PERFORMANCE OF PERFORATED CLAY BRICKS WITH CHARCOAL WASTE AS AN ADDITIVE

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(Civil Engineering)

JOMO KENYATTA UNIVERSITY
OF
AGRICULTURE AND TECHNOLOGY

2024

Performance of Perforated Clay Bricks with Charcoal Waste as an Additive

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A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science in Civil Engineering (Structures) of the Jomo Kenyatta University of Agriculture and Technology

2024

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature............…………………………………… Date………..………………

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This thesis has been submitted for examination with our approval as University Supervisors

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DEDICATION

This work is dedicated to the Almighty God.

ACKNOWLEGMENT

I would like to sincerely thank my supervisors Dr. Eng. Charles Kabubo and Dr. Isaac Fundi Sanewu for their supportive advice and guidance over the whole period of the research work. Am profoundly grateful to the different JKUAT laboratory technicians' team; structural engineering laboratory team, soil engineering team, Food science laboratory team and Agriculture laboratory team.

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ACRONYMS AND ABBREVIATIONS

ASTM	American Standards for Testing Materials
BS	British standard
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Clay soil
CW	Charcoal waste
LOI	Loss on ignition
NO_2	Nitrogen dioxide
OM	Organic matter
PCB	Perforated clay bricks
SO_2	Sulphur dioxide
SPM	Suspended particulate matter
XRD	X-ray Diffractometer

LIST OF SYMBOLS

L_s	Linear shrinkage

ABSTRACT

In Rwanda, the traditional fired solid bricks embody high consumption of fuel and quantity of clay during their moulding. The traditional solid bricks are also heavy compared to perforated bricks. This study aimed at investigating the performance of perforated clay bricks made of clay soil (CS) mixed with charcoal waste (CW) as an additive. The physical, chemical and mechanical properties of CS mixed with 0, 10, 30, 40 and 50% of CW were determined at JKUAT laboratories. The bricks were extruded manually with inclusion of varied number of perforations: 0, 4, 8, 12 and 15 number perforations which correspond to the percentages of perforations 0%, 6.15%, 12.3%, 18.45%, and 23.06%, respectively. The chemical analysis included determination of organic carbon, exchangeable acidity and chemical components by X-ray diffractometer of soil matrix. The chemical analysis depicted an increase in calcium oxide proportions with increase of charcoal waste content. There was also an increase in amounts of exchangeable cations. The research found that with increase in perforations, there is reduced loss of weight. However, non-perforated bricks depicted least abrasion resistance followed by bricks with 4 perforations. As the CW content increased from 0 to 50%, bricks with 15 and 12 perforations displayed highest abrasion resistance. The research concludes that increase of charcoal waste led to increase in linear shrinkage of clay soil bricks due to the increase of calcium cation and reduction of magnesium cations in the soil. With an optimum of 30% of charcoal waste identified for linear shrinkage of clay soil bricks. Bricks having 12 perforations and below with 30% charcoal waste additive can be categorized as category I (load bearing) bricks.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Clay brick is one of the oldest building materials and has been used since the early civilizations. It is a kind of crystalline ceramic and is among the most common construction materials found all over the world. To develop clay brick as a sustainable building material, the utilization of agricultural and industrial waste materials is a practical solution. Various waste materials in different compositions as additional raw materials at different dosage levels have been suggested for making of fired masonry bricks. The prime function of these waste materials is to act as a pore former in the clay body (Phonphuak and Chindaprasirt, 2015).

The current Rwanda local brick production sector consists of traditional solid bricks that work in unfavourable working conditions and do not meet the environmental requirements. The traditional solid bricks firing consists of high consumption of fuel and quantity of clay required during its moulding work (National Industrial Research and Development Agency (NIRDA) report, 2020). The use of energy in Rwanda country is dominated by biomass at 86% (where 57% are in the form of firewood, 23% for charcoal, and 6% both crop residues and peat). The 14% consist of energy use which is not biomass: with 11% is from petroleum products and 3% from electricity (Sander and Hendriksen, 2012). However, previous research has shown that many types of waste are used successfully in brick production, such as waste of coffee (Rahim, Jamil and Kadir, 2015), butts of cigarette (Mohajerani and Kadir, 2015), waste of palm oil (Kadir, Mohd and Azizi, 2013), mosaic vases (Rahim, Jamil and Kadir, 2015), fly ash (Lin, 2006), and sawdust (Banhidi, 2008). The use of these wastes reduces environmental impacts and their elimination.

According to the research conducted by Dangol, Adhikari and Byanju (2013), when charcoal was used as internal fuel in vertical shaft brick kiln (VSBK), their conclusion and recommendations are based on the solid clay bricks, not for the perforated clays bricks. Based on this research in VSBK by considering the solid bricks, the obtained optimum ratio was 60% for energy consumption pattern, gases emission. Their conclusion showed that the use of the charcoal as an internal fuel not only reduces the external fuel (coal) consumption but also reduces the pollution emission and increase the brick quality in VSBK outputs.

Masonry walls constructed using perforated clay bricks have been found to have excellent characteristics including thermal and sound insulation, high durability and excellent fire resistant, (Fioretti and Principi, 2014). Perforated clay bricks are nowadays used for masonry construction industry in different districts of Rwanda due to their good insulation properties and the reduction of clay consumption. This research therefore, investigated performance characteristics of perforated clay bricks (PCB) blended with charcoal waste at different dosage percentages.

1.2 Problem Statement

The Rwanda domestic market recapturing strategy (DMRS) report of 2015 indicated that the potential currency savings through the DMRS is 17.8% of the import bill. One third, among of these percentage is cement. Nevertheless, cement has been found to be relatively expensive, often imported and non-environmentally friendly. In this regard, the Ministry of Trade and Industry, Rwanda (2016), initiated a new strategy to promote the local products called "Made in Rwanda policy". To achieve this policy, Rwandan construction industry regulators have argued developers to embrace construction which will assure long-term quality for life including energy use and low impact on environment.

In Rwanda, there is only one plant (Ruliba Clays) that operates as an industrial site for production of clay products. This clay plant however, does not use internal fuel as an additive for the manufacture of clay bricks in order to reduce use of external fuel.

Many Rwanda local brick manufacturers still work under conventional conditions in producing solid traditional bricks. Most of these bricks, unfortunately do not meet the standard brick requirements. This has compounded the challenge of averting the emerging environmental challenges. The conventional methods lead to usage of higher volumes of clay and increases the cost of fuel during production and firing. Further, the produced bricks are heavier compared to their perforated counterparts.

It has been found that the use of biomass energy continues to dominant the small sector comprising domestic uses and small industry. This therefore necessitates protection and management of forests and wood plantation so that charcoal production is carried around while ensuring environment efficiency. In Rwanda there are 7,000 woodcutters and 8,000 charcoal producers with a production of around 157,000 tons of charcoal per year (Fabien, 2010). During charcoal production, up to 20% is considered as waste. Normally, these wastes are being recovered by the production of low-quality briquette and for some improved domestic cooking practice (Fabien, 2010). It is with this backdrop that this research studied the performance of perforated clay bricks utilizing charcoal waste as an additive.

1.3 Objectives

1.3.1 Main Objective

The main objective of the study was to investigate the performance of perforated clay bricks with charcoal wastes as an additive.

