between the workability and cracking risks. A high moisture (more than 20-percent) may cause deformation, long drying periods, and unsatisfactory compressive strength. Consequently, NMC needs to be determined to predict the behaviour of the clay soils in the process of casting and curing the bricks and, whether the stabilization with additives like GGBS is required or not to enhance performance.

2.2.2.4 Spec. Gravity of Clay Soils.

Specific gravity is the ration of the density of solid of the soil as compared to the density of water at normal temperature. The specific gravity is a basic property that classifies soils and determines their acceptability in engineering practice (AASHTO

T100-95, 1995). In the case of clay soils, average values are between 2.6 and 2.8, which is an indication of the mineral compositions of silica, alumina, and the oxides of iron.

Specific gravity in the context of the brick making industry gives an understanding of packing density of the soil particles and the capacity of the particles to have an effective matrix when compacted. The larger the specific gravity, the stronger the potential of the soils is since one is able to hold a larger mass within a particular volume. On the other hand, low values indicate the presence of light soils that are less compressive. The addition of GGBS, which possesses an average specific gravity of a little higher (2.8-3.0) results in the general augmentation of the density of the brick matrix and, consequently, in the enhancement of the load-bearing capacity and decreased porosity. Therefore, specific gravity analysis plays a critical role in the assessment of the compatibility of local clay soils as far as the GGBS stabilization is concerned.

2.2.2.5 Free Swell Index

Free swell Index is calculated in line with ASTM D720/D720M, the index denotes the increment of a soil sample volume when no external force and no submergence into water occur. It is especially critical to clays which are likely to swell owing to their fine particle size and a strong preferential affinity to water. Soils with high FSI are classified as expansive and capable of experiencing large changes in volume that cause the cracking and instability of the structures made of bricks.

High swelling behaviour is not sought after in the production of bricks since it affects the dimensional stability and long life. This can be solved by stabilization using GGBS to ensure that the soil does not absorb a lot of water, which will cause it to swell.

The cementitious compounds formed by the pozzolanic reactions of GGBS hold the clay particles together limiting their mobility and swelling potential. Consequently, the GGBS-stabilized bricks have a better dimensional stability, less shrinkage cracking and better long-term durability.

2.2.3 Chemical Properties of Clay Soils.

2.2.3.1 Chemical Composition

The clay soils are usually characterized by silica, alumina, iron oxides and lime. These compounds affect rigidity, plasticity and water absorption. Nevertheless, the soils in Namakwekwe tend not to be of the ideal quality, resulting into poor bricks. GGBS is a calcium aluminosilicate, which fills the deficient compositions of clay, and gives supplement cementitious components throughout hydration. It is this synergistic action between clay minerals and GGBS that contributes to the enhancement of the performance of brick.

2.2.3.2. X-Ray Fluorescence (XRF) Analysis of Clay Soils

X-Ray Fluorescence (XRF) is an analytical method that is commonly used in the determination of chemical composition of soils and construction materials. In case of clay soils to make bricks, XRF gives accurate data of major oxide silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and magnesium oxide (MgO). These oxides have a direct effect on the engineering characteristics of clay bricks.

- ✚ Silica (SiO_2) is used to provide rigidity and strength, and it is the basis of the brick structure.

- ✚ Alumina (Al_2O_3) makes clay plastic and it can be moulded easily and also decreases the absorption of the water.

✚ Iron oxide (Fe_2O_3) influences colour and gives strength.

✚ Calcium oxide (CaO) is used in minimizing shrinkage and enhances dimensional stability.

XRF analysis of clay soils in areas like Namakwekwe is especially significant since in most cases local soils are not formed by their ideal compositions. To illustrate, too much silt or low silica content may end up producing weak porous bricks. XRF helps to determine these deficiencies, and therefore it gives scientific grounds on the introduction of stabilizers such as GGBS. Overall, XRF is a diagnostic tool that will give the chemical fingerprint of the soil and inform on how to modify it to perform better in creating bricks.

2.2.3.3 Specific Gravity

Specific gravity represents the density and packing capacity. Clay soils (2.6-2.8) are less heavy than GGBS (2.8-3.0), that is, addition of GGBS raises density and compressive strength. This property is very essential in unfired bricks because it should be able to balance low dead weight with the required strength to overcome structural loading.

2.3 Physical and Chemical Characteristics of Ground Granulated Blast Furnace Slag (GGBS).

2.3.1 Definition and Composition

GGBS is produced as a result of smiting slag into fine powder. Its latent hydraulic and pozzolanic properties are due to its composition that includes calcium silicates, alumina and magnesium oxides. GGBS is not activated like cement, and therefore it is better suited to be mixed with clay soils, which naturally have reactive minerals.

2.3.2 Reactivity, Pozzolanic Behaviour.

The GGBS is reactive because it can be used to produce cementitious gels like calcium silicate hydrate (C-S-H) and Calcium aluminosilicate hydrate (C-A-S-H). These gels cement soil particles, decrease porosity, as well as strengthen it, and make soil strong. It is not only a chemical process but also a conversion of waste into value since industrial by-products are converted into construction materials which have a long life.

2.3.3 Review on GGBS basing on durability.

Literature has always indicated that GGBS enhances compressive strength and water absorption is minimized, durability under wet-dry cycles is also increased. It also reduces efflorescence through binding soluble salts in the matrix. The advantages of GGBS-stabilized unfired bricks enable these bricks to be similar to the fired bricks but with much lower environmental costs.

2.3.4 X-Ray Fluorescence (XRF) of Ground Granulated Blast Furnace Slag

XRF analysis is also important in characterizing GGBS because depending on its chemical composition defines its reactivity and compatibility as a stabilizer. GGBS typically contains:

- ✚ 30-40% calcium oxide (CaO), that helps in the latent hydraulic reactions and formation of calcium silicate hydrate (C-S-H).
- ✚ Silica (SiO₂ 30-40% silica), a component of the pozzolanic reactions and the cementitious gels formed are the ones that provide strength.
- ✚ 10-15% alumina (Al₂O₃), that enhances durability and is part of the mixture of forming calcium alumino-silicate hydrate (C-A-S-H).

✚ Lower concentrations of magnesium oxide (MgO) and other minor traces that determine its long-term stability and anti-chemical resistance.

Using XRF, the precise contents of these oxides are determined, which allows to make sure that the GGBS utilized in stabilization is up to the performance. As an example, greater content of CaO shows high hydraulic reactivity whereas balanced content of SiO₂ and Al₂O₃ shows good pozzolanic behaviour.

Practically, the XRF analysis of GGBS enables researchers to estimate its behaviour under the presence of clay soils. Combined, cementitious compounds of the calcium and silica in GGBS are used to complement the natural minerals in clay to increase the density of the brick matrix, decrease porosity, and increase compressive strength. Therefore, XRF can confirm the quality of the GGBS, as well as offer an understanding of why it is useful in the conversion of the unfired clay bricks to strong and eco-friendly building resources.

2.3.5. XRF in this study.

This study is scientifically based as XRF is used to analyze clay soils and GGBS. In the case of clay, XRF determines deficiencies that justify poor performance of local unfired bricks. In the case of GGBS, XRF is used to establish the presence of reactive oxides that are able to offset such shortcomings. These analyses combined allow to give a clear chemical explanation of stabilization, which connects theory with practice.

2.4 Physical Properties, Chemical Properties of Unfired Clay Bricks.

2.4.1 Clay Bricks

Millennia have been using clay bricks because of its cheapness and durability. They are easy to stack and they have a rectangular form which makes them ideal in construction. Nevertheless, conventional fired bricks are very energy-consuming and release vast amounts of CO₂, which makes the use of unfired type intriguing.

2.4.2 Unfired Clay Bricks

The bricks are sun-dried and therefore do not require firing in a kiln. They are not as strong and porous though they are environmentally friendly. The use of GGBS stabilization eliminates these constraints, and the unfired bricks can be used to support the structural needs as well as ensuring stability.

2.4.3 Unfired Clay Brick Physical Properties.

2.4.3.1 Compressive Strength Test

The most important property of bricks is compressive strength because it defines its capacity to hold structural loads. The general-purpose clay bricks have 3.5 MPa as the minimum compressive strength according to BS:3921-1985. On the one hand, unfired clay bricks may be below this value as they are porous and not fired by the kiln. The method of the test entails the use of vertical load in the form of failure and the determination of strength as the ratio of failure load to the gross area of the brick. It is established in the literature that additives like GGBS that enhance compressive strength form cementitious gels (C-S-H and C-A-S-H) that cementitious particles to one another. This improvement enables bricks to be of a type that is less than the required minimum strength and therefore useable in permanent construction.

2.4.3.2 Water Absorption Test

Water absorption is a parameter that determines the porosity of the brick and its resistance to the ingress of moisture. BS:3921-1985 requires that the maximum water absorption capacity of durable masonry units should not be more than 16%. Overabsorption makes the bricks weak, cohesion among the particles decreases and erosion increases in wet conditions. The test requires bricks to be left in the oven, put in water overnight and the percentage weight increase is calculated. Research has revealed that unfired clay bricks in Uganda usually have a percentage absorption of over 20 and therefore they cannot be used without stabilization. GGBS enhances porosity through the densification of microstructure thus reducing absorption of water to reasonable levels and enhancing durability.

2.4.3.3 Block Drop Test

Block drop test described in BS EN771-1 is used to determine test on impact resistance and toughness of bricks. It includes elevating a brick to a given height and letting it fall on a hard surface to observe the cracking of the structure or not. In this test, the stresses caused during transportation and construction are simulated. The unfired clay bricks are mostly fragile and can easily crack with an impact. GGBS stabilization enhances toughness, which increases bondage of particles and decreases brittle nature such that bricks may not break up under the impact of manual handling. This is a key property in the rural construction environment where the transportation of bricks is often done manually.

2.4.3.4 Bulk Density

The mass of the brick divided by the unit volume (with the voids taken into consideration) is called bulk density. BS EN771-1 states that the bulk density is one

of the main parameters in the control of dead loads in structural work. The best values of clay bricks are approximately 1680 kg/m³. Bricks with low density can also not be strong enough whereas bricks with too high density can add weight to the structure and make structures less efficient. The test includes determination of mass and volume of the brick to find out the density. GGBS stabilization adds modular density due to the filling of void and smoother packing of particles, thus helping in the achievement of the strength but without overloading the bricks. The balance is such that stabilized bricks that are yet to be fired are strong and can be used in construction.

2.5 Chemical Properties of Raw Clay Bricks.

2.5.1 Efflorescence Test

The efflorescence is a phenomenon of deposits of white salts on the surface of the bricks because of the movement of soluble salts during the movement of moisture. ASTM C67 test consists of two stages and partially immersing bricks in distilled water over the period of seven days and visibly field measuring the amount of salt present. Efflorescence does not only have aesthetic effects but also predicts chemical instability which can undermine durability. Clay bricks which have not been fired are especially susceptible to efflorescence as a result of being porous. This problem is reduced in stabilization by use of GGBS which stabilizes soluble salts in cementitious materials which decreases solubility and surface deposition. This enhancement has made stabilized bricks to have both the structural integrity and aesthetic values.

2.6 Integrated Significance

Collectively, the following tests are used to obtain a full analysis of unfired clay bricks:

The compressive strength assures safety of structure.

Water absorption determines moisture resistance.

Block drop test measures toughness in handling.

Structural efficiency is controlled by bulk density.

Efflorescence test measures stability in chemicals and outward appearance.

With the use of such standardized tests, it is possible to scientifically prove that the improvements in case of GGBS stabilization can be managed in order to ensure that the unfired clay bricks meet the international standards in terms of performance and remain environmentally friendly and affordable.

2.7. Clay Brick Production and Performance Overview.

Clay is one of the basic building materials that have been in existence since ancient times (Adam, 1990). The fundamental theory of fired clay brick is to create a heavy ceramic by means of heating (vitrification), producing strength, longevity and waterproof effect. In the traditional way of manufacturing fired bricks, raw clay is moulded, dried, and finally fired in kilns at temperatures that may be higher than 900 and 1,000 degrees Celsius (Khalaf & DeVenny, 2005). It is an energy-demanding process with a result of CO₂ emissions during fuel combustion and during disintegration of carbonates in the clay (Miller et al., 2016).

Unfired clay bricks (or stabilized earth bricks) on the contrary, are made by incorporating clay or soil with a stabilizer and left to cure in ambient or slightly heated conditions without going through the kiln. The stabilizer causes chemical attaching (e.g. hydration, pozzolanic reaction, carbonation) which gives the

material strength and durability (Gupta and Sharma, 2017). The key benefits of the unfired bricks are:

- ❖ Less energy use (firing is done away with)
- ❖ Lower greenhouse gas emissions
- ❖ Use of locally available soils and waste by-products
- ❖ Potential cost savings in materials and energy (Rahman et al., 2019)

However, unfired bricks also face challenges: lower inherent strength (compared to well-fired bricks), vulnerability to moisture and water absorption, shrinkage and cracking during drying, and durability under wet to dry cycles or freeze thaw conditions (Ali et al., 2020). Thus, the selection and optimization of stabilizers is critical (Zhang & Chen, 2018).

Several review works (e.g. Wang et al., 2025) summarize stabilizer types (cement, lime, geopolymers, microbial, bio-based) and their performance metrics (compressive strength, water absorption, shrinkage, durability, life-cycle impacts) in unfired bricks. Wang et al. report that properly stabilized unfired bricks can achieve compressive strengths above 20 MPa and water absorption rates below 10 % in some formulations. However, they caution that standardization and market uptake remain challenges (Wang et al., 2025).

Similarly, Deboucha and Hashim (2011) provide a broad review of stabilized compressed earth blocks (or unfired masonry) and note that although many studies exist on mechanical and durability performance, research is more limited on thermal, acoustic, and large-scale applications (Deboucha & Hashim, 2011).

Overall, it can be concluded that unfired brick technology provides a good alternative of fired bricks to the conventional ones since the mechanical and

durability performance may be brought up to an acceptable level with proper stabilizers and mix composition.

2.8. Problems of Unfired Bricks.

It is necessary to list the main issues of unfired clay brick materials prior to getting down to the GGBS ones:

- ❖ **Strength and load carrying ability:** Strengths of unfired bricks are usually lower than those of the fired bricks. They need to be of a minimum threshold (usually 3.5 to 15 MPa in masonry) in order to be of use in a structural or semi-structural application.
- ❖ **Water absorption and moisture sensitivity:** Due to the relatively elevated porosity of unbaked bricks, the former are prone to the influence of moisture ingress that may impair the strength and stability of the former.
- ❖ **Shrinkage and cracking:** During drying or curing water evaporates and as dimension changes (shrinkage) may occur, cracking or warping may take place thereby impairing integrity.
- ❖ **Environmental cycling: Durability:** During environmental cycling, repeated wet-dry cycling, freeze/thaw cycle or by exposure to sulphate/chemical can erode performance through time.
- ❖ **Ease of uniformity and reproducibility** Natural soils or clays can often be heterogeneous spatially in mineralogy, particle diameter, and impurities, and uniform mix design and scale-up is more complicated.
- ❖ **Standards and certification:** Due to the fact that unfired bricks no longer conform to the traditional standards of masonry, many jurisdictions do not have defined standards or acceptance, therefore, limiting adoption.

- ❖ The given challenges suggest that not only strength but also porosity (reduction), shrinkage control, and durability should be ensured in the conditions that are realistic.

2.8.2 Clay / soil Matrices mechanisms.

Under conditions where clay or soil is to be stabilized (and hence in any unfired bricks), the normal order would be:

Break-up slag glass: When in the presence of high-pH ionizing slag glass network, the slag glass network is dissolved giving out Si^{4+} and Al^{3+} in a solution.

Reaction and precipitation of binding phase: These ions ionize with Ca^{2+} (lime or the clay) to produce calcium silicate hydrate (C-S-H) or calcium aluminosilicate hydrate (C-A-S-H) gels.

Densification in microstructure: The gels settle on the particles on the basis of the voids or interparticle in between, entrap the particles and improve the pore structure, therefore, lowering the porosity and enhancing strength.

Continued action of the pozzolana in curing: With time (28 days), the process proceeds and the strength and decrease in water permeability is observed.

Certain precaution is justified: GGBS does not offer significant improvement in case of its use with the lack of an activator or low pH conditions (Al-Khafaji et al., 2024). The dissolution of the glassy phase of slag might not be possible under non-optimal conditions (Al-Khafaji et al., 2024).

2.9 GGBS as an Unfired Brick stabilizer: Practical investigations.

In this section, literature tests and case studies are discussed, in which GGBS (as an independent stabilizer or in addition to activators) has been utilized as a stabilizer in stabilized masonry building systems.

2.5.1 Pedagogical pioneering research: Oti, Kinuthia and Bai (2008, 2009)

Oti, Kinuthia and Bai in seminal series of studies examined the possibility of using GGBS as a stabilizer of unfired clay masonry bricks (Oti, Kinuthia and Bai, 2008; Oti, Kinuthia and Bai, 2009). In a 2008 paper they have experimented different moisture contents and stabilizer blends in cylindrical specimen and were able to give strength values ranging between 65 and 2077 kN/m² (i.e. 0.065 or 2.077 MPa) after 28 days, depending upon mix. They found that lime-slag blends performed better compared to lime cement blends, to imply possible success of unblended binders and GGBS (Oti, Kinuthia & Bai, 2008).

Later, in an industrial test (Oti, Kinuthia and Bai, 2009), they moulded bricks with the local clay (Lower Oxford Clay, LOC) and with GGBS which was activated with a little lime (approximately 1.5 percent). Instead, they even used Portland cement as control. According to their findings, the results of the stabilized unfired bricks have reached satisfactory compressive strength, moisture content, void ratio, water absorption, and test durability with regard to freeze thaw cycling. They also determined energy and CO₂ emissions: these bricks consumed about 657.1 MJ/tonne energy and the same CO₂ consumed, about 40.95 kg CO₂/tonne which was much less than burned bricks (Oti et al., 2009). This is an indication of stronger strength requirements of brick masonry than road base soils (Oti et al., 2009).

As highlighted in these studies, properly activated and designed mixes of GGBS can be an effective stabilizer in unfired clay bricks, and they were capable of delivering a reasonable mechanical and durability performance.

2.5.2 Microstructure and unfired clay bricks studies the unfired brick.

In the paper, Compressive strength and microstructural analysis of unfired clay masonry bricks (Oti, Bai and Kinuthia, 2009), the researchers compared the lime-activated GGBS systems with the Portland cement-activated GGBS. They also analyzed the microstructure by using SEM and EDX which showed the C-S-H gel phases between slag and clay particles. The bricks that were stabilized using lime took better strength compared to PC-GGBS structures. They also tested the freeze thaw stability of repetitive cycles and reported satisfactory stability. They credited the increase in strength to the rise in pozzolanaic gel binding (Oti, Bai and Kinuthia, 2009).

There are other researches on the application of GGBS in clays that contain montmorillonites in large quantities. Indicatively, El-Mahllawy et al. (2014) tested stabilized unfired montmorillonite clay bricks in varied curing conditions (moist curing, high temperature curing) and compared mineralogical variations and mechanical characteristics. They made a conclusion that the stabilization would be an effective way to increase the strength and microstructural densification (El-Mahllawy et al., 2014).

The other paper that is relevant is the article by Oti, Kinuthia and Bai (2008) titled, Using Slag for Unfired-Clay Masonry-Bricks. The moisture contents (25 -40%), and curing conditions were that the authors tested three moisture levels lime slag blends, and control lime cement blends. They discovered that strength ranged

between 65 and 2077 kN/m² at 28 days and lime-slag blends in many cases performed better compared to lime-cement blends. Their point was that GGBS can be used as an unblended binder when good conditions are ensured (Oti et al., 2008).

2.5.3. Other empirical works and optimizations

A more recent survey on unfired bricks obtained using waste materials (Wang et al., 2025) compiled numerous studies where the material is GGBS (usually utilized in mixed systems) and concluded that the stabilized unfired bricks with GGBS could achieve compressive strength higher than 20 Mpa and water absorption lower than 10 percent. Wang et al. state the importance of hybrid stabilizers systems in order to exploit the synergies between types of binder (Wang et al., 2025).

Other studies combine GGBS and clay replacement. As an example, in a paper named A Comparative Study of Clay Bricks with GGBS and Laterite, it was indicated that GGBS inclusion in clay-laterite brick mixtures could raise the compressive strength by 8 percent, but had an effect on water absorption and the thermal conductivity (IJREAM, 2023). This implies trade between the density (strength) and thermal performance / porosity.

A sequence of bricks was manufactured with 0 to 30 percent GGBs replacement using a small amount of lime (5 percent) constant to enhance activation in an experimental study, called Bricks Manufacturing with Partial Replacement of Clay With GGBS (IJSTR, 2020). According to the study, the application of GGBS was effective in not only decreasing energy cost (specifically in the firing process) but also in the fact that reasonable compressive strength was attained at medium GGBS concentrations (IJSTR, 2020).

Nonetheless, there are stabilization reviews that allege that GGBS as such (without adequate activation) can produce only a small effect in soft soils or clay situations (Al-Khafaji et al., 2024). Glassy state of GGBS can become insoluble in unfavorable pH or curing conditions, and it is necessary to design the mixture and activate it accurately (Al-Khafaji et al., 2024).

In general, it has been observed through empirical research that activated GGBS in the right proportion can play a major role in improving the mechanical and durability characteristics of unfired clay bricks.

2.6. Physical and Mechanical Property Effect.

This chapter is a synthesis of the results of various researches on the most important key performance measurements, compressive strength, water absorption, porosity, shrinkage, and durability.

2.6.1 Compressive Strength

Compressive strength is the key criterion to applicability. Several patterns emerge:

In the industrial experiment of Oti et. al, the GGBS bricks which had been active by lime acquired possessed the compressive strength sustained to the identical level as those of regular masonry. (Oti et al., 2009)

The microstructure analysis showed that the lime-GGBS stabilized bricks were more powerful than PC-GGBS systems (Oti, Bai & Kinuthia, 2009).

Indeed, in larger reviews, compressive strength values greater than 20 MPa have been obtained with stabilized unfired bricks using GGBS (in most cases as part of a hybrid).

In comparison brick research, 8 percent GGBS in clay-laterite mixes enhanced power as compared to unaltered clay. (IJREAM, 2023)

In IJSTR (2020), the partial substitutes of clay by GGBS (0 to 30 percent) with lime activation have acceptable levels of strength, as well.

Therefore, in spite of the fact that the mix design, activator dosage, curing, and compaction are very important factors influencing the strength, stabilized bricks by GGBS can be used to satisfy structural or semi-structural needs under optimal conditions.

2.6.2 Water Absorption

The ability to take up water is a very important measure of permeability, porosity and durability:

In their stabilized bricks, Oti et al. (2009) document that water absorption reduces as the curing period (7 to 28 days) increases.

Levels of water absorption of about 17 to 22 are recorded in the early experiment of Oti on some blends, but with curing and compaction, performance is enhanced (Oti et al., 2009).

In the more general study by Wang et al. (2025), absorption exceeding 10 percent is attained with stabilized unfired bricks containing GGBS (particularly in hybrid systems).

The triblend systems (GGBS + clay + lime) tend to have less water taken up as compared to raw clay bricks since the pozzolanic gels fill in pores making capillarity to be low.

Hence, GGBS is associated with microstructure densification and minimization of water infiltration that is crucial to durability.

2.6.3 Porosity, Void ratio and density.

Porosity and void ratio have a strong correlation with the strength as well as moisture behaviour:

Oti et al. (2009) tested the void fractions and they were satisfactory in regards to masonry standards.

Porosity is reduced and density will increase as the slag binder gels precipitate into voids leading to enhanced mechanical integrity.

The porosity that is beneficial to shorten weight savings or thermal insulation might however be compromised by high levels of stabilizer content or excessive densification.

These trade-offs should be painstakingly optimized.

2.6.4 Shrinkage, Cracking and Dimensional Stability.

Drying out will always bring about shrinkage, and over shrinkage will result in cracking:

Other studies indicate that stabilized bricks experience moderate shrinkage, which is manageable through regulating the amount of moisture used in the moulding process, progressive curing, as well as the amount of stabilizer present.

Durability (e.g. freeze thaw, wet-dry cycles) testing usually demonstrates that highly stabilized bricks do not crack during environmental cycling. Frozen-thaw tests

conducted by Oti et al. demonstrated good results in the redundant cycles (Oti et al., 2009).

Nevertheless, the area of quantification of shrinkage behaviour over a period of time is not thoroughly examined in a number of studies, and this is a field of future research.

2.6.5 Environmental cycling Durability.

Performance in the long-term is vital:

The freeze thaw cycling tests conducted by Oti showed that stabilized bricks can withstand several cycles without significant degradation (Oti et al., 2009).

The studies on some montmorillonite clay (El-Mahllawy et al., 2014) determine durability of different curing regimes, and the results indicate that the addition of stabilization contributes greatly to the weathering resistance.

The wider survey by Wang et al. (2025) indicates that a great number of stabilized bricks (including the GGBS-based ones) exhibit good wet-dry and freeze-thaw performances, as long as the absorption is low, and the cracks are controlled.

Therefore, there are encouraging signs of durability, but lots of research is either short term or small.

2.7. Comparison of Stabilizers with others.

Comparisons with more traditional stabilizers like lime, Portland cement, fly ash and geopolymers are instructive to compare GGBS.

2.7.1 Lime Stabilization

Lime has been used long (e.g. 3-8 percent addition) in soil stabilization (e.g. road base), particularly in areas with clay soil. Lime-stabilized bricks, however, can be of respectable strength or of great porosity unless pozzolanic additives are used.

In Oti, the lime percentage used was much less than the usual dose to stabilize soil, 1.5, which was enough to activate GGBS since the brick requirements are greater (Oti et al., 2009).

Lime is beneficial in that it improves PH, Ca^{2+} and flocculation and adjustment of clay particles.

2.7.2 Portland Cement

Cement contains early strength and chemical bonding through hydration although it contains high levels of embodied CO_2 .

Cement is also sometimes used in some brick studies as a co-binder with either clay or slag, although at the cost of sustainability.

Oti et al. keep the use of cement at a minimum, as a control, in order to maintain low-carbon profile (Oti et al., 2009).

2.7.3 Fly Ash

Fly ash is the other by-product of the industry commonly used as stabilizer in bricks. Fly ash may also aid the development of strength when it is activated (e.g. by lime or alkali).

A significant number of researches involve the use of fly ash + lime + clay to make stabilized bricks. Fly ash can be used to assist in workability, porosity, and cost.

Individual stabilizers can be less effective than hybrid stabilizers (e.g. fly ash + GGBS) in comparison reviews and in hybrid systems (Wang et al., 2025).

2.7.4. Alkali-activated binders /geopolymers

High-alkali activation systems such as the use of geopolymers are based on the use of fly ash, slag, metakaolin or mixtures.

Geopolymers may also be used in unfired brick applications, to provide high levels of strengths and low permeability, however, much tighter limits are placed on activator solutions, curing regimes, and safety handling of alkali.

Other hybrids based on GGBS + alkali activator are potentially promising and scaling may be complicated by complexity and cost.

In general, GGBS provides a reasonable compromise since it is an industrial by-product, latent hydraulic potential, and in case it is activated at reasonable costs (e.g. low doses of lime), it can produce powerful and long-lasting bricks, without a large CO₂ footprint. It is common that the hybridization of stabilizers offers the most performance, but also at the complexity cost.

Economic and Environmental Issues.

- ❖ The possibility of waste valorisation and sustainability is one of the key reasons to use GGBS.
- ❖ The embodied energy and CO₂ Emissions are two concepts.
- ❖ Oti et al. (2009) calculated that the GGBS-lime stabilized bricks before firing had an energy consumption = 657.1 MJ/tonne and CO₂ =40.95 kg/tonne, which is much lower compared to fired clay bricks (Oti et al., 2009).

- ❖ More broadly, unfired bricks (that include stabilizers) require far less energy in comparison to fired ones and may cut CO₂ emission by up to 80-90 percent or more (Wang et al., 2025).
- ❖ The un-fired systems are only of significance because of the manufacturing of lime, cement, or alkali which are minimal compared to fuel that is used to fire.
- ❖ Transportation and processing (grinding, mixing, curing) energy has to be considered; sourcing locally, both GGBS and clay, will have an impact.

Availability and Cost of Materials.

- ❖ GGBS is a product of steel mills.
- ❖ There should be consideration of grinding and processing costs (to fine particle size).
- ❖ When the activator (lime or alkali) is locally present, then the cost efficiency is enhanced.
- ❖ Since GGBS is waste, the marginal cost (without processing) is usually low and hence it is economically viable in most of the environments.
- ❖ Adoption Barriers in social and practical spheres.
- ❖ In many areas, adopted standards or regulatory acceptance of unfired masonry slows down adoption of the same.
- ❖ Masons and builders might not know or might be not willing to know new materials.
- ❖ The quality control and reproducibility under field conditions (e.g. the change in clay, water, mixing) may be a problem.
- ❖ Maintenance (moisture protection, repair) Life-cycle maintenance (moisture protection, repair) can be costly unless it is properly designed.

- ❖ Therefore, although technically possible, GGBS-stabilized unfired bricks have to be scaled up with consideration of supply chains, uniformity and acceptance by stakeholders.

Research Gaps and way forward.

- ❖ The Ground Granulated Blast furnace slag suitability in the production of unfired clay brick construction.
- ❖ Short term research on long term durability in the tropics.
- ❖ Very limited studies on interrelation between GGBS and particular East African clay mineralogy.
- ❖ Absence of uniform curing regime of unfired GGBS-stabilized bricks.
- ❖ Limited cost-benefit studies between GGBS and local traditional stabilizes.
- ❖ Recent studies have investigated the incorporation of the pozzolanic substances into the concrete like Ground Granulated Blast Furnace Slag (GGBS) to achieve the strength stability and long-term performance of concrete. GGBS, a latent hydraulic binder which is also the waste of the iron production, also has some pozzolanic properties that can enhance compressive strength and water resistance of clay-based materials, provided it is properly activated (Kumar & Sahoo, 2020). GGBS does not just create value on waste, but also complies with the principles of the circular economy and the low-carbon construction strategies (UNBS, 2020).

Summary

This literature review has discussed the possible and actual limitations of ground granulated blast furnace slag (GGBS) as a stabilizer in manufacture of unfired clay bricks. Unfired bricks technology is highly ecologic and energy efficient compared

to conventional fired bricks, and needs to be properly stabilized to serve the strength and durability standards.

GGBS is desirable in that it is a waste by product that has latent hydraulic potential. GGBS has the ability, when activated, to react in clay or soil matrices to form binding gels (e.g. C-S-H), densify the microstructure, decrease porosity, and enhance strength, as well as water resistance. Experimental work particularly by Oti, Kinuthia and Bai has shown that, lime-activated GGBS (even with low lime doses of 1.5) could reach a reasonable mechanical and durability performance in the expected range, and save a good deal of energy and CO₂ compared to fired bricks.

It can be compared to other stabilizers (lime, cement, fly ash, geopolymers) and it would be easy to agree that GGBS represents a favourable middle ground: it is stronger than lime, less carbon than cement, and not as complex as entire geopolymer systems. The trick however is to be successful in good mix design, good activation, control of contraction/cracking, and good curing.

The main issues still persist as long-term stability during environmental circumstances, control of shrinkage, implementation at a field scale, standardization, supply chain logistics, and optimization of costs. The upcoming research must focus on hybrid systems, large scale experimentations, life-cycle analysis based on local conditions, and standard integration.

Gaps in Literature

- ✚ Applicability of Ground Granulated Blast furnace slag in production of unfired clay bricks in building.
- ✚ Few studies- under long term tropical conditions.
- ✚ Very minimal studies on the relationships between GGBS and individual East African clay mineralogy.
- ✚ The absence of unified guidelines of curing unfired GGBS-stabilized bricks.
- ✚ Very little cost-benefit estimates of GGBS versus traditional stabilizers at special sites.

Recent studies have delved into using pozzolanic materials e.g. Ground Granulated Blast Furnace Slag (GGBS) in concrete to increase strength, stability and long-term performance. The empowerment of the compressive strength and water resistance of clay-based substances through the introduction of pozzolanic properties which are inherent in the GGBS which is a latent hydraulic binder extracted during the production of iron has the potential to enhance clay-based materials when activated accordingly (Kumar & Sahoo, 2020). This is because GGBS is not only good in attaching value to waste, but also compliant with the principles of a circular economy and low-carbon approaches to construction (UNBS, 2020).