1.3.2 Specific Objectives

The specific objectives of this study were;

i. To investigate the properties of clay soil mixed with charcoal waste at different percentages.
ii. To investigate the properties of perforated clay bricks made with different mixes of clay soil and charcoal waste.
iii. To determine the optimum mixes of charcoal wastes for standard perforated clay bricks.

1.4 Research Questions

The study was guided by the following questions;

i. What are the properties of clay soil mixed with charcoal waste at different percentages?
ii. What are the properties of perforated clay bricks made with different mixing of clay soil and charcoal waste?
iii. What are the optimum mixes of charcoal waste for standard perforated clay bricks?

1.5 Justification and Significance of the Study

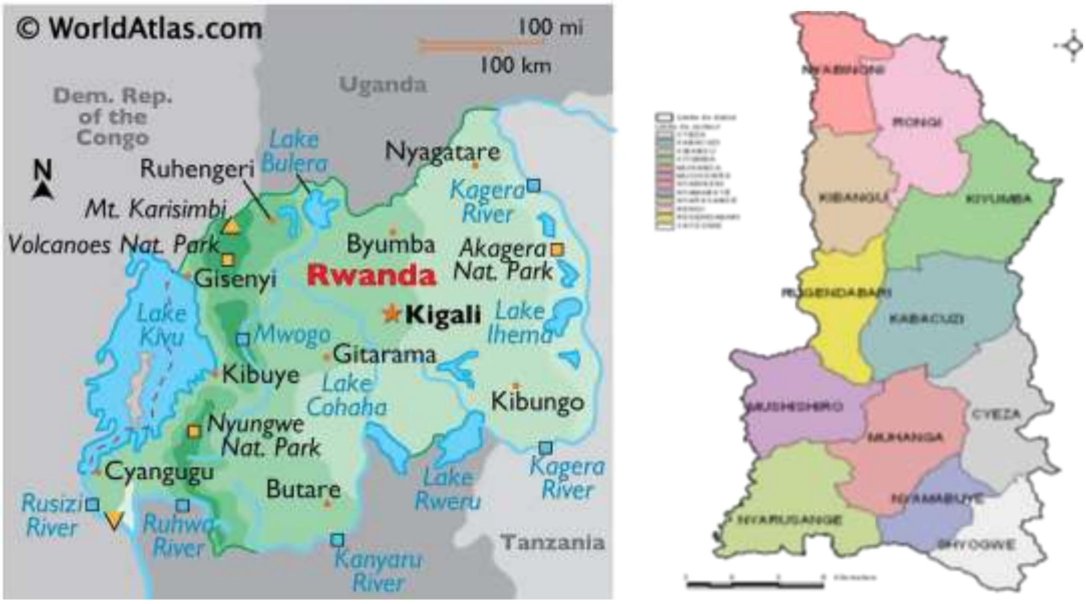
Rwanda housing sector is under development and the clay brick is one of the building materials used. Brick industry is the one of main sectors for which local construction material are produced due to the availability of local clay potential zones in different district of Rwanda. Building materials occupy 51% of recent investments comprising the largest and fastest growing component in Rwanda's manufacturing sector (Rwanda Development Board report of 2017). There is therefore a need to investigate the sustainability of affordable construction materials. This study is important because it contributes to the use of local natural resource and encourages the transformation of traditional brick production sector into modern brick production sector (or industrial and semi-industrial brick production). The study also contributes towards minimization of the use of natural clay soil and fuel quantity. The production of perforated bricks leads to bricks that can effectively insulate built spaces and have light weight structures.

The study is important to brick makers whose working conditions will be improved and reduce use of external fuel. The study is important to engineers, architects, real estate developers and clients in general who will get the affordable construction material which is fulfilling the standard conditions in housing sector.

It is also important to Rwanda country development because it promotes the "made in Rwanda" policy promotion due to the foreign expensive cements decrease in the construction industry market.

1.6 Scope and Limitations

The study focused on the investigation of the performance of perforated clay bricks through use of charcoal waste as an additive. The clay soil (CS) used was excavated in potential quarry zone of Rugeramigozi located in Shyogwe sector, Muhanga district Southern province, Rwanda as shown in Figure 1.1. The charcoal waste (CW) was collected from charcoal production site using Eucalptus timber species at Muhanga district. The research tests were conducted in the Civil and Construction Engineering laboratory, soil engineering laboratory, Agriculture laboratory and Food science laboratory of Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. Different properties including chemical element composition, exchangeable acidity, X-ray diffraction analysis, water absorption and compressive strength were determined. The results were analysed according to Rwanda standard (RS), East African standard (EAS), British standards (BS), EuroCode and AASHTO.



(a) Rwanda country

(b) Southern province Rwanda

Figure 1.1: Clay zone of Rugeramigozi in Muhanga District, Southern Province Rwanda

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Housing shortages in many developing countries have stimulated efforts to develop construction methods that use cheap and durable local materials. It is essential to develop technologies that use minimal energy because of the increasing shortage of firewood. One of the building materials is the fired clay brick.

Clay bricks were amongst the first artificial materials produced by men for building purposes that proved to be easy to produce, resistant, and durable, as attested by the numerous examples that can be seen all around the world that endured centuries of rough climacteric conditions and wars. Clay bricks are simply produced by mixing clay and water. Hardening methods evolved from sun drying to industrial ovens, which allowed strength and durability to increase. While clay brick's durability was initially affected by inadequate raw materials and usage contamination, today, urban pollution and incorrect use of materials fosters an even more rapid deterioration of existing bricks, adding to the general lack of maintenance observed in most buildings. Nevertheless, the understanding how bricks deteriorate was a series of methods and materials established for the repair of these bricks, extending their life expectancy (Francisco and Fernandes, 2019).

Clay is an important and abundant raw material and has amazing variety of uses and properties that depend on the composition and other factors as enumerated by Grim (1968). Clays are composed of various groups of hydrous aluminum, magnesium, and iron silicates that may contain sodium, calcium, potassium and other ions. These silicates collectively make up the major clay minerals (kaolins, smectites, illites, chlorites, and hormites). The specific clay minerals are identified by several techniques including X-ray diffraction (Brindley and Brown, 1980), differential thermal analysis (Smothers and Chiang, 1966), electron microscopy (Van der Marel and Beutelspacher, 1976), and infrared spectrometry (Van der Marel and Beutelspacher, 1976).

2.2 Properties of Clay Soil

2.2.1 Physical Properties of Clay

Generally, soil comprises all materials found in the surface layer of the earth's crust. This natural foundation soil forms the base for buildings, roads, and pavement construction. Soil is characterized as particulate components, while the air and water contents are considered porosity. However, in examining the actual physical properties of a soil system, due consideration must be given to the volume percentages of the component phases and the distribution of the different soil phases throughout the system (NRCS, 2013)

The mixture of clay soil with water produces a plastic mass that can be shaped into different forms. These different shapes come from the moulding and drying works. The property of the final product formed after firing at certain temperature is contributed by the kin of clay used. The different clay properties such as plasticity, Atterberg limit, texture, swelling, shrinkage, porosity, fusibility and colour are important in clay value determination.

Water molecules are strongly attracted to clay minerals surfaces. The range of water percentage that is needed to make the plastic property for a clay material is between 15-35%. The shrinkage and swelling ability of clay products depend on the changes in environmental factors and work done on clay (such as; extrusion pressure during moulding, quantity of water mixture, pore space inside of clay material, the amount of additional sand mixture, level of drying and firing degree).

In order to get the size of the required brick it is necessary to know the shrinkage of both in drying and in burning (Duggal, 2008). Most of the relevant industrial properties of the raw clay are dependent on the composition and the particle size distribution of the clay as well as the grain shape. All these factors control the plasticity of the clay which plays a very important role in its industrial application (Akpokodje, Etu-Efeotor and Olurufemi, 1991).

2.2.2 Chemical Properties of Clay Soil

It has been noted that chemical properties of clays are important in understanding their behaviour. Clay minerals are described by presence of two-dimensional sheets, tetrahedral (SiO_4) and octahedral (Al_2O_3). As noted by Neeraj and Mohan (2021), there are different clay minerals which are categorized based on presence of tetrahedral and octahedral layer in their structure like kaolinite (1:1 of tetrahedral and octahedral layers), smecticite group of clay minerals (2:1 of tetrahedral and octahedral layers) and chlorite (2:1:1 of tetrahedral, octahedral and octahedral layers).

Naturally, the clay soils can resist high temperature more than 1580°C and can be low resistant to the high temperature when it contains high content of alumina and low content of some impurities like Fe_2O_3 (Duggal, 2008). The examination of clay soil has shown that it is composed of chemical elements of SiO_2, Al_2O_3 and Fe_2O_3 as major constituents, along with traces of Na_2O, K_2O, MgO, CaO and TiO_2 in the form of impurities. Some clay samples are composed of high quantity of SiO_2 and some compositions in Al_2O_3. The presence of oxides such as K_2O, Fe_2O_3, CaO, MgO and TiO_2 in clay soil have been found to have role in melting the silicates and binding when the action of clay burning is happening (Manoharan *et al*., 2012). A study by Rahim, Jamil and Kadir (2015) indicated that the quantities of Silicon dioxide (SiO_2) and Aluminum Oxide (Al_2O_3) are 65.77% and 23.73% respectively in clay soil. However, Barium Oxide (BaO) occupies 0.27% (Table 2.1).

The difference between the red clay soil and alluvial clay soil is the high composition of Fe_2O_3 with high loss on ignition in red clay soil than in alluvial clay soil. Manoharan, Sutharsan, Dhanapandian and Venkatachalapathy (2012) found that the losses on ignition of clay soils is influenced by their composition of clay minerals, hydroxides and organic matter. The organic carbon oxidizing to CO_2 has been found to be the major cause of loss on ignition (LOI). Soils with over 10% organic matter display 1-2% on loss on ignition as a result. Considering the high clay soils, water of hydration may be lost during the firing which is the cause of an additional error.

Despite their unique characteristics, volcanic soils, including red clay soils, are highly desirable for various engineering purposes when hydrated halloysite is the predominant mineral (Wesley, 2010; Xue *et al*., 2020). However, engineers often face challenges in adequately classifying red clay soils, incorrectly labeling them as "laterite." The handling of these soils, especially those containing halloysite, can be problematic, as they are mistakenly perceived as suitable foundation soil for buildings or roads (Makwana & Kumar, 2019). Consequently, due to economic considerations, road works tend to adopt conservative design approaches with a higher risk of failure and a shorter design life. For building foundations, a recommended conservative allowable bearing pressure of 80 kN/m^2 is suggested (Elsharief, 2021).

On the other hand, Matthiessen et al., (2005) found that the ignition temperature and the heating time influence the results on LOI as organic matter may not be completely converted into CO_2 if temperature is too low or if burning time is too short. On the contrary, if temperature is too high or heating too long, inorganic compounds such as carbonates and sulphate may be converted to CO_2 and SO_2.

Table 2.1: Chemical Composition of Clay Soil

Composition	Formula	Concentration (%)
Iron Oxide	Fe_2O_3	1.19
Calcium Oxide	CaO	1.14
Magnesium Oxide	MgO	0.92
Zirconium Dioxide	ZrO_2	0.83
Silicon Dioxide	SiO_2	65.77
Aluminum Oxide	Al_2O_3	23.73
Sodium Oxide	Na_2O	2.99
Phosphorus pentoxide	P_2O_5	0.4
Titanium Oxide	TiO_2	0.39
Barium Oxide	BaO	0.27

Source: (Rahim, Jamil & Kadir, 2015).

2.3 Soil minerals and Relation of Physical Properties to Exchangeable Bases

Clay minerals act as chemical sponges as they have capacity to hold water and dissolved plant nutrients eroded from other minerals due to the presence of some unbalanced electrical charge on their surface (Barton and Karathanasis, 2002). Clay minerals have the ability to exchange ions which relate to the charged surface of clay minerals. Ions can be attracted to the surface of a clay particle or taken up within the surface of the se minerals. The ability of clay minerals to adsorb certain cations/anions and their retention around outside of structural unit depends on positive or negative charge deficiency in their mineral structure. The exchange of these adsorbed ion takes place with other ions. The cation exchange capacity (CEC) of a soil has been found to contribute towards the soil capacity to retain nutrients like K, NH_4^+ and Ca_2^+.

The investigation and analysis using X-ray, optical, chemical and dehydration methods have shown that clay soil generally are aggregates of extremely minute crystalline particles of one or more species of a small group of minerals known as the clay minerals.

Replacements within the lattice of the illite and montmorillonite minerals, chiefly Al^{3+} for Si^{4+} and Mg^{2+} for Al^{3+}, are considered in relation to base-exchange capacity and particle size characteristics (Ralph, 1939). Physical properties of clays soil depend on the relation between clay minerals composition and the behaviour of the exchangeable bases that are present. In general plasticity, bond strength, and shrinkage are relatively high for montmorillonite clay soil and low for kaolinite clay soil. Some investigators, consider that Na^+ increases the plasticity of clays, others that this property is decreased. Cations of low hydration, such as H^+ and the trivalent ions Al^{3+} and Fe^{3+}, impart low plasticity to clays (Ralph, 1939).

Recent studies indicate that the best plastic properties are found when an ion of intermediate or relatively low hydration, like Ca^{2+}, is the exchangeable base present. Once the exchangeable bases are substituted by sodium, the drying shrinkage will be increased. Ralph (1939) noted that clays soil composed of Al^{3+}, Fe^{3+} have lower shrinkage than those carrying Ca^{2+} and Mg^{2+}. Further, he indicated that, it is possible for the Si^{4+} or Al^{3+} in the basic crystal structure to be replaced by Al^{3+}, Fe^{3+}, Mg^{2+}, or Ca^{2+} without undue disturbance to the crystal structure.

2.4 Clay Bricks

Clay bricks are made from selected clays that are moulded or cut into shape and fired in ovens. The firing process transforms the clay brick into a building component with high compressive strength and excellent weathering qualities. Clay bricks are most widely used as external cladding and loadbearing wall medium. Clay bricks are generally affordable, require little or no maintenance and possess high durability and load bearing capacity. Their most desirable acoustic and thermal properties derive from their relatively high mass. A clay brick has been defined by BS 3921 (1985) as a unit of dimensions (mm) 337.5×225×112.5 (l×w×t).