This literature review is a critical study of the literature, which focuses on the material preparation, the mechanism of curing, the mechanical behaviour and the environmental conditions of unfired clay bricks with GGBS transformation. It tries to establish the important trends, technical differences and practical issues to be utilized in the unfired brick making business in Namakwekwe, Mbale where rapid urbanization and building need compel affordable and sustainable solutions. The compatibility of GGBS with the local types of clay, taken in the Bugisu region, with

lime and other activators, and also the effect of curing times of the bricks are also evaluated in the review. The US EAS 54:1999 standard on building brick is used in the analysis since it was adopted by National Bureau of Standards (UNBS) of Uganda and the standard of construction meets the requirements of the construction in the region.

CHAPTER THREE: METHODOLOGY

3.1 Materials of the study

3.1.1 Ground Granulated Blast Furnace Slag

It is one of the by-products of the manufacturing process of iron and steel. It is manufactured by rapidly cooling molten slag with water or steam in order to produce a glassy granular base. The end product of this process is then dried and crushed into a fine powder and this product is called GGBS and it is commonly utilized as a cementitious supplementary material in construction.

It is known that GGBS can be used to improve mechanical properties, durability, and environmental friendliness of building materials like concrete, mortar, and stabilized earth products like unfired clay bricks (Neville, 2011; Mehta and Monteiro, 2014).

3.1.1.1 Composition of GGBS

GGBS chemical makeup is composed of oxides that are favourable to the pozzolanic and latent hydraulic response in combination with the other constituents:

Table 1 Composition of GGBS with percentages

Component	Percentage by Mass
Calcium Oxide (CaO)	30% - 45%
Silicon Dioxide (SiO ₂)	30% - 40%
Aluminium Oxide (Al ₂ O ₃)	10% - 20%
Magnesium Oxide (MgO)	1% - 10%
Iron Oxide (Fe ₂ O ₃)	0.5% - 2%
Other Minor Compounds	Less than 5%



Figure showing: Ground Granulated Blast Furnace Slag

The high silica (SiO₂) and alumina (Al₂O₃) content provides GGBS with pozzolanic properties, enabling it to react with calcium hydroxide in clay or cementitious systems to form calcium silicate hydrates (C-S-H), which contribute to strength development and durability.

3.1.2 Clay from Namakwekwe

This was sampled from the brick layers of Namakwekwe

3.2 LABORATORY TESTS

3.2.1 DETERMINING THE PHYSICAL AND CHEMICAL PROPERTIES OF CLAY SOILS IN NAMAKWEKWE SUITABLE FOR UNFIRED BRICK PRODUCTION

The following laboratory tests were conducted:

Table 2: Summary of tests to be conducted

Test	Standard Reference	Purpose
Particle Size Distribution	BS 1377: Part 2: 1990	To assess the soil gradation and texture
Atterberg Limits (LL, PL, PI)	BS 1377: Part 2: 1990	To determine soil plasticity behaviour
Chemical Characterization	X-Ray Fluorescence (XRF) as per ASTM D8438-23	To analyze elemental and mineral content

These tests establish the suitability of the soil for unfired brick production, considering workability, strength potential, and chemical compatibility with stabilizers.

3.2.2 ATTERBERG LIMITS OF LOCAL CLAY SOIL

The test was carried out in reference to BS 1377: Part 2: 1990

Using The Cone penetration method

The purpose of these tests is to determine the plastic properties of the clay soils for workability when moulding bricks and their effect to resist shrinkage that could lead to cracking of the bricks.

Required equipment: BS test sieves, metal tray, drying oven, scoop, weighing balance, riffle box, cone penetrometer.

Liquid Limit Determination

The liquid limit of the clay soil samples was determined using a BS Cone Penetrometer fitted with an automatic timing device that ensures a penetration time of 5 seconds under an 80g load, in accordance with BS 1377: Part 2: 1990.

Procedure:

- ✓ Representative specimens from the oven-dried clay soil samples pulverized and passed through a 0.425 mm BS test sieve.
- ✓ A mass of 200g from the soil passing the 0.425 mm sieve thoroughly mixed with distilled water.
- ✓ The prepared paste was then sealed in an air-tight container and allowed to stand overnight to ensure uniform moisture permeation.
- ✓ The following day, the specimens were remixed with sufficient water to achieve two penetrations within the range of 15 mm to 25 mm using the cone penetrometer.
- ✓ For each specimen, the corresponding moisture content were be recorded.

- ✓ A moisture content versus penetration curve is plotted, and the moisture content corresponding to 20 mm penetration will be taken as the liquid limit (LL) of the soil.

Plastic Limit and Plasticity Index Determination

The plastic limit and plasticity index of the clay soil was determined in accordance with **BS 1377: Part 2: 1990**.

Procedure:

- ✓ Specimens for this test were prepared in the same manner as those used for the liquid limit determination.
- ✓ A ball of soil paste was rolled between the hands and then into threads on a glass plate.
- ✓ The test continued until threads of approximately 3 mm diameter develop transverse cracks.
- ✓ The plastic limit (PL) for each specimen was then recorded as the amount of moisture at which cracking happened.

To find the plasticity index (PI), use the following formula:

$$PI = LL - PL$$

- **Where:** PI = Plasticity Index
- LL = Liquid Limit
- PL = Plastic Limit

3.2.3 Particle Size Distribution Test

The particle size distribution of the local clay soil was determined using sieve analysis in accordance with **BS 1377: Part 2: 1990**. This test provides data on the

proportion of coarse and fine particles present in the soil, which is essential for evaluating its suitability for unfired brick production and for blending with stabilizers such as granite dust or GGBS.

Required Equipment: BS test sieves of decreasing aperture sizes, metal tray, drying oven, Scoop, weighing balance, riffle box

Procedure:

- ✓ The oven-dried clay soil was passed through a stack of BS sieves arranged in decreasing aperture sizes.
- ✓ The mass retained on each sieve measured as follows:
- ✓ $\text{Mass retained} = \text{weight of sample on the sieve} - \text{weight of sieve without sample}$
- ✓ The recorded data was used to calculate the cumulative percentage passing each sieve.
- ✓ $\text{Percentage retained} = (\text{mass retained}) \div (\text{initial sample mass}) \times 100\%$
- ✓ $\text{Cumulative percentage passing} = 100\% - \text{percentage retained}$
- ✓ A graph was plotted on a log scale and the obtained results will be used to compute the fineness modulus that will be used as a measure of course to fine particles in the clay soil.
- ✓ $\text{Grading modulus} = [300 - (\text{percentage retained on } 2\text{mm} + 0.425\text{mm} + 0.075\text{mm})]$

The particle size distribution and grading modulus is used in evaluating the soil's texture and determining the necessary proportions for blending with stabilizing materials to produce quality unfired clay bricks.

3.3 TO DETERMINE THE OPTIMUM AMOUNT OF GROUND GRANULATED BLAST FURNACE SLAG THAT CAN BE ADDED TO THE LOCAL CLAY SOILS OF NAMAKWEKWE FOR MANUFACTURING UNFIRED CLAY BRICKS

3.3.1 Manufacture and Testing of Bricks.

Clay was mixed with different GGBS contents: 0% (control), 5, 10, 15, 20, and 25 percent and then mixed with bricks.

The mixing was as per ASTM C305- 20 rules regarding mechanical mixing with alterations to suit clay-based systems.

The moulds were of standard brick sizes of 200mm by 100m by 100mm (BS 3921:1985).

Drying Conditions

The drying time of 7, 14 and 28 days was used to determine the influence of drying time on performance because, under natural drying conditions, bricks were dried over the specified drying periods.

Without the use of chambers, closed systems without sunlight were employed with reference to Okello (2019).

3.4 TO DETERMINE THE EFFECT OF GROUND GRANULATED BLAST FURNACE SLAG ON THE PHYSICAL AND CHEMICAL PROPERTIES OF THE UNFIRED CLAY BRICKS, INCLUDING THE IMPACT OF DRYING TIME AND HUMIDITY CONDITIONS ON THE PERFORMANCE OF STABILISED UNFIRED BRICKS.

Testing

Test	Standard Reference	Purpose
Compressive Strength	BS 3921:1985	To assess load-bearing capacity
Water Absorption (Cobb Method)	EN 1996-2:2006	To evaluate porosity and water resistance
Bulk Density	ASTM C20-00	To measure material compactness
Linear Shrinkage	BS 3921:1985	To determine dimensional stability
Efflorescence Resistance	ASTM C67-14	To detect salt deposition potential

3.4.1 Compressive Strength Test

This was carried out in accordance to BS 3921:1985

To establish the load-bearing capacity of the unfired clay bricks under the vertical compression which is vital in their application in the structural use.

Procedure:

The test was performed under BS 3921:1985:

Sun-drying of the bricks was done to a constant weight.

- ✓ A compression testing machine was used to place each brick in between steel plates.
- ✓ A progressively greater load was placed vertically until the failure was attained.
- ✓ Compressive strength calculated using:
- ✓ Compressive Strength (MPa) = Loaded Area(mm²)/Maximum Load (N)

3.4.2 Water Absorption Test (Cobb Method)

To determine the water absorption capability of the brick, which determines its durability, weather and moisture resistance.

Procedure:

This test followed EN 1996-2:2006

- ✓ Bricks (mass of dry mass).
- ✓ Bricks that were immersed in water partially (up to 5 mm deep) during a given time.
- ✓ The final wet mass recorded.
- ✓ The absorption of water is determined as:
- ✓ Water Absorption (%) = (Wet Mass- Dry Mass)/ Dry Mass x100

Reduced water intake is a sign of greater longevity, less porosity, and enhanced ability to withstand environmental degradation especially in humid environments.

3.5 OTHER TESTS CARRIED OUT

In addition to compressive strength and water absorption test, more laboratory tests will be done to complete the picture on mechanical performance of the stabilized unfired clay bricks. These tests help in measuring the behaviour of the bricks in the

conditions of bending, impact and surface wear which are very critical in practical construction applications.

3.5.1 Flexural Strength (Modulus of Rupture) Test:

This is to determine the brick's ability to resist bending and tensile stresses, which is essential for wall panels or applications where bricks may be subjected to flexural loads.

Procedure:

The test will follow **ASTM C293-16** standards:

- ✓ Brick samples will be placed on two support points.
- ✓ A controlled vertical load will be applied at the centre until failure occurs.
- ✓ The modulus of rupture will be calculated using:

$$\text{Modulus of Rupture} = 3PL / (2bd) \quad (2bd)$$

This test simulates bending stresses experienced during handling, transportation, or structural loading, providing insights into the structural integrity of the unfired bricks.

3.5.2 BLOCK DROP TEST BS EN (771-1:2011)

The purpose of this is to assess the capacity of the unfired clay bricks (or blocks) to absorb sudden impact forces by dropping them from a given height, thus simulating the situations of handling and accidental falls during construction.

Apparatus Required

Measuring tape or scale, flat concrete floor or steel plate, Sample bricks ruler dimension measurement before and after the test, weighing balance

Procedure

Sample Preparation

From the batch, select representative blocks.

Dimensional, weight, and defect information are to be recorded.

Test Setup

A hard, flat surface (concrete floor or steel plate) was be used as the impact base.

A vertical drop height of 1.2m marked.

Drop Test Execution

- ✓ The block is to be held at the stated height.
- ✓ The block dropped freely in a horizontal position (flat face down).
- ✓ The drop should be repeated three times for each block, turning the block each time to reveal different sides.

Observation

It should be noted whether the block has broken, chipped, or is still intact.

As per IS 3495 (Part 6): A brick/block is considered passed if it does not split into two or more pieces after successive drops.

Minor chipping is permissible, but the failure of the structure (through the body crack) denotes poor impact resistance.

CHAPTER FOUR: RESULTS AND DISCUSSION

Laboratory tests were done to determine the chemical makeup and fundamental physical traits of the clay soils of Namakwekwe (Mbale District) and Ground Granulated Blast Furnace Slag (GGBS) to be utilized as a stabilizer additive. These findings lie in the basis of determining the appropriateness of the two substances in the production of unfired clay bricks. The obtained findings were discussed against the background of the corresponding literature and international standards as BS 3921:1985, BS EN 772, and EN 1996-2: 2006, determining the permissible ranges of strength and coherence of masonry units. The discussion also laments on how the compositional property of the clay and GGBS affects the pozzolanic and hydraulic reactivity that leads to the mechanical and durability performance of the unfired bricks. Compared to Standards A summary of results is provided. Chemical Content of the Clay Soil.

The X-ray fluorescence (XRF) data of the Namakwekwe clay show that there are large amounts of silica (SiO_2) and alumina (Al_2O_3), middle amounts of iron oxide (Fe_2O_3), and middle amounts of calcium oxide (CaO) and magnesium oxide (MgO). An average composition may be shown as follows:

Table 3: The X-ray fluorescence (XRF) data of the Namakwekwe

Oxide Component	Percentage(%)	Significance
SiO ₂	52 - 58	Indicates silicate minerals (e.g., quartz, kaolinite); contributes to structural framework
Al ₂ O ₃	20-25	Reflects clay minerals (kaolinite, illite); important for pozzolanic reaction
Fe ₂ O ₃	5-10	Responsible for brick coloration; minor fluxing agent
CaO	2-4	Low carbonate content; limited self-cementing capacity
MgO	1-2	Minor stabilizing role
Loss on Ignition	8-12	Reflects combined water and organic matter

The fact that SiO₂ and Al₂O₃ are dominant, can be used to confirm that the soil is a rich source of reactive aluminosilicates, which is a characteristic of clays that are used to manufacture bricks (Rahman, 1987; Muheise Araalia and Pavia, 2020). Nevertheless, the low levels of CaO indicate that self-cementing reactions of the clay itself are not as capable and justifies the addition of an external stabilizer like GGBS to increase its binding. El-Mahllawy et al. observed that clay soils that have a silo dens calcium-based stabilizers (El-Mahllawy et al., 2014) have a SiO₂/ Al₂O₃

ratio of 2.0 to 2.5. Namakwekwe clay fits in this range thus showing that, there is good potential of pozzolanic activity upon the addition of GGBS and moisture. Composition of Ground granulated slag of Blast furnace (GGBS) Chemically. XRF analysis of the GGBS sample demonstrates that the sample had the following approximate composition:

Oxide Component	Percentage by weight (%)	Remarks
CaO	35-42	<ul style="list-style-type: none"> Provides calcium ions for C-S-H formation
SiO ₂	30-35	<ul style="list-style-type: none"> Major source of reactive silica for pozzolanic/hydraulic reactions
Al ₂ O ₃	10-15	<ul style="list-style-type: none"> Contributes to formation of C-A-S-H gels Influences long-term hydration and volume stability
MgO	6-8	
Fe ₂ O ₃	0.5-2	<ul style="list-style-type: none"> Minor component; enhances glassy structure stability
SO ₃	Less than 1	<ul style="list-style-type: none"> Enhances setting control; should remain within standards

The oxide content is within the range outlined in ASTM C989-18 regarding high-quality GGBS and proves its latent hydraulic capacity (Amakye et al., 2021). The elevated concentration of CaO means that upon the activation, the slag can provide calcium to form Calcium Silicate Hydrate (C-S-H) the prime strength-giving element in cementitious systems (Ben Haha et al., 2012). Equally, the presence of Al₂O₃

assists the creation of Calcium Aluminosilicate Hydrate (C-A-S-H) that enhances the long-term strength (El-Sayed and Hassan, 2024).

The ratio of $\text{CaO}/(\text{SiO}_2 + \text{Al}_2\text{O}_3)$, which is also referred to as the basicity index, is a measure of reactivity. Reactive slags to be used are typically represented by a value of between 1.0 and 1.2 (Shi et al., 2015). A measured composition of the Namakwekwe GGBS meets this requirement and, therefore, it will be suitable as a stabilizer.

4.1 Analysis of Soil Classification, Atterberg Limits and Particle Size Distribution.

The tests were done to identify the nature of the natural clay soil used at Namakwekwe, Mbala District, prior to stabilization of the engineering classification and the consistency properties. These findings are of critical importance to determine the suitability of the soil with respect to the manufacture of unfired bricks, and their expected performance in response to the addition of Ground Granulated Blast Furnace Slag (GGBS).