2.4.1 Clay Brick Classification

Brick classification include grade, class, type, application and use. The criteria for classification may include exposure or use conditions, appearance, physical properties needed for performance, tolerance on dimensions and distortions, chippage and void area. It has been argued that while most bricks can be manufactured to attain all the attributes desired by a user, certain attributes may be dictated by the production method, durability classification or appearance classification. Bricks can be classified based on (BS 3921, 1985):

i. Quality
ii. Building process
iii. Manufacturing method
iv. Raw materials
v. Using location
vi. Weather resisting capability
vii. Purpose of using
viii. Shape
ix. Region

This study considered the brick type by the manufacturing method. Perforated clay bricks have holes passing through it. The BS 3921 (1985) recommends that the cross-sectional area of perforations shall be between 30% and 45% of the total area of the corresponding face of the brick. For the production of perforated bricks, a brick extrusion machine is required for the moulding of green bricks. The advantages of perforated clay bricks re:

- Reduced clay consumption
- Reduced energy consumption in firing of bricks
- Improved thermal insulation of bricks
- Better surface finish and product quality

2.4.2 Properties of Perforated Clay Bricks

The most important mechanical property of perforated clay brick is the compressive strength. This property provides information about the adequacy of the use of perforated bricks in load bearing or non-loadbearing walls. The compressive strength of bricks is obtained from uniaxial compression tests based on provisions of BS 3921 (1985). The code directs that the minimum average compressive strength of perforated bricks is 7N/mm^2.

In order to achieve optimum brick/mortar bond strength, it is recommended that there must be compatibility between the absorptive properties of the brick and the water-retentive characteristics of the mortar. The suction of bricks in normally gauged by the standard initial rate of absorption; which is a measure of the bricks' ability to draw water. Bricks contain pores that allows air to escape when tested in the 24hr absorption test according to BS 3921 (1985). However, it is seldom possible to fill more than about 75% of the pores by simple immersion in cold water; therefore, boiling method is adopted or measuring complete absorption. The absorption is the amount of water which is taken up to fill these pores in a brick by displacing the air. The saturation coefficient is the ratio of 24h cold absorption to maximum absorption in vacuum or boiling. The absorption of clay bricks varies from 4.5 to 21% by weight.

Linear shrinkage of bricks indicates the expansion/contraction behaviour during the firing process. Linear shrinkage has been found by Eduardo et al., (2018) to depend on the quantity of liquid phase produced in the firing process, as well as the decomposition of the gas phases. The firing shrinkage always gives an indication of the ability of clay bricks to withstand thermal shock (Sani, Bashir, Danshehu and Isah, 2013). Usually, a good quality of brick exhibit shrinkage below 8% (BIA, 2004).

Bulk density is the mass per unit volume of the materials ignoring the volume occupied by pores. It depends upon the true specific gravity and the porosity (Sani, Bashir, Danshehu and Isah, 2013).

2.5 Charcoal Waste

Consumption of Biomass

Biomass energy occupies the highest percentage (85%) of the overall source of energy in Rwanda. The dwellings use 91% of biomass, while industries consume 4% (Figure 2.1). The biomass is mainly sourced from wood, charcoal and dung. With the high reliance on fuelwood, it has led to significant deforestation across the country.

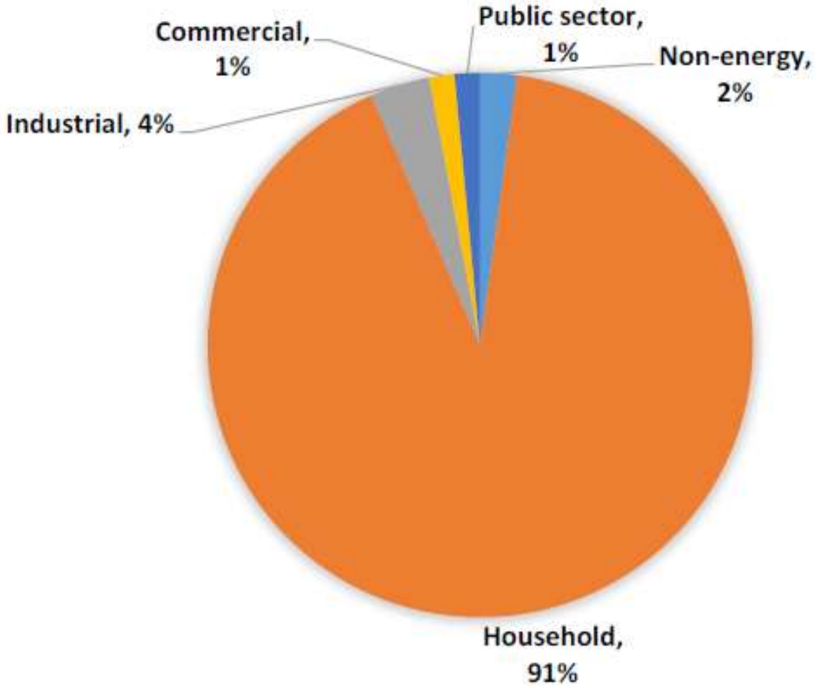


Figure 2.1: Biomass Consumption by User Category in Rwanda

In Rwanda, there is 83.3% of dwellings which use firewood for their cooking needs. The rural areas are dominated by the firewood use compared to the urban areas, where charcoal is the main option for cooking. This is due to its long-life storage and relatively low-cost transportation, giving its smaller volume and weight compared to firewood (Hakizimana, Wali, Sandoval and Kayibanda, 2020). It has been found that the use of biomass energy continues to dominant the small sector comprising domestic uses and small industry. This therefore necessitates protection and management of forests and wood plantation so that charcoal production is carried around while ensuring environment efficiency.

In Rwanda, there are 7,000 woodcutters and 8,000 charcoal producers with a production of around 157,000 tons of charcoal per year (Fabien, 2010). During charcoal production, up to 20% is considered as waste. Normally, these wastes are being recovered by the production of low-quality briquette and for some improved domestic cooking practice.

2.6 Clay bricks with Charcoal Waste as an Additive

Most additives are waste products from industrial activities, which means that they also provide a solution to environmental problems by eliminating their potential damage to human health. However, charcoal waste can be used as additive in order to reduce the environmental degradation caused during burning of clay bricks. It has been noted by Phonphuak and Thiansem (2011) that organic combustible additives can be effectively used to generate porosity in fired clay bricks. Dangol, Adhikari and Byanju (2013) tested solid clay bricks that were mixed with charcoal waste and obtained an optimum ratio of 60% for energy consumption. Their conclusion indicated that the use of charcoal as an internal fuel not only reduced the external fuel (coal) consumption but also reduces the pollution emission and increase the brick quality in vertical shaft brick kiln (VSBK) outputs. This was achieved without using high internal fuel as compared to the one using charcoal as internal fuel.

2.7 Summary of Literature Review and Research Gap

Different reports show that up to 20% of charcoal is wasted as dusts. And those wastes have been suggested to be recovered and used to produce briquette, which are good for use by local institutions. Furthermore, the dust suggested to be utilized in specially designed improved cookstoves (Fabien, 2010). Through this research, the presented findings found a research gap on non-utilization of charcoal waste materials as an additive in clay soil to produce the fired perforated clay brick.

Different research of soil and Charcoal mixture has been done for brick making (which are solid fired and unfired brick) (Dangol, Adhikari and Byanju, 2013). The presented project found the gap where there is lack of the use of charcoal wastes as an additive to evaluate the performance of fired perforated clay bricks.

Due to the influence of different elements chemical composition of clay soil, different authors (Ralph, 1939), (Manoharan, Sutharsan, Dhanapandian and Venkatachalapathy, 2012) and (Suzanne, Hanafiah and Chowdhury, 2017), have pointed towards a research gap on the influence on the loss on ignition, plasticity and shrinkage of bricks. These influnces have not been studied on the effect of perforated clay brick incorporating charcoal wastes.

Different researches have been done on different use of waste as additives to clay soil including coffee waste (Kadir, Hermawati, and Sarani, 2015), cow dung (Olokode, Aiyedun, Raheem, Owoeye and Anyanwu, 2012) to produce clay bricks which is solid bricks, but none of them was investigating the clay bricks with charcoal waste as an additive for perforated clay bricks.

2.8 Conceptual Framework

The interaction of independent and dependent variables is show in Figure 2.2.

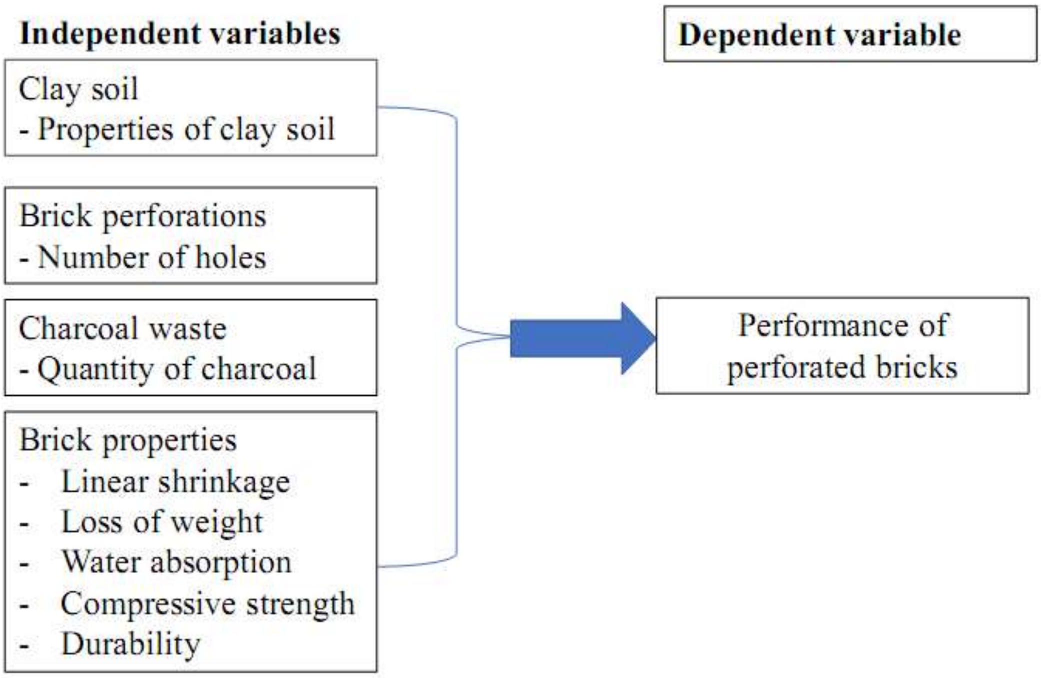


Figure 2.2: Conceptual Framework

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The clay soil (CS) used for the research was collected from quarry zone of Rugeramigozi located in Shyogwe sector, Muhanga district in the Southern province of Rwanda. On the other hand, charcoal wastes (CW) were collected from charcoal production site located at Muhanga district. The charcoal waste was obtained from Eucalyptus timber species (Figure 3.1).

Figure 3.1: Flow Diagram for Production of Clay and Charcoal Waste

The CS and CW were covered in carrier bags to reduce moisture loss. The clay soil was sieved to achieve consistency of the particle sizes. The clay soil was sieved to achieve consistency of the particle sizes. The CW was added to CS at dosages of 0%, 10%, 30%, 40% and 50%, of the dry weight of the soil. The materials were further dried using an electric kiln for 24 hours at a sustained temperature of 105 °C.

Clay soil bricks were moulded mechanically with introduction of perforations (Figure 3.2). Clay soil bricks of size 210 x 100 x 66mm were moulded. Perforations were of size 23 x 14 x 66mm in accordance to BS EN 771-1 (2003) and BS 3921 (1985). The number of perforations varied from 0, 4, 8, 12 and 15. This was equivalent to 0%, 6.15%, 12.30%, 18.45% and 25% respectively, of the whole moulded clay soil bricks.

(a) Mechanical moulds (b) Moulded clay soil bricks

Figure 3.2: Moulding of Perforated Bricks

3.2 Chemical Analysis for CS and CW Mixtures

3.2.1 Organic Carbon in Clay Soil Mixed with Charcoal Waste

In determining the organic carbon in clay and charcoal waste the Walkley-Black method was used. Representative samples were ground and those which passed through a 0.5mm sieve were considered. The samples were oxidized using chromic acid in presence of sulphuric acid. The percentage of organic carbon was determined from Equation 3.1. A multiplying factor 1.72 was used to convert organic carbon to organic matter as indicated in the Walkley-Black method.

$$Organic\ carbon\ (\%) = \frac{\{me(k2Cr2O7)\ -\ me(FeSO_4)\}0.003\ *\ 100\ *\ f}{oven\ dry\ weight(g)} \ldots\ldots equation\ 3.1$$

Where;

f = 1.33 correction factor
me – normality of solution used (ml)

3.2.2 Exchangeable Acidity in Clay Soil Mixed with Charcoal Waste (Titration Method)

Exchangeable acidity was determined using titrimetric method (standard method) according to the routine methodology adapted from Mclean (1965). Primarily, the exchangeable acidity (Al^{3+}, H^{+}) was determined by titration of 25 mL potassium chloride (KCl) extract with 0.025 mol L-1 sodium hydroxide (NaOH), using 1g L-1 phenolphthalein as an indicator (titration from colourless to pink). Then, the concentration of Al^{3+} was obtained by back-titration of the same KCl extract, previously used, after the acidification with a drop of hydrogen chloride (HCl) and addition of 40 g L-1 sodium fluoride (NaF), with 0.025 mol L-1 HCl (titration from pink to colourless).

3.2.3 X-ray Diffraction (XRD) Analysis

The samples were milled using a grinding mill before placing them in a jar. The samples were ground to particles of size 10 μm. The grinding action enabled homogenization of the particles. The samples in powder form were placed in glass slides before loading them in a D2 PHASER XRD machine. The concentrations of different elements were measured after evaluating the X-ray intensities at the given wavelengths of the elements in the XRD machine recorded as electronic signals. A search of the International Centre for Diffraction Data (ICDD) standard database of X-ray diffraction patterns enabled quick phase identification for the crystalline samples.

3.2.4 Loss on Ignition (LOI) in Samples

Clay and charcoal waste samples which had been oven dried at 105 °C were weighed and placed in a crucible. The samples were then placed in an oven and heated to 470

°C. In order to determine the LOI, Equation 3.2 as specified in BS EN 7721-1 (2011) was used.

$$LOI\ (\%) = \frac{(L - M)}{(L - J)} * 100 \ldots \ldots equation\ 3.2$$

Where:

J - weight for container
L - weight for container plus dried raw material at 105°C
M - weight of container plus raw material fired at 470°C

3.3 Physical Properties of Clay Soil Mixed with Charcoal Wastes

3.3.1 Particle Size Distribution

The particle size distribution for clay soil and charcoal waste was determined according to BS 1377-2 (1990). The soil and charcoal waste were passed through a series of stacked sieves with a pan at the lowest level. The sieves were shaken mechanically and whatever was retained on the sieves was weighed. The particles that passed through sieve size 0.075mm were subjected to hydrometer analysis in accordance to BS 1377-2 (1990) and tests done at Jomo Kenyatta University of Agriculture and Technology (JKUAT) soil engineering laboratory.