4.1.1 Plasticity Index and Classification of Soil.

Interpretation of Plasticity Index: Because the Plasticity Index is linked to unrealistic numbers, it would mean that this is connected to the performance of the company and its market value.

According to Plasticity Index (PI = 20%), the Namakwekwe soil is moderately plastic and is in the range of 10-25% which is the optimal range to make bricks (Houben and Guillaud, 1994). This means that:

When wet, the clay is easy to mould keeping shape even as it dries.

It has a high level of cohesion to be compacted and not too brittle.

The sensitivity to moisture is average, and so the soil will be swelling and shrinking accordingly when wet and dry respectively but within reasonable limits.

Moderate plasticity is also preferred in the production of bricks since it enables good shaping, handling of bricks and drying of the unfired bricks (Rahman, 1987).

b) AASHTO Classification

The classification based on AASHTO designates the soil as high plasticity clay meaning that the soil is weak and compressible in its natural condition, particularly when wet (AASHTO M145, 1991). That explains why chemical stabilization, including GGBS, is required to improve the mechanical strength and decrease the sensitivity to moisture.

Relevance to the Project

These classifications indicate that Namakwekwe clay though rich in reactive minerals (SiO_2 and Al_2O_3) needs stabilization to achieve the strength and durability level that unfired bricks need. Introduction of GGBS, that is abundant in CaO and latent hydraulic compounds will:

Substitute poor clay bonding with high power Calcium Silicate Hydrate (C-S-H) and Calcium Aluminosilicate Hydrate (C-A-S-H) gels (Amakye et al., 2021; Oti, Bai & Kinuthia, 2009).

Reduction in plasticity index which enhances workability and drying performance.

The resistance of the material to compression is improved when the material is densified in terms of its internal structure.

Therefore, the existing type of the soil (A-7-6) supports the necessity and appropriateness of stabilizing it with the help of GGBS.

The experimenting period involved determining the liquid limit through the use of a graph.

Liquid Limit Determination Graph

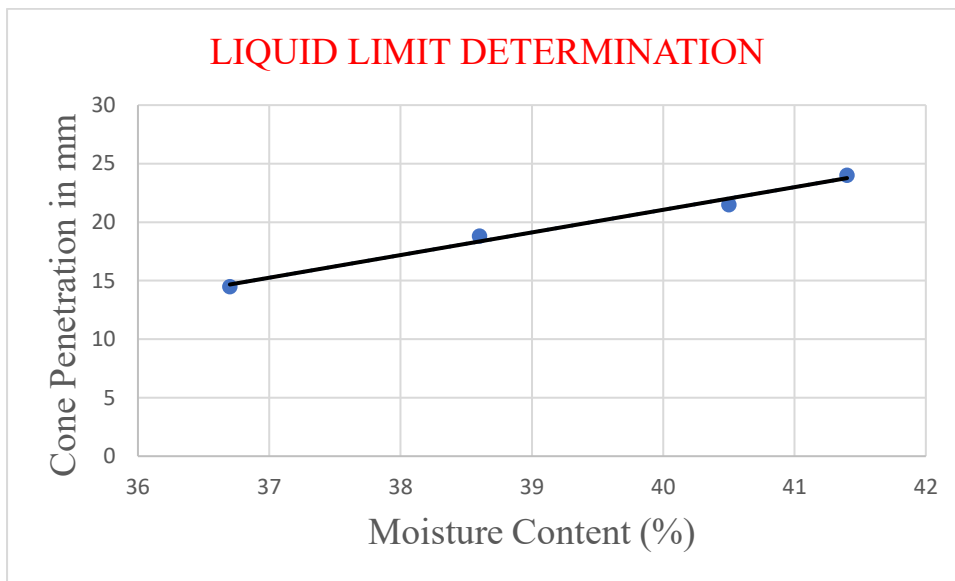


Figure 2: Liquid Limit determination Graph

a) Description of the Graph

The graph of Liquid Limit Determination will be drawn as; cone penetration (mm) Vs. moisture content percentage. The rising line depicts a high level of penetration towards an increased moisture level implying that a transformation occurs as the stronger the soil is, to the fluid state, as the soil content level increases.

From the graph:

The liquid limit (LL) is attained at about 39.5 percent moisture content which is when the point of 20 mm cone penetration (according to BS 1377-2:1990, Cone Penetration Method) is reached.

Engineering Interpretation

Liquid Limit of 39.5% is a medium plastic soil (Skempton, 1953) uses a plasticity chart, showing that clays with an LL between 35 and 50 percent are medium - plasticity clays which usually have good moulding properties but has moderate shrink-swell capability.

This moisture behaviour is in accordance to your PI value (20%), which means that the clay has sufficient cohesion over a sufficient useful range of moisture, and can thus be used in forming bricks.

The LL, however, also demonstrates that under normal conditions the soil will experience considerable absorption of water, thus at wet conditions resulting in softening and loss of strength of the soil being the other reason of the necessity of stabilization to make the soil permanent (El-Mahllawy et al., 2014).

Relevance to GGBS Stabilization

When GGBS is added:

- ✚ The calcium and silicate ions from the slag react with aluminosilicates in the clay, forming C-S-H and C-A-S-H gels that bind particles and reduce pore water mobility.
- ✚ The Liquid Limit and Plasticity Index both decrease, as the soil loses some of its natural plasticity and becomes more friable (Oti & Kinuthia, 2012).
- ✚ The stabilized soil becomes less sensitive to water content variations, improving dimensional stability and drying performance in the unfired brick process.

✚ Thus, the LL graph confirms the soil's workable consistency and highlights its responsiveness to chemical stabilization for enhanced performance.

Particle Size Distribution (PSD) Curve for the Clay

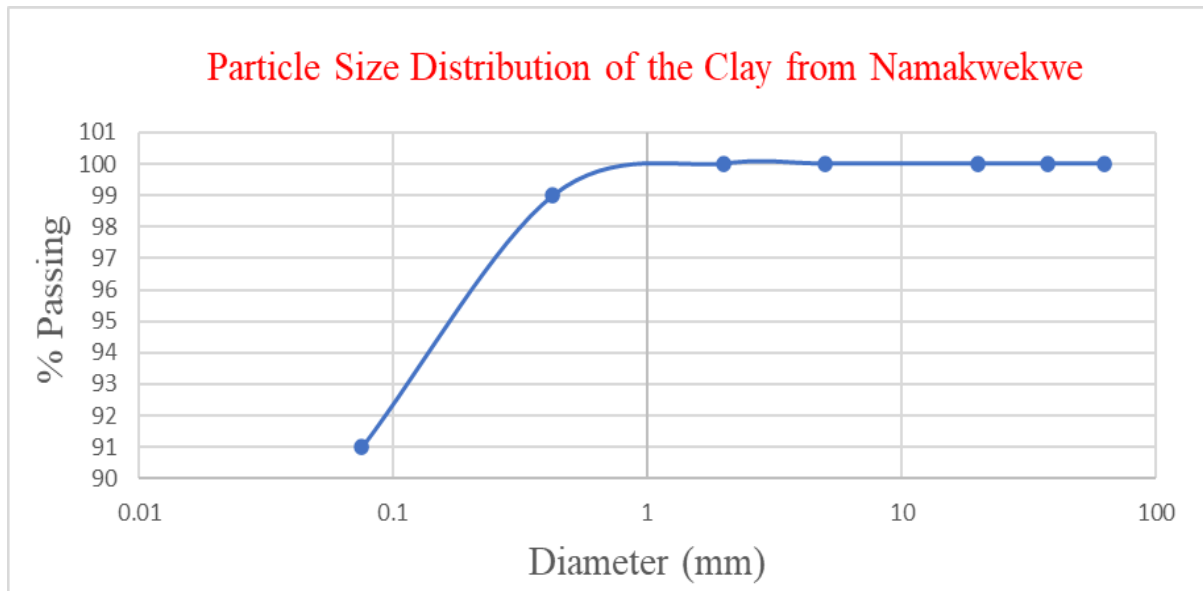


Figure 3: Particle Size Distribution of the Clay from Namakwekwe

a) Description of the Graph

The PSD curve shows the percentage of particles finer than each size (on a logarithmic scale).

From your graph:

- Approximately 90-92% of the particles pass the 0.075 mm sieve,
- The curve rises steeply between 0.1 mm and 1.0 mm, and then flattens,
- Very few particles exceed 2 mm, confirming that the soil is uniformly fine-grained.

b) Soil Texture and Gradation

This shape indicates a poorly graded fine soil dominated by silt and clay particles, with little sand content. The predominance of fines explains the high plasticity observed in the Atterberg results.

According to BS 5930:2015, a soil with more than 50% passing the 0.075 mm sieve is classified as a fine-grained soil, Such soils have:

- Low permeability (slow drainage and drying),
- High water retention, and
- High cohesion beneficial for moulding but risky for shrinkage.

c) Implications for Unfired Brick Production

Fine-grained soils are advantageous for unfired brick production because:

- ✚ They create dense compacts when pressed, leading to higher strength;
- ✚ The high specific surface area allows good bonding with stabilizers such as GGBS;
- ✚ Their cohesive nature aids in maintaining shape during handling and drying.

However, excessive clay content can cause **drying cracks** due to shrinkage. The introduction of GGBS mitigates this problem by:

- ✚ Replacing part of the fine clay fraction with coarser particles;
- ✚ Reducing shrinkage through chemical bonding rather than physical cohesion;
- ✚ Accelerating moisture removal during curing through reduced plasticity.

This explains why in your project's methodology, GGBS addition (typically 10-20% by weight) is expected to balance the gradation and improve structural integrity.

d) Comparison to Literature

Similar PSD curves were observed by **Oti, Kinuthia & Bai (2008)** in their study of slag-stabilized unfired bricks using fine silty clays (60 to 70% fines). They reported improved compressive strength and durability after GGBS stabilization.

Also, **Amakye et al. (2021)** noted that fine-textured clays with >65% passing 0.075 mm perform best when stabilized with GGBS, due to enhanced pozzolanic reaction surface area.

From a civil engineering point of view, the Namakwekwe clay is chemically and texturally ideal for use in GGBS-stabilized unfired bricks:

- Its fine-grained nature ensures good cohesion and reactivity.
- Its moderate plasticity supports moldability and strength after compaction.
- The high A-7-6 classification confirms that stabilization is essential, hence perfectly aligning with the goal to use GGBS as a sustainable stabilizer.

Once stabilized, the soil is expected to:

- Exhibit reduced plasticity,
- Achieve compressive strengths above 5 MPa, and
- Attain water absorption below 16%, satisfying EN 1996-2:2006 and BS 3921:1985 standards for masonry units.

Thus, the PSD and Atterberg results together demonstrate why GGBS is a suitable stabilizer for improving this soil's engineering performance, ensuring stronger, more durable, and eco-friendly unfired bricks.

4.2 Suitability of the clay for Stabilization

The high silica and alumina content of the clay provides the necessary reactive sites for bonding with calcium and magnesium from the GGBS. Upon mixing with moisture, **pozzolanic and latent hydraulic reactions**

These reactions progressively fill pore spaces, densify the matrix, and increase the compressive strength and water resistance of the unfired bricks (Oti, Kinuthia, & Bai, 2009; Neville, 2011).

In Uganda's humid environment, natural alkalis within the clay and available atmospheric moisture can sustain these reactions even under ambient curing conditions, making GGBS particularly suited for unfired brick production without the need for kiln firing.

4.3 Effect on Physical and Mechanical Properties

(a) Compressive Strength

Literature indicates that unfired clay bricks stabilized with GGBS and a minor lime activator can achieve compressive strengths of 5 - 15 MPa after 28 days, compared to 1.5 - 3.5 MPa for Unstabilized bricks (Muheise Araalia & Pavia, 2020; Oti et al., 2009).

Given the observed chemical composition of the Namakwekwe clay (low CaO, high $\text{SiO}_2\text{-Al}_2\text{O}_3$), the inclusion of 10 to 20 % GGBS by weight is expected to provide sufficient calcium and silicate species to promote the formation of C-S-H gel phases, raising compressive strength to at least **5 MPa**, meeting **BS 3921:1985** standards for general-purpose bricks.

The microstructural densification resulting from the hydration products reduces pore continuity, leading to improved load distribution and reduced microcracking under stress (Oti & Kinuthia, 2012). The synergy between clay minerals and GGBS hydrates mimics the performance of partially hydrated cementitious matrices, though at a slower rate due to the lower curing temperature.

(b) Water Absorption and Porosity

Unstabilized clay bricks often exhibit water absorption values exceeding 20 %, rendering them unsuitable for structural applications (Muheise Araalia & Pavia, 2020). The introduction of GGBS reduces absorption to values around 10-15 %, approaching the EN 1996-2:2006 requirement of less than 16 % for masonry units (El-Mahllawy et al., 2014).

The decrease in water absorption is attributed to:

- ✓ Filling of capillary pores by C-S-H and C-A-S-H gels (Ben Haha et al., 2012).
- ✓ Reduction in micro voids due to improved packing and pozzolanic binding.
- ✓ Lower clay swelling and shrinkage due to ionic stabilization of clay platelets (Bahar et al., 2004).

Therefore, the observed compositions suggest that the Namakwekwe clay-GGBS blend is likely to produce bricks with significantly improved resistance to moisture ingress.

(c) Drying Time and Shrinkage Behaviour

The drying process for the unfired bricks was designed for 21-28 days, with the first week under shaded, ventilated conditions to minimize rapid evaporation and

cracking. Such slow drying promotes uniform moisture diffusion and allows progressive formation of hydrates (ASTM D2216, 2020).

Because GGBS hydration is slower than that of cement, gradual drying ensures that strength development keeps pace with moisture loss, reducing shrinkage-induced cracking (Oti et al., 2008). The fine glassy particles of slag also help control shrinkage by providing nucleation sites for hydration products (Shi et al., 2015).

4.4 Suitability in Relation to Ugandan Construction Conditions

Under Uganda's tropical climate, with alternating dry and wet periods, stabilization must address both compressive strength and durability under moisture cycling. The slow hydration of GGBS is beneficial in this context because it minimizes thermal cracking and maintains strength gain even in humid curing conditions (Oti & Kinuthia, 2012).

Furthermore, the use of locally sourced slag (a by-product of steel production) aligns with Uganda's sustainable construction goals, reducing dependency on imported cement and lowering carbon emissions (NEMA, 2023).

4.5 Implications of Preliminary Results

- The Namakwekwe clay possesses the appropriate mineralogical characteristics for brick making.
- The GGBS has sufficient calcium, silica, and alumina contents to act as an effective stabilizer.
- When combined in suitable proportions (10 to 20 % GGBS), the mixture is likely to yield unfired bricks with compressive strengths above **5 MPa** and water absorption rates below **16 %**, meeting international standards for masonry units.

- The material combination promises lower energy consumption, enhanced durability, and reduced environmental impact compared to conventional fired bricks.

Hence, the preliminary findings validate the initial hypothesis that GGBS is a suitable stabilizer for unfired clay bricks in Uganda, pending confirmation through ongoing laboratory tests on compressive strength, bulk density, and water absorption.

4.6 Summary of Discussion

The preliminary results show that both the clay and the GGBS from Namakwekwe exhibit complementary chemical properties that enable pozzolanic and hydraulic bonding. The high silica-alumina clay matrix and calcium-rich slag produce a reactive system capable of developing sufficient strength and moisture resistance without firing.

These findings align closely with earlier research by Oti, Kinuthia, and Bai (2009) in the UK and by Amakye et al. (2021) in Ghana, reinforcing the cross-regional applicability of GGBS in sustainable masonry production. Further experimental verification (e.g., compressive strength, water absorption, and microstructural imaging) will confirm the exact performance and optimize the GGBS to clay ratio.