3.3.2 Clay Soil Bricks Bulk Density

All test specimens were dried at 105 ºC for 24 hours to ensure total moisture loss, and then fired to a temperature of 910 ºC using electrical furnace. The weight was measured using an electronic weighing machine. Their corresponding weights after firing was measured and recorded as W_f. The specimens were allowed to cool before immersing in water. The bricks were fully submerged and their soaked weight was measured suspended in air and recorded as W_a. They were then suspended in water in a beaker, one after the other using a sling and their respective suspended weight were measured and recorded as W_w. The bulk density was calculated using Equation 3.3 and examined referring to BS 1377-1 (1990).

$$BD = \frac{W_f}{(W_a\ - W_w)} \ldots\ldots equation\ 3.3$$

3.3.3 Loss of Weight and Water Absorption

A random selection of three bricks was made from the moulded bricks containing different CW proportions. The bricks were dried in a kiln at a temperate of 105 ºC for 24hours. The bricks were weighed (W_1) and fired in a furnace to 910 ºC before re-weighing (W_2) according to BS 1377-3 (1990). The bricks were then submerged in a water bath at a temperature 27º +/- 2 ºC for 24hours. The bricks were weighed (W_3) after air dying for 3minutes. Equations 3.4 and 3.5 were used to determine loss of weight and water absorption, respectively.

$$Loss\ of\ weight\ = W_2\ -\ W_1\ \ldots\ \ldots\ equation\ 3.4$$

$$L_S = \frac{W_3 - W_2}{W_2} * 100 \ldots\ldots equation\ 3.5$$

3.3.4 Linear Shrinkage

The test specimens were dried in a furnace for 24 hours at 105 ºC before their dimensions (length, breath and height) were measured using vernier calliper. The dimensions were recorded as dry length (L_D) and then fired in a furnace to temperature of 910 ºC. The bricks were cooled to room temperature and their measurement recorded as fired length (L_F). For each sample, 3 specimens were measured and the averages of the dimensions were used to calculate the linear shrinkage (L_S) using Equation 3.6, according to BS 3921 (1985).

$$L_S = \frac{L_D - L_F}{L_F} * 100 \ldots\ldots equation\ 3.6$$

3.3.5 Compressive Strength

The compressive strength is the only mechanical property used in brick specification; it is the failure stress measured normal to the bed face. The perforated clay bricks were tested wet. The load was applied at a rate of 0.05N/mm^2/s until the bricks failed after which the maximum compressive load of the bricks was recorded. The compressive strength (C_s in MPa) was computed using Equation 3.7 in which P is the maximum compressive load of the bricks and A (mm^2) is surface area in contact with the platen. The test carried out according to RS 359: 2009 and KS EAS 54: (1999).

$$Cs = \frac{P}{A} \ldots \ldots equation\ 3.7$$

3.3.6 Durability of Perforated Clay Bricks

Through abrasion test each brick sample was weighed before the test was conducted. The sample brick was placed on a flat horizontal table-top secured against sliding as prescribed in AASHTO - T 96-02 (2010). The top side of the sample was given 50 strokes of wire brush, after which the sample was reweighed, and the depth of abrasion measured and recorded (Figure 3.3). The abrasion value (α) was computed by Equation 3.8 in which w_1 (weight before abrasion) and w_2 (weight after abrasion). The tests were carried out according to BS EN 7721-1: (2011) and AASHTO - T 96-02 (2010).

$$\alpha\ (\%) = (\frac{W_1\ - W_2}{W_1}) * 100 \ldots \ldots equation\ 3.8$$

Figure 3.3: Abrasion Testing of Blocks

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physical Characterization

4.1.1 Particle Size Distribution

The particle size distribution for the clay soil (Figure 4.1) indicates that with addition of charcoal waste the percentage of particles passing a sieve reduced considerable beyond 30% of addition. However, from the results as shown in Figure 4.1, the particle distribution does not change considerable with addition of charcoal waste. The soil was classified as a low plastic clay based on the Unified Soil Classification System (USCS). This was in agreement with the findings of Chima, Adedeji and Uloho (2013).

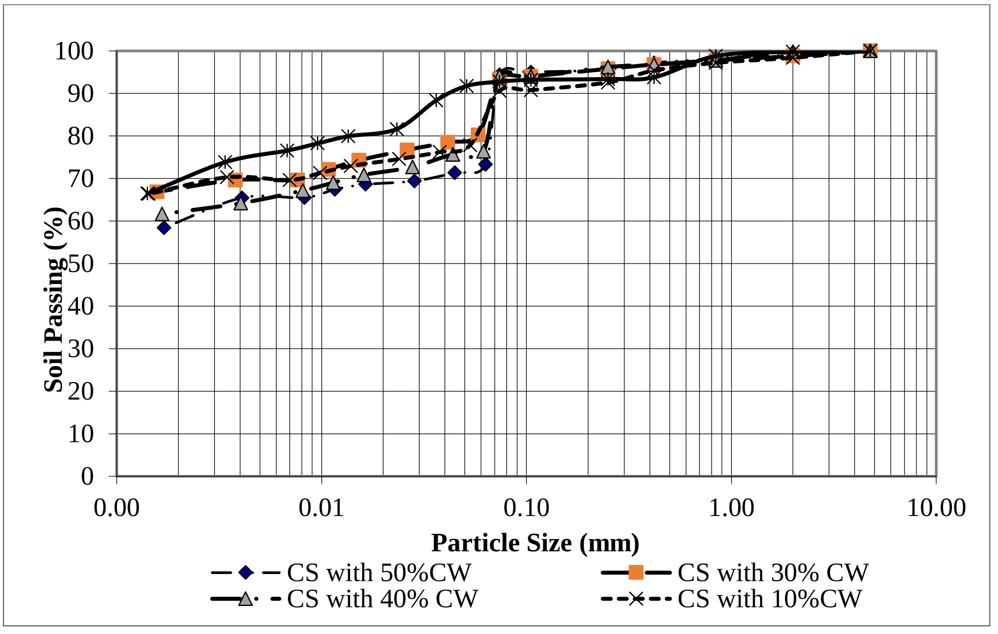


Figure 4.1: Particle Size Distribution for Clay Soil Mixed with Charcoal Waste

4.1.2 Chemical Characterization

The laterite soil plasticity index (12.09%) lies in the range (5 – 15%) proposed by Sanewu (2020) for soils which can be effectively stabilized using cement (Table 4.1). The plasticity index versus liquid limit comparison in a Casagrande Plasticity index chart indicates that laterite soil is inorganic with a low compressibility while clay soil is dense and has medium compressibility. This shows that clay soil can withstand greater applied load than laterite soil in its un-stabilized state.

As shown in Table 4.1, the chemical analysis showed that Iron Oxide (Fe_2O_3) was not detected (ND). The dominant oxides in charcoal waste are silicon dioxide and aluminium oxide (Table 4.1). According to Manoharan, Sutharsan, Dhanapandian and Venkatachalapathy (2012), this described the soil matrix as of clean alluvial clay type. The proportion of CaO increased with charcoal waste content. As the CaO increased, it reacted with water and formed calcium hydroxide solution that could have coalesced the clay soil particles and cause them to harden. This could have an effected on the compressive strength of the bricks as it contributes to cementing properties of the clay matrix.