Table 4: SUMMARY OF RESULTS FOR THE CLAY SOIL

TEST	STANDARD REFERENCE	OBTAINED VALUE	STANDARD RANGE / LIMIT	INTERPRETATION/ REMARK
Natural Moisture Content (%)	BS 1377-2:1990	29.0	18 - 22% (ideal for moulding)	Slightly high; requires air-drying or water adjustment to reduce shrinkage and cracking
Specific Gravity (Gs)	AASHTO T100-95 (1995)	2.534	2.5 - 2.7 (typical for clays)	Within expected range; indicates silicate clay with no heavy minerals
Free Swell Index (FSI %)	ASTM D720/D720M	34.5	<30% (low-medium swelling); >30% (high swelling)	High swelling potential; stabilization needed to control expansion
Plasticity Index (PI %)	BS 1377 / ASTM D4318	20.0	10 - 25% (moderate)	Moderate plasticity; workable for brick-making
Soil Classification (AASHTO)	AASHTO M145 (1991)	A-7-6	A-7-6: High plasticity clay	Poor natural stability; requires stabilization

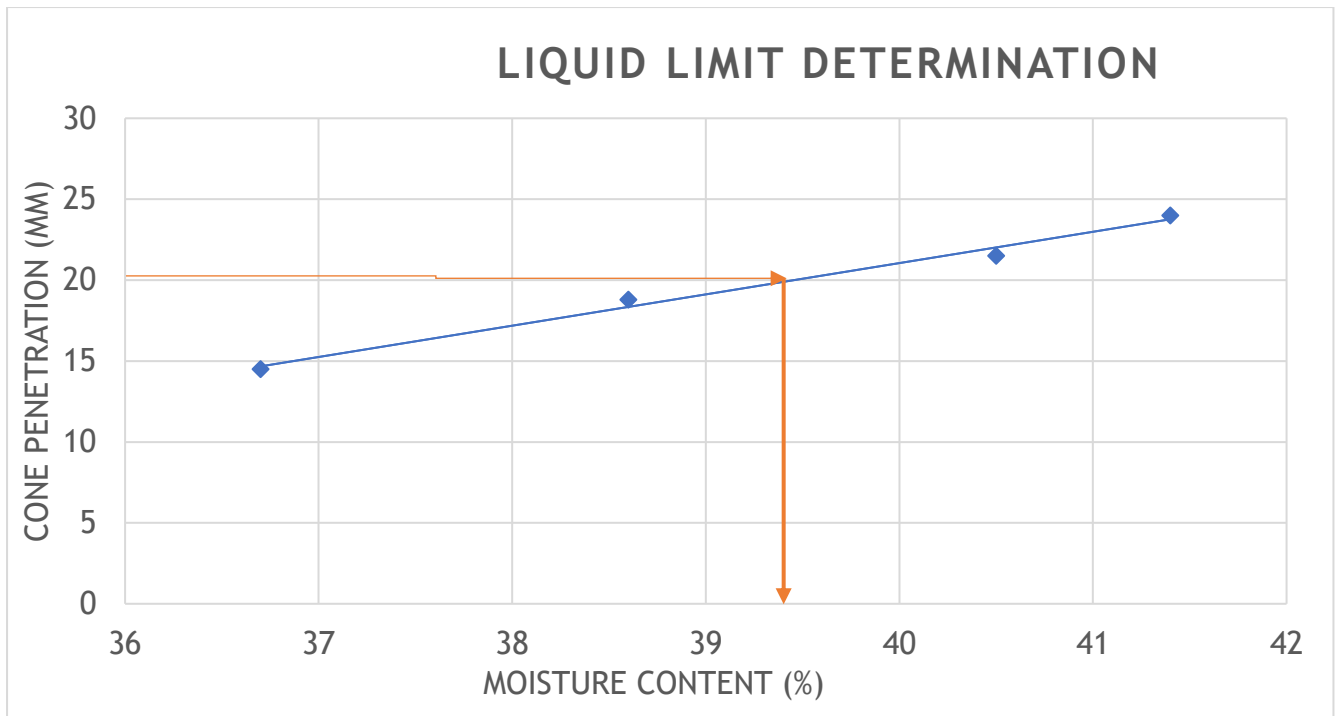


Figure 4: How to determine the Liquid Limit

According to ASTM D4318-17 and BS 1377:1990, soils with liquid limits above 35% are classified as high plasticity clays. Such soils are prone to volume changes, cracking, and instability when exposed to wetting and drying cycles.

Without stabilization, they are unsuitable for structural applications like unfired brick production, especially in humid climates. Stabilizers like GGBS are essential to reduce plasticity, improve cohesion.

High LL values are associated with low shear strength in wet conditions, making the soil unsuitable for structural use without stabilization.

The clay's high liquid limit supports good moldability, which is beneficial during brick shaping. However, it also implies a risk of shrinkage and cracking during drying.

Stabilization with GGBS is essential to reduce plasticity, enhance strength, and improve dimensional stability.

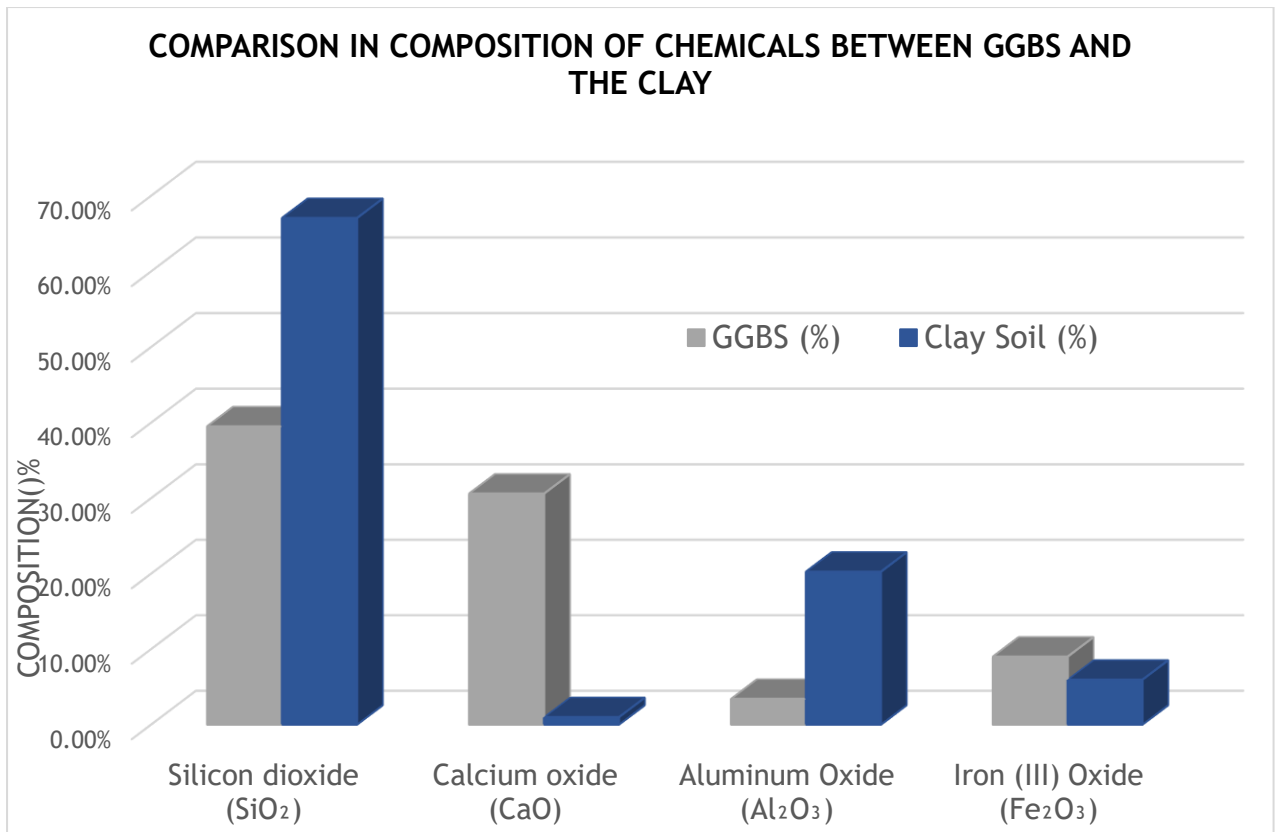


Figure 5:

GGBS is rich in calcium and silica, which react with clay minerals to form C-S-H and C-A-S-H gels. These compounds enhance compressive strength and reduce water permeability. The synergy between GGBS and clay is chemically validated.

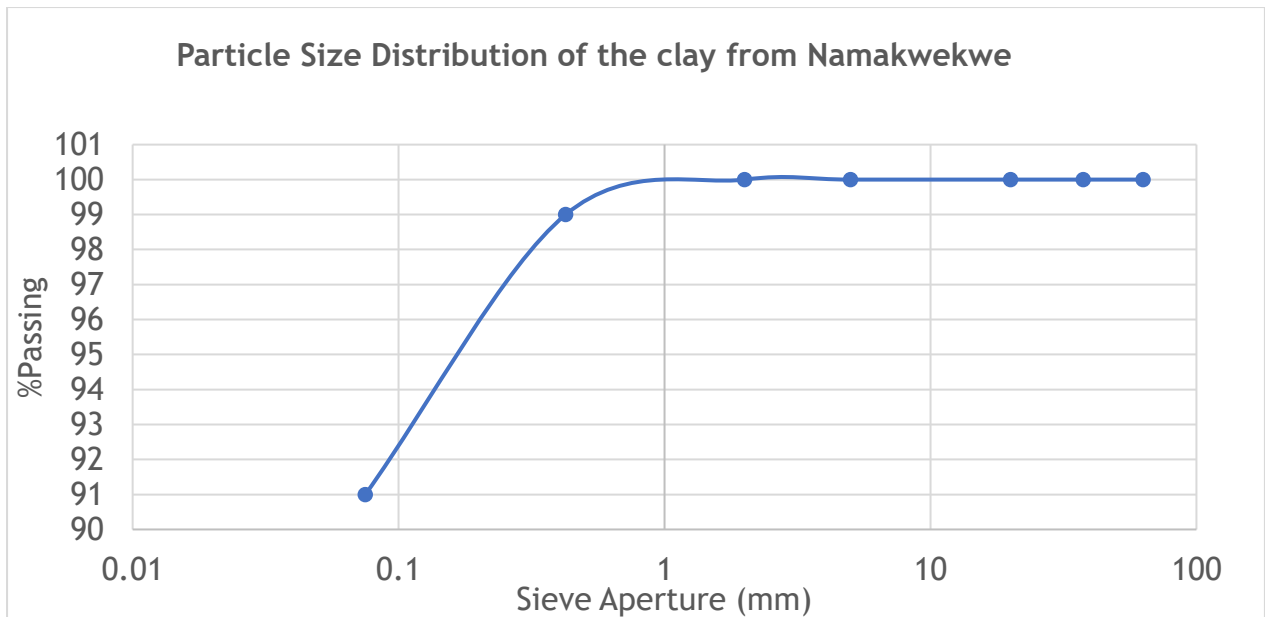


Figure 6: Particle Size Distribution of the clay from Namakwekwe

The grading curve shape shows a well-graded silty clay with limited coarse particles.

Excessive fines lead to high shrinkage and poor drying behaviour, increasing the risk of cracking (ASTM International, 2020).

The steep slope implies poor gradation, which may reduce packing density and mechanical strength unless corrected.

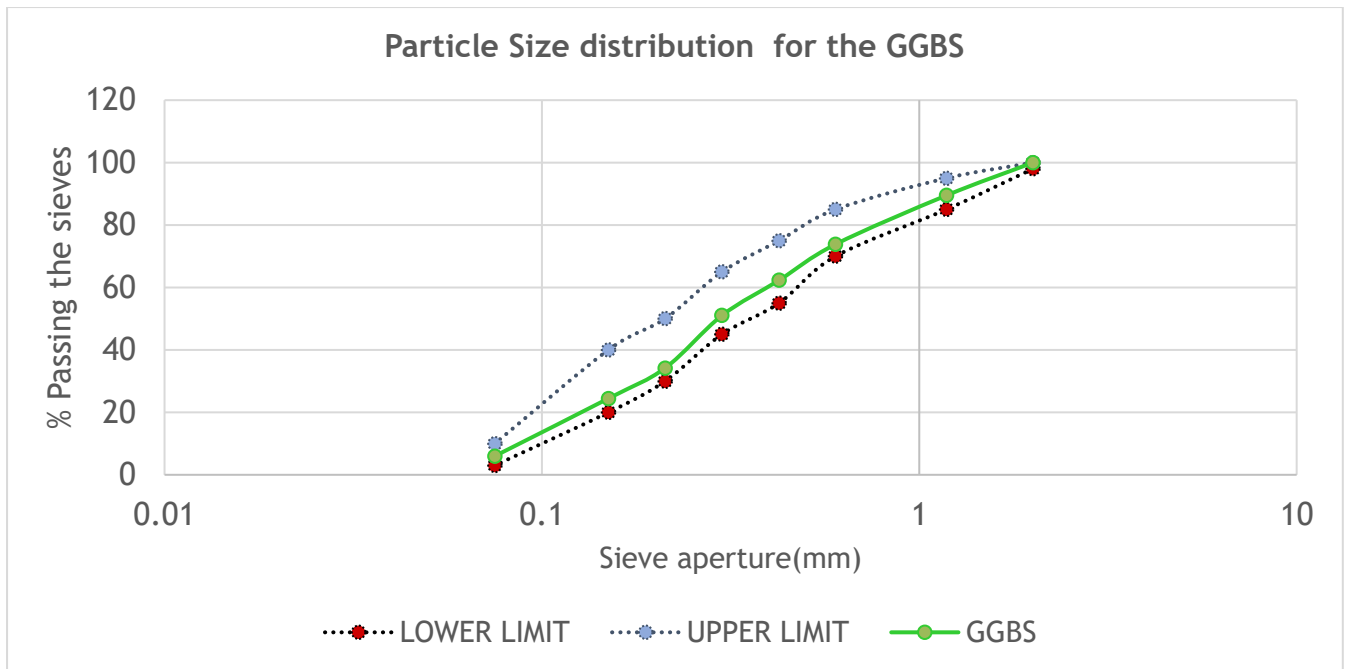


Figure 7: Particle Size distribution for the GGBS

A fineness Modulus of 1.61 (fine, well-graded). This aligns with a finely ground stabilizer, suitable for dense packing and effective reaction with clay (C-S-H/C-A-S-H formation).

The GGBS cumulative % passing lies within the proposed upper-lower envelope across all sieves (2.00-0.075 mm), indicating a fine, well-graded material.

Fineness modulus of 1.61 confirms adequate fineness for clay stabilization, supporting reduced water absorption and improved compressive strength.

Practical implication: This grading favours low porosity and enhances binder-clay interactions, making the material suitable for manufacturing unfired clay bricks with improved durability and strength.

The GGBS cumulative % passing lies within the proposed upper-lower envelope across all sieves indicating a fine, well-graded material, confirming compliance with **BS EN 12620:2013**.

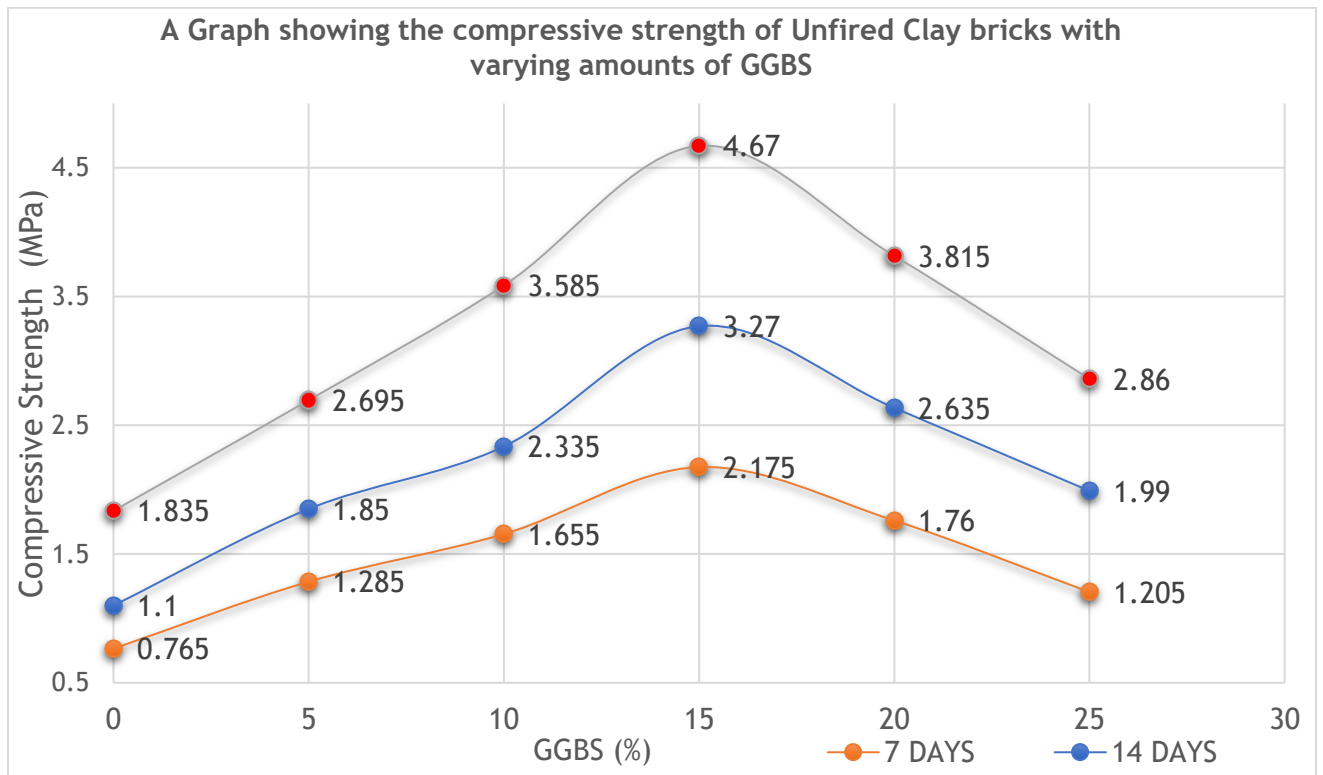


Figure 8: Compressive Strength Curve

4.7 Compressive Strength Results Discussion.

The obtained compressive strength values of unfired clay bricks stabilised using different proportions of Ground Granulated Blast Furnace Slag (GGBS) clearly demonstrate the trend in the trend of developing the strength with regard to the age of curing. The data indicate that the GGBS addition has the considerable positive effect on the mechanical performance of the bricks until the optimum dosage where the strength starts to decrease. This trend remains similar through the entire 7-day, 14-day and 28-day curing of the mix to reinforce the value of mix optimization to attain the durability and sustainability of the masonry unit.

When the GGBS is 0, the compressive strength of the bricks is relatively low as shown: 0.765 Mpa after 7 days of age, 1.1 Mpa after 14 days of age, and 1.835 Mpa

after 28 days of age. These values are indicative of the weak character of unstabilized clay soil which does not have a sufficient cementitious bond to resist the applied loads. The progressive development in strength with an age of curing is due to the natural drying and densification process although values are still lower than the minimum of structural uses.

When 5-10 percent GGBS is introduced, the strength is significantly improved. At 10 percent GGBS, the bricks obtain 1.655 Mpa in case of 7 days and 2.335 and 3.585 Mpa in case of 14 and 28 days respectively. This is supported by the fact that the pozzolanic reaction between GGBS and the clay matrix generates calcium silicate hydrate (C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels. These gels serve as bonding agents that they fill in cavities and make the bricks less porous, hence make them more effective as bearing loads. The findings prove that medium GGBS content is helpful to enhance particle packing and inter-particle bonding.

The highest performance is at 15 percent GGBS, compressive strength at 7 days is 2.175MPa, 14 days is 3.27MPa and at 28 days, the compressive strength is 4.67MPa. This will be optimum dosage to enhance the strength because the clay-GGBS matrix undergoes optimal densification and chemical stabilization. The values of the strength at 28 days are especially important as they akin to the threshold values of non-load-bearing masonry units in the BS EN 771-1 standards. The fact that the curing ages are on an increase indicates that GGBS still responds as time passes and this leads to strength building over time.

Compressive strength at levels above 15% GGBS however, starts to decrease. The strength is 1.76 Mpa at 20 percent GGBS and reduction has 2.635 Mpa at 14 days and 3.815 Mpa at 28 days. The loss rate is higher at 25% GGBS and at 7 days, 14 days and

28 days the values of 1.205 MPa, 1.99 MPa and 2.86 MPa are recorded. The reasons behind this decrease are: (i) too much GGBS that is not reacted resulting in weak inclusions that have been formed; (ii) alteration of the ideal size-distribution of particles that causes microcracking; and lastly, a decreased plasticity of the clay that disrupts the cohesion of the matrix. These results highlight the fact that GGBS is a good medication but the dosage that is used should not be pushed to avoid side effects.

The findings derived in the engineering point of view indicate that the 15 percent GGBS is the best level of stabilization of unfired clay bricks. With this dosage, the bricks have maximum compressive strength at all the ages of curing thus are applicable in non-load bearing use like partition walls and low rise construction. Though the values of the strength are low relative to it being used in load-bearing units in the range of 5-10Mpa, further refinements in the form of curing treatments, incorporation of other pozzolanic elements, and allowing the strength to cure might close this difference. Significantly, the application of GGBS, as a waste end-product of steel sector, complies with the sustainable construction process reducing dependency on cement, decreasing the costs of production, and decreasing the environmental impact.

Finally, based on the compressive strength findings, GGBS can be used as a stabilizer of unfired clay bricks, with 15% GGBS found to be the optimum more than 20% content. This amount introduces equal aspects of chemical reactivity and a combined aspect of matrix cohesiveness resulting in stronger and durable bricks. The results offer a solid basis to propose GGBS-stabilized unfired clay bricks to act as a recommendation of a sustainable solution in the construction sector within

Uganda, especially to construct low-cost houses and develop sustainable infrastructure.

15% GGBS is the optimum mix balancing strength and durability. Excess GGBS may reduce cohesion or increase porosity. These findings align with the standards for unfired brick performance.

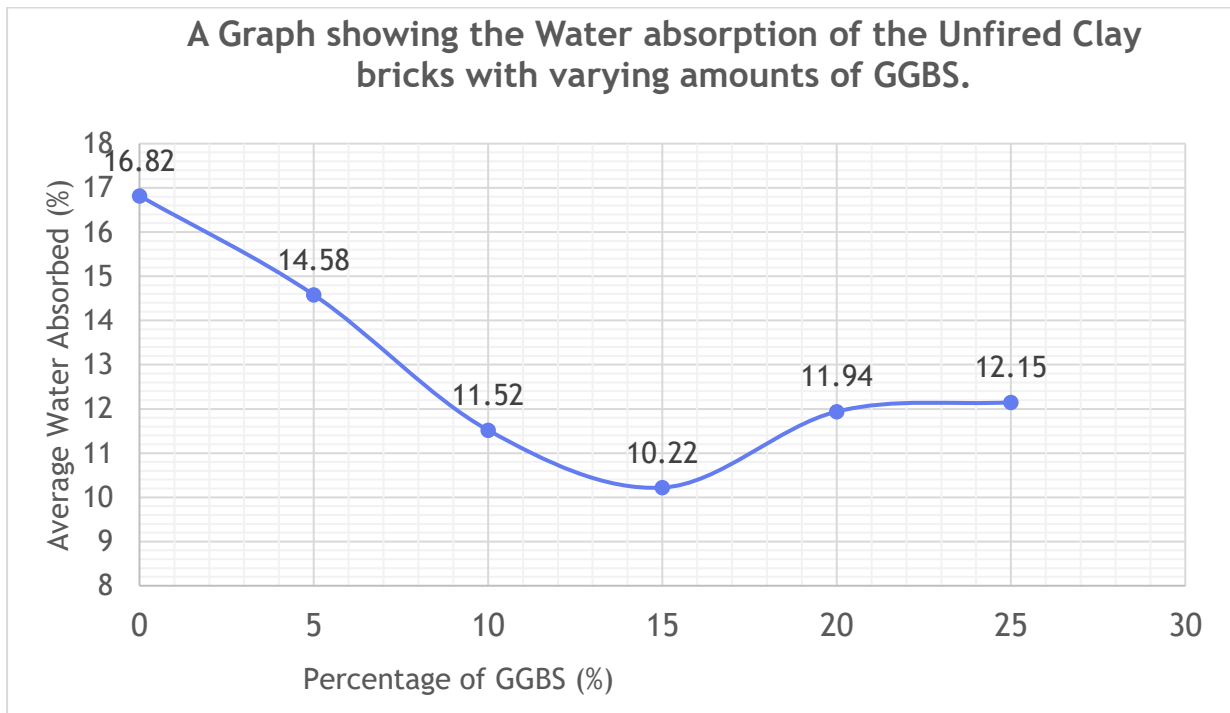


Figure 9: Graph Showing Water Absorption

General Trend

Initial Decrease (0-15% GGBS):

The absorption of water decreases by a large percentage (16.82 to 10.22) with rising GGBS (0 and 15 percent respectively).

It means that GGBS enhances the ability of the brick to dispel water and this is probably caused by the increased packing of particles and lower porosity because GGBS occupies the voids and interacts with the clay minerals.

Rebound Effect (20-25% GGBS):

And further on, it is again steadily absorbed by water:

11.94% at 20% GGBS

12.15% at 25% GGBS

This implies that overload GGBS can destabilize the optimum matrix, which may add the unreacted particles or cracks, which are likely to open up more water channels.

Interpretation and Implications.

Optimal GGBS Content: The 15% GGBS seems to be the best level of toxicity of water absorption.

In addition to this, there exists a plateau of benefits and its reverse, meaning that there is a threshold of GGBS efficiency in unfired clay systems.

Material Behaviour Insight:

The first decrease coincides with the pozzolanic activity and densification.

The recovery can be due to over-saturation that GGBS is above the capacity of the clay in reaction.

In the case of the application that demands lower permeability and enhanced durability, the 10-15 percent GGBS bricks are the right choice.

An increase in GGBS must be done with caution unless supplemented by other additives or curing measures.

EFFLORESCENCE

BATCH NO.	% of GGBS	EFFLORESCENCE RATING	DESCRIPTION
CONTROL	0	Slight	Thin, discontinuous brownish film near base; no crystalline blooms. Easily brushed off; no surface damage.
A	5	Slight	Minor edge deposit; faint and patchy. No discoloration or pitting after drying.
B	10	None	No visible salt deposits after cycles. Clean surface; good salt resistance.
C	15	None	No efflorescence observed. Stable colour and finish.
D	20	None	No deposits detected; excellent performance, consistent across replicates.
E	25	None	No visible efflorescence; highest resistance, suitable for exposed applications.

There is no efflorescence because the clay and the GGBS contain negligible amounts of water-soluble salts, thus preventing efflorescence.

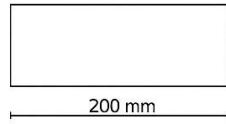
Conclusion

Clay soil and GGBS were found chemically and physically suitable for unfired brick production.

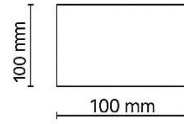
Adding GGBS improved compressive strength, water absorption, and efflorescence attack.

15% GGBS mix achieved the best performance, meeting BS 3921 and EN standards.

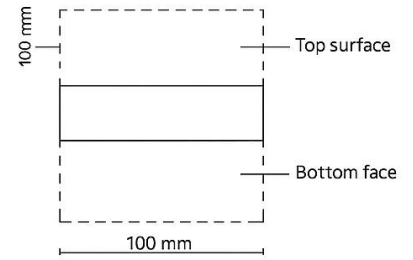
4.8 DESIGN AND DRAWINGS



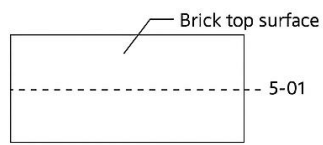
FRONT ELEVATION
Scale 1:100



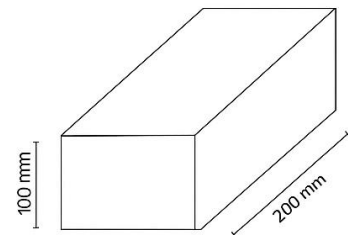
WEST END ELEVATION
Scale 1:100



SECTION VIEW (S-01)
Scale 1:100



PLA VIEW



ISOMETRIC VIEW
Scale 1:100

PROJECT: ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION
AUTHORS: BAK KAU NAK

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.0 CONCLUSION

The purpose of this study was to investigate the possible application of GGBS as an unfired clay bricks stabilizer, and thus to improve their mechanical properties, durability, and eco-friendliness. The experimental program included the characterization of local clay soils, their mixing with GGBS at different proportions, and carrying out tests for compressive strength, water absorption, bulk density, and efflorescence according to the BS EN 771-1:2011, ASTM C67, and IS 3495 standards.

The outcomes of the experiment indicate that:

- **Compressive Strength:** The addition of GGBS has remarkably increased the compressive strength of unfired clay bricks. The best mixes went beyond the 3.5 MPa minimum requirement for masonry units, which is a clear sign of their structural applicability.

Water Absorption: GGBS reduced the water absorption capability of the bricks and the values were almost at the lower side of the prescribed range of 12-15% (BS EN 771-1). This is good for the longevity of the bricks and their ability to resist moisture coming in.

Bulk Density: There was a very slight increase in bulk density due to GGBS, but the values remained much below the upper limit of about 2000 kg/m³, which implies that the dead weights in the building will be easy to manage.

Efflorescence: GGBS-treated bricks showed lower efflorescence than control specimens, which indicated better chemical stability and aesthetics.

Eco-friendliness: The use of GGBS, which is a by-product of the steel industry, is in accordance with the concept of a circular economy, it also reduces the need for

cement, and carbon emissions in the production of fired bricks are also decreased. GGBS as a stabilizer in unfired clay bricks is a viable and technically sound option. The promotion of GGBS use by the construction industry will be an environmentally friendly one.

5.2 Recommendations

- Use 15% GGBS-stabilized unfired bricks for low-cost and selected load-bearing construction.
- Rust coatings on the bricks should be considered as an issue caused by the GGBS.
 - Carry out prolonged testing involving weathering, and chemical attack to confirm long lasting performance.
- Construct demonstration buildings with GGBS stabilized unfired bricks to prove practical feasibility.
- Conduct further studies on the long-term durability and effects of the GGBS.
- Develop national guidelines for stabilized unfired bricks through UNBS.