It was noted from the chemical results that as the CW was increased, the calcium cation increased while magnesium cation reduced. As it has been argued out by Schwieger (1965), that there is a positive correlation between clay plasticity index with the type and concentration of the exchangeable cations in the soil system. The calcium cations led to coagulation of soil particles and help to displace water. The high plasticity with increased dosage of CW could have contributed to higher linear shrinkage experienced with the bricks beyond 30% addition of CW.

4.1.3 Loss on Ignition

As indicated in Table 4.1, the loss on ignition reduced with increase in percentage dosage of charcoal waste. The research found that, as the percentage of charcoal waste was added, the more the presence of organic carbon was observed. This could have been the contributing factor to the reduction in loss of ignition. It therefore indicates that there is less ash in pure charcoal compared to the CS and CW mix samples.

Table 4.1: Chemical Properties of Clay Soil with Charcoal Waste

Parameter	Charcoal waste content				
	0 %	**10 %**	**30 %**	**40%**	**50%**
Calcium oxide (CaO), %	0.250	0.804	1.455	3.209	4.137
Magnesium Oxide (MgO), %	6.563	1.783	ND	ND	ND
Aluminum Oxide (Al_2O_3), %	27.843	28.826	28.454	26.195	22.199
Silicon Dioxide (SiO_2), %	61.122	63.404	63.599	63.826	63.866
Iron Oxide (Fe_2O_3), %	ND	ND	ND	ND	ND
Potassium Oxide (K_2O), %	0.983	1.402	1.659	2.228	2.774
Sodium Oxide (Na_2O), %	ND	ND	ND	ND	ND
Magnesium (mg/kg)	17.455	14.595	6.721	3.681	2.667
Potassium (mg/kg)	14.249	25.630	39.747	60.749	72.954
Calcium (mg/kg)	20.035	34.520	56.437	86.705	101.231
Iron (mg/kg)	1.054	1.728	1.926	2.333	3.194
Chlorine (%)	0.018	0.057	0.146	0.251	0.258
Organic carbon (%)	6.652	9.524	13.969	16.024	18.600
LOI (%)	99.348	90.744	86.080	84.001	81.400
Exchangeable acidity	0.60	0.15	0.10	0.20	0.10
$Mg^{(2+)}$ (mg/kg)	17.455	14.595	6.721	3.681	2.667
$Ca^{(2+)}$ (mg/kg)	20.035	34.520	56.437	86.705	101.231
Exchangeable cations -Na (meq/100g)	0.15	0.80	0.30	0.44	0.50
Exchangeable cations -K (meq/100g)	0.39	2.53	1.55	1.92	2.31
Exchangeable cations Ca (meq/100g)	1.01	4.15	1.77	1.82	2.14
Exchangeable cations-Mg (meq/100g)	1.22	3.52	1.44	1.40	1.43

As shown in Table 4.1, an addition of CW leads to increase in presence of exchangeable cations. As much as the ion exchange capacity of the clays does not affect the structure of the clay mineral, the ions alter the plastic characteristics of soils (Hanie, Hojat and Ghanizadeh, 2020). The exchangeable calcium ions were highest when 10% of CW was added. In presence of silica in the clay soil, the calcium ion form hydro-silicate gel compounds that ultimately enhance the soil mechanical properties as argued by Behrouz, Navid and Ahad (2024). This has a contribution in increasing the compressive strength of the clay soil by providing a cementing agent between soil particles thereby stablishing bonds and providing better locking of soil particle.

4.2 Behaviour of Stabilized Interlocking Soil Blocks When Subjected to Loading, Abrasion and Wet Conditions

4.2.1 Brick Linear Shrinkage

The bricks experienced a decrease in linear shrinkage with an increase in charcoal waste content up to 30% of CW (Figure 4.2). Beyond the optimum value of 30% an increase in CW led to increase in linear shrinkage. As urged by Alabi, Adegun and Olatunji (2020), the increase in linear shrinkage could have been contributed by additional unburnt charcoal waste which occupied spaces in the soil leading to linear reduction on drying. This was experienced irrespective of the number of perforations in the bricks. Usually, a good quality of brick exhibits shrinkage below 8% (Brick Industry Association, 2004). The research found that with exception of bricks with 15 perforations, all other bricks recorded linear shrinkage below 8% with up to 50% CW addition. This indicated that they are bricks of good quality.

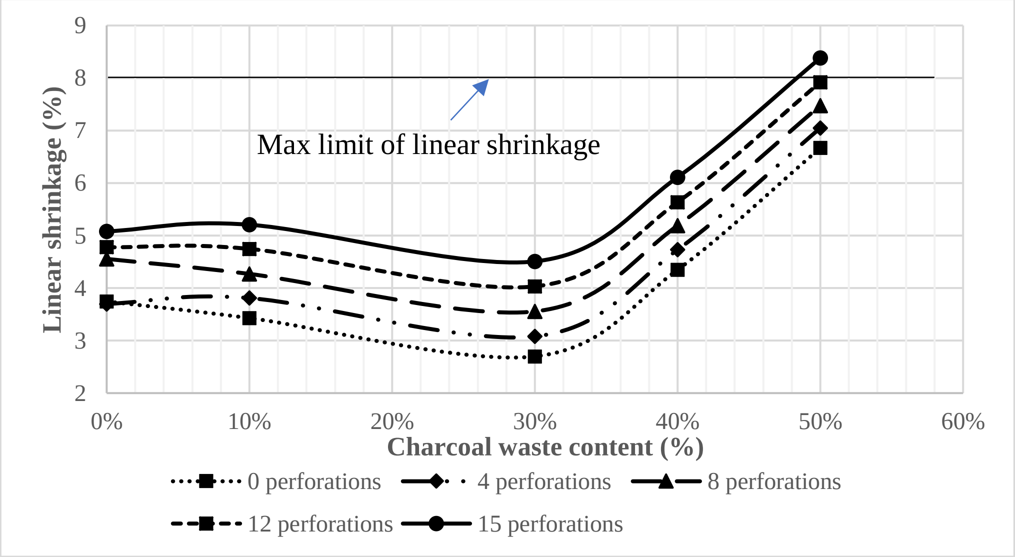


Figure 4.2: Clay Soil with Charcoal Waste Bricks Linear Shrinkage

4.2.2 Loss of Weight and Water Absorption

The bricks' water absorption capacity increased with increase in CW content (Figure 4.3). This observation corresponds well with the findings of Dizhur, Lumantarna, Biggs, and Ingham (2017) that wood ash increases porosity in a clay mass thus increasing water absorption. The high content of CW introduced high porosity that caused water absorption by capillary by the bricks. However, there was a general reduction of water absorption with increase in the number of perforations. This observation can be associated with the reduction of solid mass thereby reducing the amount of water to be absorbed. The bricks water absorption capacity is greater than the recommended by BS 3921 (1985), RS 359 (2009) and KS EAS 54 (1999) for Engineering bricks (Class 'B's should be ≤ 7%) and Damp proof course (Class 'A's should be ≤ 4.5%). The bonding of the bricks with mortar is however compromised when the bricks absorb too much water.