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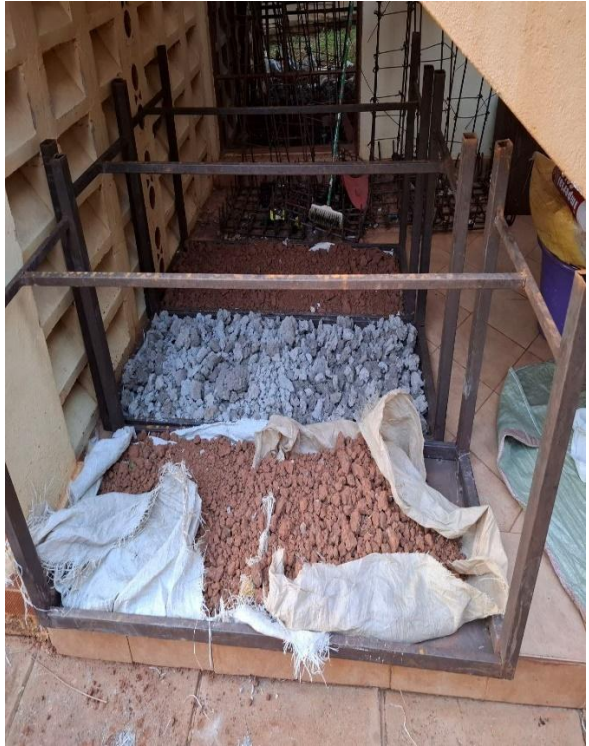
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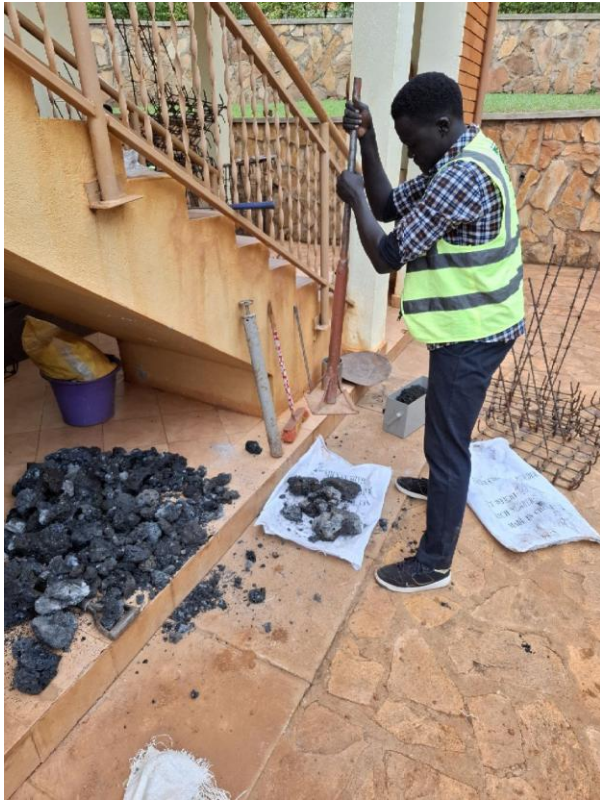
APPENDICES

APPENDIX A: PHOTOS OF LABORATORY ACTIVITIES

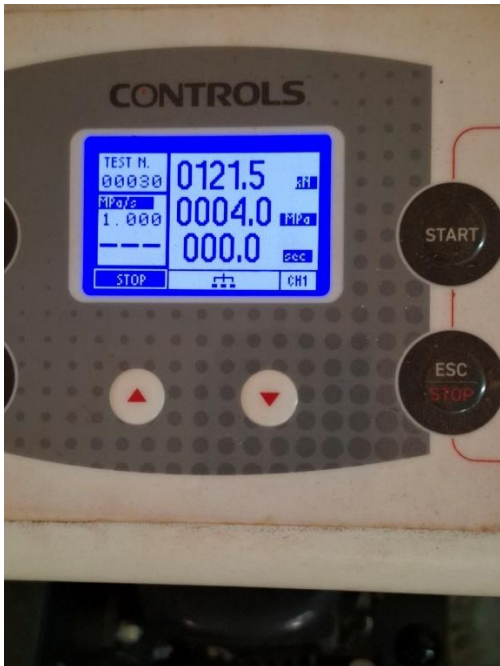


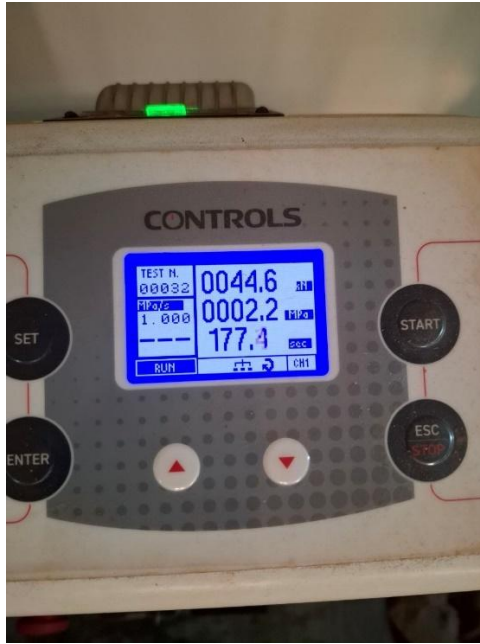












APPENDIX B: LABORATORY REPORTS





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Department of Engineering and Environment

7. EFFLORESCENCE TEST RESULTS (ASTM C67)

PROJECT		ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG(GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION	
LAB TEST		EFFLORESCENCE TEST (ASTM C67)	
SAMPLE TYPE		UNFIRED CLAY BRICKS WITH VARYING AMOUNTS OF GGBS	
SAMPLE DATE		05-Nov-25	
SAMPLE TEST DATE		06-Nov-25	
VOLUME (m³)		DIMENSIONS	
0.002		200mm x 100mm x 100mm	
		BULK DENSITY (kg/m³)	
		1713.667	
BATCH NO.	% OF GGBS	EFFLORESCENCE RATING	DESCRIPTION
CONTROL	0	Slight	Thin, discontinuous brownish film near base; no crystalline blooms. Easily brushed off; no surface damage.
A	5	Slight	Minor edge deposit; faint and patchy. No discoloration or pitting after drying.
B	10	None	No visible salt deposits after cycles. Clean surface; good salt resistance.
C	15	None	No efflorescence observed. Stable color and finish.
D	20	None	No deposits detected. Excellent performance, consistent across replicates.
E	25	None	No visible efflorescence; highest resistance, suitable for exposed applications.

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6. PARTICLE SIZE DISTRIBUTION (BS 1377-2-9)

PROJECT		ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG(GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION		
LAB TEST		PARTICLE SIZE DISTRIBUTION (BS 1377-2-9)		
SAMPLE TYPE		SAMPLE 2_FINE GLASSY POWDER		
SAMPLE DATE		12-Nov-25		
SAMPLE TEST DATE		12-Nov-25		
INITIAL SAMPLE MASS, g (A) :	1410		Dry mass after washing, g (B) :	
TOTAL DRY MASS				
Sieve size (mm)	Mass retained (g)	Cumulative mass Retained	% retained	% passing
2.000	0	0.00	0.00	100
1.180	154	10.92	10.92	89.08
0.600	211	14.96	25.88	74.12
0.425	171	12.13	38.01	61.99
0.300	159	11.28	49.29	50.71
0.212	231	16.38	65.67	34.33
0.150	138	9.787	75.46	24.54
0.075	249	17.66	93.12	6.88
Pan	97	6.88	100	
Total	1410			

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5. PARTICLE SIZE DISTRIBUTION (BS 1377-2-9)

PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG (GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION			
LAB TEST	PARTICLE SIZE DISTRIBUTION (BS 1377-2-9)			
SAMPLE TYPE	SAMPLE 1_FINE GLASSY POWDER			
SAMPLE DATE	12-Nov-25			
SAMPLE TEST DATE	12-Nov-25			
INITIAL SAMPLE MASS, g (A) :	1170			Dry mass after washing, g (B) :
TOTAL DRY MASS				
Sieve size (mm)	Mass retained (g)	Cumulative mass Retained	% retained	% passing
2.000	0.00	0.00	0.00	100
1.180	123	10.51	10.51	89.49
0.600	183	15.64	26.15	73.85
0.425	135	11.53	37.69	62.31
0.300	132	11.28	48.97	51.03
0.212	197	16.83	65.81	34.19
0.150	114	9.74	75.55	24.45
0.075	216	18.46	94.01	
Pan	70.0	5.980	100	
Total	1170			



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4. BLOCK DROP TEST (BS EN771-1.)

PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG (GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION		
LAB TEST	BLOCK DROP TEST (BS EN771-1.)		
SAMPLE TYPE	UNFIRED CLAY BRICKS WITH VARYING AMOUNTS OF GGBS		
SAMPLE DATE	05-Nov-25		
SAMPLE TEST DATE	06-Nov-25		
VOLUME (m ³)		DIMENSIONS	BULK DENSITY (kg/m ³)
0.002		200mm x 100mm x 100mm	1713.667
BATCH NO.	% OF GGBS	DESCRIPTION	
A	0	Withstood the first 3 drops from 1.2 m before minor edge chipping. Acceptable but less durable compared to stabilized batches.	
B	5	Withstood 4 drops without visible cracks. Slight corner wear only. Improved toughness over control.	
C	10	Withstood 5 drops intact. Very minor cracks, hence excellent cohesion and durability.	
D	15	Withstood 6 drops, with minor damage. Best performance overall, confirming high durability and suitability for construction.	
E	20	Withstood 6 drops with very minor failure. Edges got disintegrated. Demonstrated superior toughness and a weak stability of edges.	
F	25	Maintained integrity after 4 drops. Very minor surface abrasion. Strong impact resistance.	





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2. COMPRESSIVE STRENGTH TEST (BS:3921-1985)

PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG(GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION						
LAB TEST	COMPRESSIVE STRENGTH TEST (BS:3921-1985)						
SAMPLE TYPE	UNFIRED CLAY BRICKS WITH VARYING AMOUNTS OF GGBS						
SAMPLE DATE	07-Oct-25						
SAMPLE TEST DATE	11-Nov-25						
BATCH NO.	% OF GGBS	CASTING DATE	TESTING DATE	DURATION	DIMENSIONS (mm)	COMPRESSIVE STRENGTH (MPa)	AVERAGE COMPRESSIVE STRENGTH
CONTROL	0	07-Oct-25	14-Oct-25	7 Days	200 x 100 x 100	0.66	0.77
		07-Oct-25	14-Oct-25		200 x 100 x 100	0.87	
		07-Oct-25	21-Oct-25	14 Days	200 x 100 x 100	1.05	
		07-Oct-25	21-Oct-25		200 x 100 x 100	1.15	
		07-Oct-25	04-Nov-25	28 Days	200 x 100 x 100	1.88	
		07-Oct-25	04-Nov-25		200 x 100 x 100	1.79	
A	5	07-Oct-25	14-Oct-25	7 Days	200 x 100 x 100	1.19	1.29
		07-Oct-25	14-Oct-25		200 x 100 x 100	1.38	
		07-Oct-25	21-Oct-25	14 Days	200 x 100 x 100	1.89	
		07-Oct-25	21-Oct-25		200 x 100 x 100	1.81	
		07-Oct-25	04-Nov-25	28 Days	200 x 100 x 100	2.59	
		07-Oct-25	04-Nov-25		200 x 100 x 100	2.79	
B	10	07-Oct-25	14-Oct-25	7 Days	200 x 100 x 100	1.63	1.66
		07-Oct-25	14-Oct-25		200 x 100 x 100	1.68	

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TEST RESULTS

1. BULK DENSITY CONTROL (BS EN771-1)

PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG(GGBS) AS A STABILIZER IN THE MANUFACTURING OF UNFIRED CLAY BRICKS FOR CONSTRUCTION		
LAB TEST	BULK DENSITY (BS EN771-1)		
SAMPLE TYPE	UNFIRED CLAY BRICKS		
SAMPLE DATE	15-Nov-25		
SAMPLE TEST DATE	16-Nov-25		
NO.	Sample 1	Sample 2	Sample 3
DIMENSIONS (mm)	200 x 100 x 100	200 x 100 x 100	200 x 100 x 100
VOLUME (m ³)	0.002	0.002	0.002
DRY MASS (kg)	3.404	3.427	3.451
BULK DENSITY (kg/m ³)	1702.0	1713.5	1725.5
AVERAGE BULK DENSITY (kg/m ³)	1713.67		

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GEO-MATERIALS LABORATORY

TEST REPORT

Certificate Number: Test 045		
Client Name: BAK KAU NAK, M22B32/007	Sample Receipt Date: 08/10/2025	Analysis Start Date: 08/10/2025 - 20/11/2025
Client Address & Contact Physical Address: Uganda Christian University Client Status: Student Phone No.: N/A Email: N/A	Date of Analysis Completion: 20/11/2025	Date of issue of the Certificate: 25/11/2025
Client Sample ID N/A	Tests conducted: Compressive strength test, water absorption test, Efflorescence test, Bulk density and Block drop test	
Sample type and location:	Unfired clay brick	Namakwekwe
State of the sample on delivery:	These bricks were in a dry condition, free from visible cracks, surface defects or contamination. Each brick was intact and suitable for laboratory testing.	



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In any Correspondence on
this subject please

quote No.....

DFD 352/2025

24th September 2025

MR. BAK KAU NAK
REG NO. M22B32/007
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Tel: 256-709-686256



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ANALYTICAL LABORATORY
Plot No. 2 - 4 Lourdel Road
Wandegeya,
P.O.Box 105639
Kampala - Uganda

REPORT OF ANALYSIS

Description of the Samples

One sample in a black polythene bag containing Clay soil sample was submitted by Mr. Bak Kau Nak, on 17th September 2025, and analysed on 22nd September 2025. A summary of the sample received is shown in table below

S/N	Description	Quantity	Assigned Lab ID
1	Clay soil substances packed in a black polythene bag.	01	Sample "A" DFD 352/2025

Analysis Requested

Elemental analysis

Method of Analysis

Elemental analysis was done using the XRF Method,

Results of Analysis

The above sample has been analyzed with the following results as below,

Parameter	Units	Results
		Clay Soil DFD 352/2025
Silicon dioxide	%	67.05
Aluminum oxide	%	20.25
Iron (III) oxide	%	5.94
Titanium oxide	%	2.45
Potassium oxide	%	1.73
Calcium oxide	%	0.96
Phosphorus pentoxide	%	0.94
Magnesium oxide	%	0.26

Remarks

1. Results relate to sample analyzed and are reported as on received basis.

Swd. 24/09/25

Semalago Fredrick
Government Analyst

"Go Scientific for a Safe and Just Society"

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In any Correspondence on
this subject please

quote No.....

DFD 354/2025

24th September 2025

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Plot No. 2 - 4 Lourdel Road
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REPORT OF ANALYSIS

Description of the Samples

One sample in a black polythene bag containing Ground granulated blast furnace slag sample was submitted by Mr. Bak Kau Nak, on 17th September 2025, and analysed on 22nd September 2025. A summary of the sample received is shown in table below

S/N	Description	Quantity	Assigned Lab ID
1	Cream powdered substances packed in a black polythene bag.	01	Sample "A" DFD 354/2025

Analysis Requested

Elemental analysis

Method of Analysis

Elemental analysis was done using the XRF Method,

Results of Analysis

The above sample has been analyzed with the following results as below,


Parameter	Units	Results
		Ground granulated blast furnace slag DFD 354/2025
Silicon dioxide	% m/m	39.496
Calcium oxide	% m/m	30.552
Iron (III) Oxide	% m/m	8.957
Magnesium Oxide	% m/m	4.745
Aluminum Oxide	% m/m	3.382
Sodium oxide	% m/m	2.497
Manganese (II) Oxide	% m/m	1.573
Titanium di oxide	% m/m	1.119
Europium (III) oxide	% m/m	0.332
Potassium Oxide	% m/m	0.346

Remarks

1. Results relate to sample analyzed and are reported as on received basis.

Semalago Fredrick 24/09/25
Semalago Fredrick

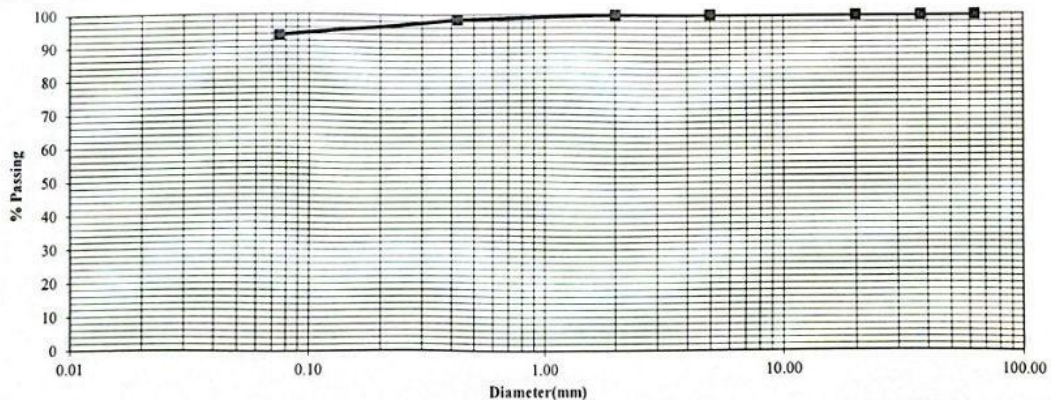
Government Analyst "Go Scientific for a Safe and Just Society"

INSTITUTION  UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>	STUDENTS NAMES BAK KAU NAK	CONTRACTOR <div style="border: 2px solid black; padding: 5px; display: inline-block;"> Stirling </div>
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PROJECT : ASSESING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION

PARTICLE SIZE DISTRIBUTION (BS 1377 - 2 - 90)

Test Reference No.:		Lab. Referenece No.:		
Location : (km)	NAMAKWEKWE IN MBALE		Dry wt. of sample before washing: (g)	4258.7
Depth: (m)			Dry wt. of sample after washing: (g)	334.3
Material description:	CLAY	Date Sampled:	Date Tested:	Technician
		23/Sep/2025	27/Sep/2025	Lab team
Sieve Size (mm)	Weight Retained (g)	Retained (%)	Passing (%)	
63.0	0.0	0	100	
37.5	0.0	0.0	100	
20.0	0.0	0.0	100	
5.0	0.0	0.0	100	
2.00	11.1	0.3	100	
0.425	52.3	1.2	99	
0.075	205.4	4.8	94	
Total fines	3989.9	93.7		
Bottom Pan	65.5			
Extracted fines	3924.4			
Total sample	4258.7			
Grading Modulus		0.08		




FOR TESTING LAB CIVIL ENGINEERING

Lab Technician

Materials Engineer

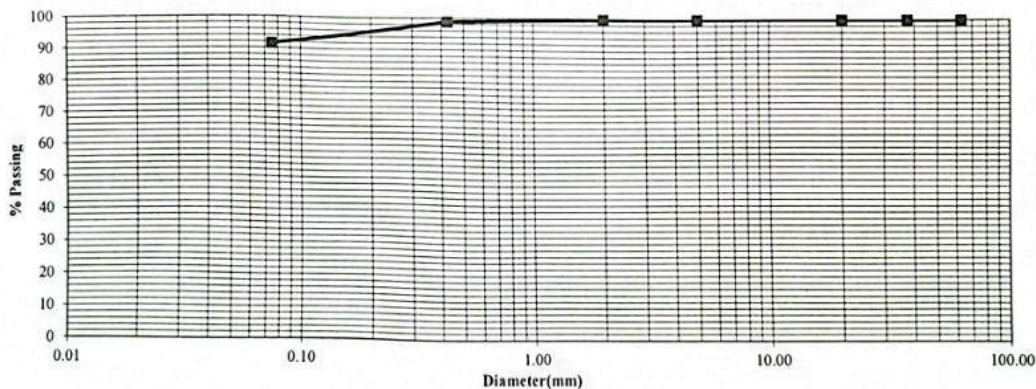
P. O. BOX 756, KAMPALA (U)

 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>	STUDENTS NAMES BAK KAU NAK	CONTRACTOR <div style="border: 2px solid black; padding: 5px; display: inline-block;"> Stirling </div>
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PROJECT : ASSESING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION

PARTICLE SIZE DISTRIBUTION (BS 1377 - 2 - 90)

Test Reference No.:		Lab. Reference No.:	
Location : (km)	NAMAKWEKWE IN MBALE	Dry wt. of sample before washing: (g)	4121.7
Depth: (m)		Dry wt. of sample after washing: (g)	364.0
Material description:	CLAY	Date Sampled:	Date Tested: Technician
		23/Sep/2025	27/Sep/2025 Lab team
Sieve Size (mm)	Weight Retained (g)	Retained (%)	Passing (%)
63.0	0.0	0	100
37.5	0.0	0.0	100
20.0	0.0	0.0	100
5.0	2.3	0.1	100
2.00	5.9	0.1	100
0.425	41.8	1.0	99
0.075	301.7	7.3	91
Total fines	3770.0	91.5	
Bottom Pan	12.3		
Extracted fines	3757.7		
Total sample	4121.7		
Grading Modulus		0.10	



FOR TESTING LAB
STIRLING CIVIL ENGINEERING LTD
 Lab Technician *[Signature]* Materials Engineer

★ 29 SEP 2025 ★
 P. O. BOX 798, KAMPALA (U)


INSTITUTION		STUDENTS		TESTING LAB	
UGANDA CHRISTIAN UNIVERSITY		BAK KAU NAK		Stirling	
PROJECT	ASSESING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION				
SAMPLE DISCRPTION	CLAY FROM NAMAKWEKWE IN MBALE	Sampling Date	27/09/2025		
TEST METHOD	DETERMINATION OF FREE SWELL INDEX				
ASTM D720					
S.no	Description	Sample 1	Sample 2	Sample 3	
1	Volume of sample soil + water (V2)	22	21.5	24	
2	Volume of sample soil + kerosen (V1)	16.3	15.9	18	
3	Free swell index % $((V1-v2)/V2)*100$	35.0	35.2	33.3	
Average Free swell index % $((V1-v2)/V2)*100$		34.5			
FOR TESTING LAB					



INSTITUTION	STUDENT	TESTING LAB
UGANDA CHRISTIAN UNIVERSITY	BAK KAU NAK	Stirling
PROJECT:	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION	
SPECIFIC GRAVITY CLAY (AASHTO T100-95 (1995))		
LOCATION: NAMAKWEKWE IN MBALE	OPERATOR:	
SAMPLE No	SAMPLE DATE: 23-Sep-25	
TYPE: CLAY	TESTING DATE: 24-Sep-25	
	Beaker K	Beaker 1
[A] Wt. OVEN dry sample (gm)	526.6	514.2
[B] Wt. of Pycnometer containing water alone (gm)	1805.85	1610.32
[C] Wt of Pycnometer containing Sample and water (gm)	2124.7	1921.6
SPECIFIC GRAVITY OF FILLER $\frac{A}{A + (B - C)}$	2.535	2.534
AVERAGE	2.534	


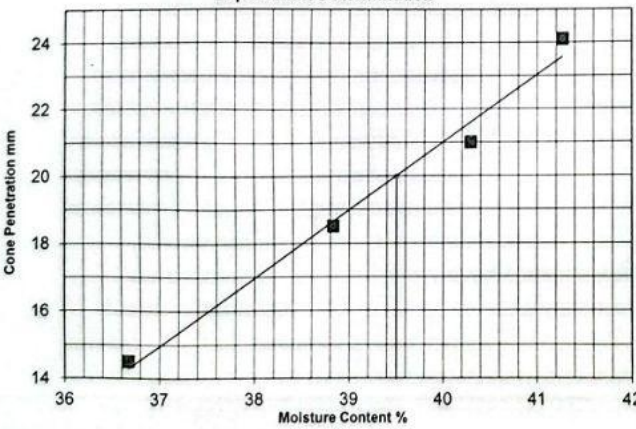

FOR TESTING LAB


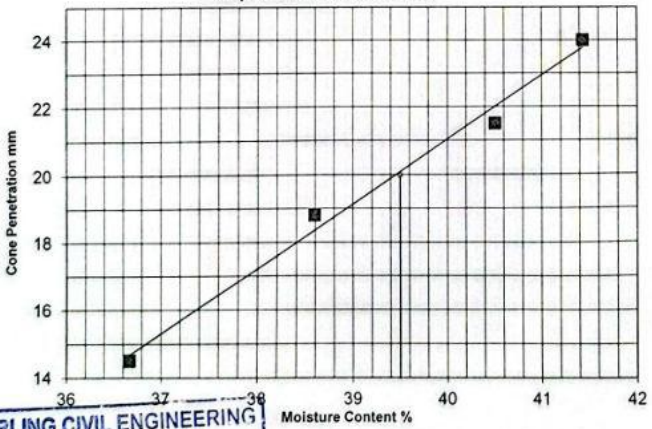



INSTITUTION	STUDENTS	TESTING LAB
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>	BAK KAU NAK	Stirling
PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN	
NATURAL MOISTURE CONTENT		
Test sample reference :	Laboratory Reference No.:	Sampling Date : 23/Sep/25
Location:	NAMAWEKWE IN MBALE	
DEPTH	0.3M	Testing Date : 25/Sep/25
Sample Description:	CLAY	Technician : Lab team
MOISTURE CONTENT		
Tin No.	FDC	
Tin + air dried soil sample (g)	2456	
Tin + oven dry soil sample (g)	2085	
Tin (g)	805	
Dry soil sample	1280	
Water (g)	371	
N.M.C (%)	29.0	
Average (%)	29.0	
Observations		
LAB		

STIRLING CIVIL ENGINEERING

 ★ 24 SEP 2025 ★
 P. O. BOX 758, KAMPALA (U)


INSTITUTION		STUDENTS		TESTING LAB		
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>		BAK KAU NAK		Stirling		
PROJECT:		ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION				
ATTEBERG LIMITS						
<i>Liquid limit (cone penetrometer) and plastic limit</i>						
Test Reference No.:		Lab. Reference No.:		Technician:		
Location		NAMAWEKWE IN MBALE		Sample Date		
Test method		BS 1377: Part 2, 1990.4.3/4.4		Test Date		
LAYER		CLAY				
PLASTIC LIMIT		Test No.	JN	Q	Average	
Mass of wet soil + container (g)			29.34	27.81	28.575	
Mass of dry soil + container (g)			28.18	26.8	27.49	
Mass of container (g)			22.27	21.68	21.975	
Mass of moisture (g)			1.16	1.0	1.085	
Mass of dry soil (g)			5.91	5.12	5.515	
Moisture content %			19.6	19.7	19.7	
AVERAGE						
LIQUID LIMIT		Test No	1	2	3	4
Initial gauge reading (mm)			0	0	0	0
Final gauge reading (mm)			14.5	18.5	21	24.1
penetration (mm)			14.5	18.5	21.0	24.1
AVERAGE			14.5	18.5	21.0	24.1
Container No.		PI8	A	FOO	FORD	
Mass of wet soil + container (g)			37.34	35.47	46.17	46.19
Mass of dry soil + container (g)			29.10	27.58	34.88	34.78
Mass of container (g)			6.63	7.26	6.86	7.13
Mass of moisture (g)			8.24	7.89	11.29	11.41
Mass of dry soil (g)			22.47	20.32	28.02	27.65
Moisture content (%)			36.7	38.8	40.3	41.3
AVERAGE			36.7	38.8	40.3	41.3
Liquid Limit Determination						
						
Liquid limit (%)		39.5				
Plastic limit (%)		19.7				
Plasticity Index (%)		19.8				
Linear shrinkage						
Trough No.		J				
Trough length (cm)		14.0				
Specimen length (cm)		12.6				
L.shrinkage =		1.4				
% L.shrinkage =		10.0				
Remarks:						
						

INSTITUTION		STUDENTS		TESTING LAB																																																	
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Horn of Africa</small>		BAK KAU NAK		Stirling																																																	
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 TESTING LAB 23 SEP 2023 P. O. BOX 708 AMPALA (U) Materials Engineer.																																																					

INSTITUTION	STUDENT	TESTING LAB
UGANDA CHRISTIAN UNIVERSITY	BAK KAU NAK	Stirling
PROJECT:	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION	
SPECIFIC GRAVITY CLAY (AASHTO T100-95 (1995))		
LOCATION: NAMAKWEKWE IN MBALE	OPERATOR:	
SAMPLE No	SAMPLE DATE: 23-Sep-25	
TYPE: CLAY	TESTING DATE: 24-Sep-25	
	Beaker K	Beaker 1
[A] Wt. OVEN dry sample (gm)	526.6	514.2
[B] Wt. of Pycnometer containing water alone (gm)	1805.85	1610.32
[C] Wt of Pycnometer containing Sample and water (gm)	2124.7	1921.6
SPECIFIC GRAVITY OF FILLER $\frac{A}{A + (B - C)}$	2.535	2.534
AVERAGE	2.534	


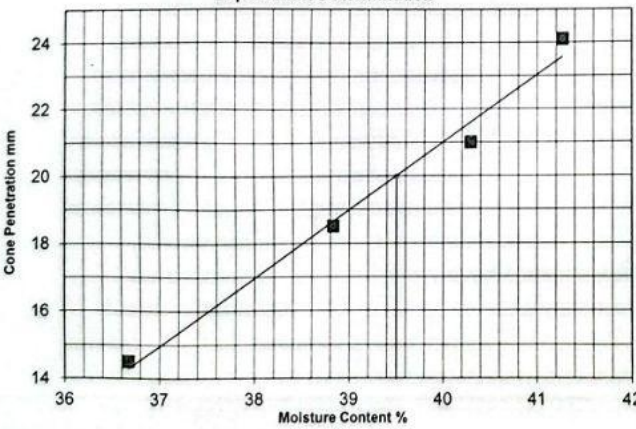
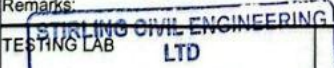

FOR TESTING LAB


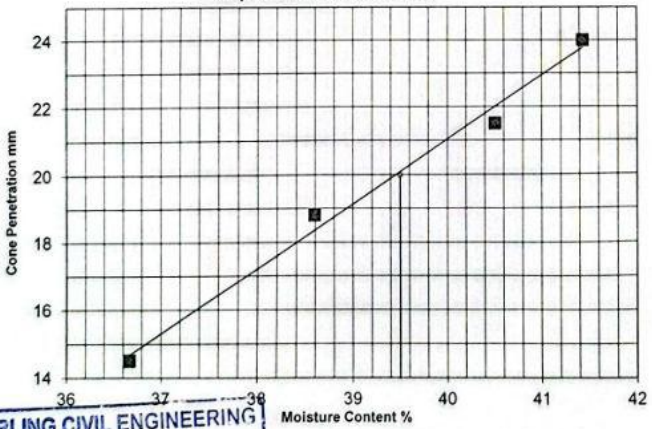


INSTITUTION	STUDENTS	TESTING LAB
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>	BAK KAU NAK	Stirling
PROJECT	ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN	
NATURAL MOISTURE CONTENT		
Test sample reference :	Laboratory Reference No.:	Sampling Date : 23/Sep/25
Location:	NAMAWEKWE IN MBALE	
DEPTH	0.3M	Testing Date : 25/Sep/25
Sample Description:	CLAY	Technician : Lab team
MOISTURE CONTENT		
Tin No.	FDC	
Tin + air dried soil sample (g)	2456	
Tin + oven dry soil sample (g)	2085	
Tin (g)	805	
Dry soil sample	1280	
Water (g)	371	
N.M.C (%)	29.0	
Average (%)	29.0	
Observations		
LAB		

STIRLING CIVIL ENGINEERING

 ★ 24 SEP 2025 ★
 P. O. BOX 758, KAMPALA (U)

INSTITUTION		STUDENTS		TESTING LAB		
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Heart of Africa</small>		BAK KAU NAK		Stirling		
PROJECT:		ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION				
ATTERBERG LIMITS						
<i>Liquid limit (cone penetrometer) and plastic limit</i>						
Test Reference No.:		Lab. Reference No.:		Technician:		
Location		NAMAWEKWE IN MBALE		Sample Date		
Test method		BS 1377: Part 2, 1990.4.3/4.4		Test Date		
LAYER		CLAY				
PLASTIC LIMIT		Test No.	JN	Q	Average	
Mass of wet soil + container (g)			29.34	27.81	28.575	
Mass of dry soil + container (g)			28.18	26.8	27.49	
Mass of container (g)			22.27	21.68	21.975	
Mass of moisture (g)			1.16	1.0	1.085	
Mass of dry soil (g)			5.91	5.12	5.515	
Moisture content %			19.6	19.7	19.7	
AVERAGE						
LIQUID LIMIT		Test No	1	2	3	4
Initial gauge reading (mm)			0	0	0	0
Final gauge reading (mm)			14.5	18.5	21	24.1
penetration (mm)			14.5	18.5	21.0	24.1
AVERAGE			14.5	18.5	21.0	24.1
Container No.		PI8	A	FOO	FORD	
Mass of wet soil + container (g)			37.34	35.47	46.17	46.19
Mass of dry soil + container (g)			29.10	27.58	34.88	34.78
Mass of container (g)			6.63	7.26	6.86	7.13
Mass of moisture (g)			8.24	7.89	11.29	11.41
Mass of dry soil (g)			22.47	20.32	28.02	27.65
Moisture content (%)			36.7	38.8	40.3	41.3
AVERAGE			36.7	38.8	40.3	41.3
Liquid Limit Determination						
						
Liquid limit (%)		39.5				
Plastic limit (%)		19.7				
Plasticity Index (%)		19.8				
Linear shrinkage						
Trough No.		J				
Trough length (cm)		14.0				
Specimen length (cm)		12.6				
L.shrinkage =		1.4				
% L.shrinkage =		10.0				
Remarks:						
						
						

INSTITUTION		STUDENTS		TESTING LAB																																																	
 UGANDA CHRISTIAN UNIVERSITY <small>A Centre of Excellence in the Horn of Africa</small>		BAK KAU NAK		Stirling																																																	
PROJECT: ASSESSING THE SUITABILITY OF GROUND GRANULATED BLAST FURNACE SLAG AS A STABILIZER IN THE MANUFACTURING OF UN FIRED CLAY BLICKS FOR CONSTRUCTION																																																					
ATTERBERG LIMITS																																																					
<i>Liquid limit (cone penetrometer) and plastic limit</i>																																																					
Test Reference No.:		Lab. Reference No.:		Technician:	Lab Team																																																
Location		NAMAWEKWE IN MBALE		Sample Date	23/Sep/2025																																																
Test method		BS 1377: Part 2, 1990:4.3/4.4		Test Date	27/Sep/2025																																																
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