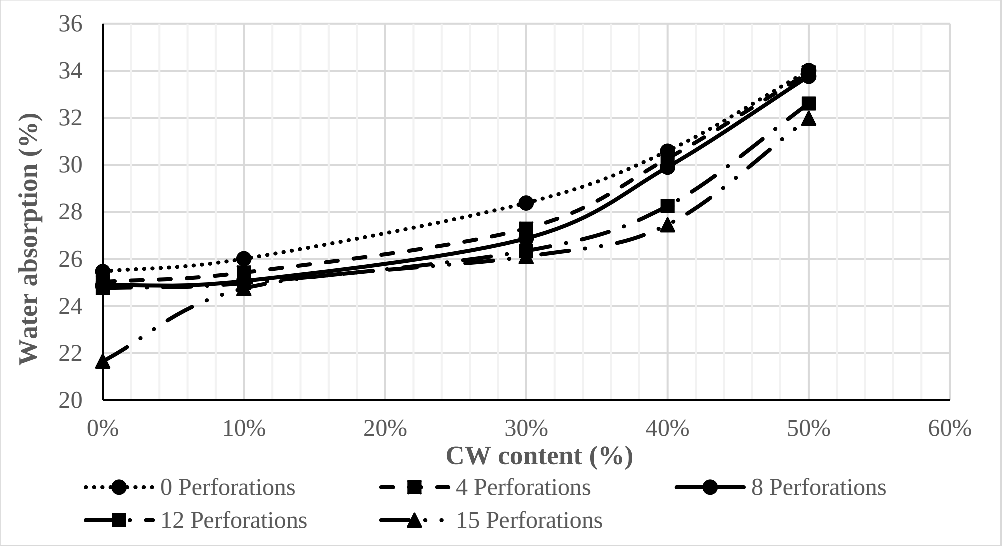


Figure 4.3: Bricks Water Absorption

It was observed that with increase in perforations, there is reduced loss of weight. However, there was no significant change of weight loss with increase in CW percentages (Figure 4.4). The research deduced that an increase in perforations led to lightweight bricks which tend to suffer less weight loss and absorb low amounts of water. This is associated with efficient fire transfer through the perforations and the presence of CW reduces the weight which in addition acts as an internal fuel which accelerates the firing.

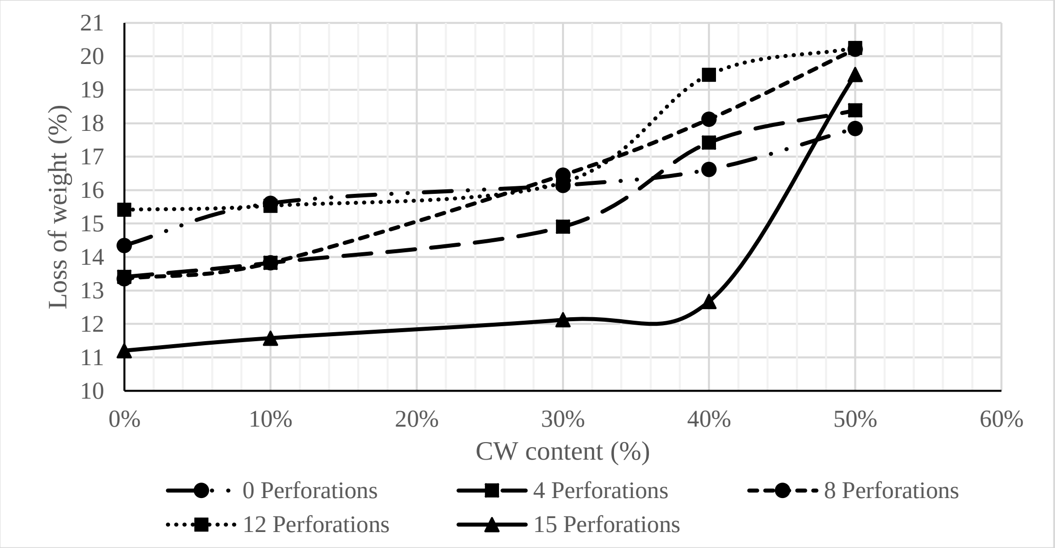


Figure 4.4: Loss of Weight

4.2.3 Durability

Figure 4.5 show that at 0% CW, bricks with no perforation had least abrasion index followed by bricks with 4 perforations (0.05%). As the CW content increased from 0 to 50%, bricks with no perforations experienced 85.19% increase in abrasion while those with 4 perforations had 82.14% increase in abrasion index. Bricks with 15 and 12 perforations displayed least abrasion indices with increase in CW to 50%; at 42.11 and 45.45%, respectively. It can be deduced that, clay bricks with 12 and 15 perforations produce better durability as the CW content is increased.

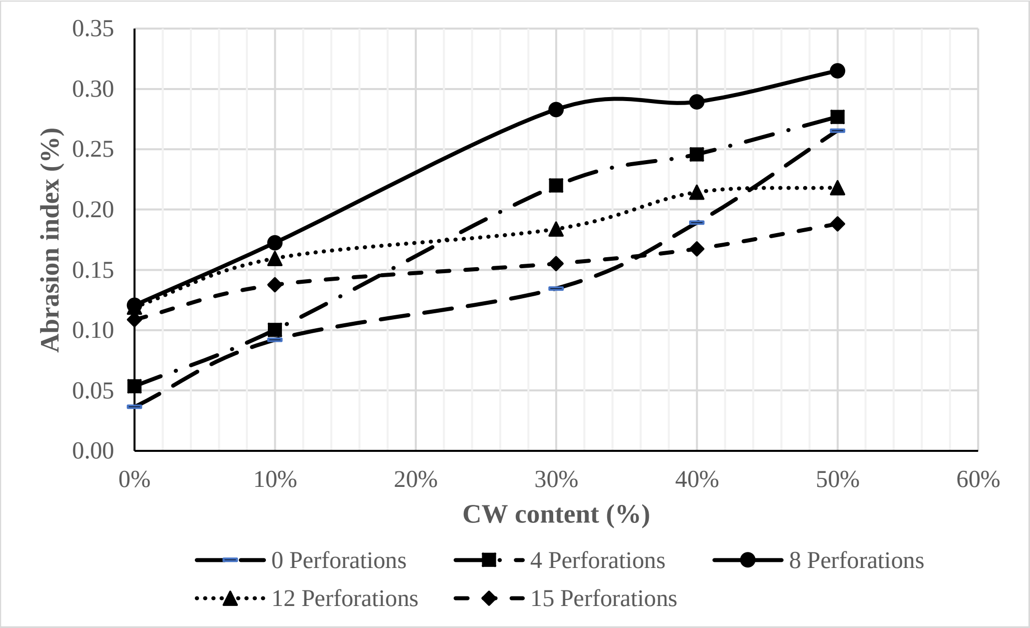


Figure 4.5: Abrasion Index for Clay Soil Bricks

4.2.4 Compressive Strength and Bulk Density

The bricks compressive strength decreased with increase in CW and number of perforations. According to Kenya standard (2018), the bricks can be classified under category I (load bearing) with a minimum compressive strength of 7N/mm^2 (Figure 4.6).

With increase in CW there is decrease in bulk density. Moreso, with increase in number of perforations, the bricks experienced decrease in bulk density (Figure 4.7). An optimum value of 30% CW was achieved with an exception of bricks with 12 perforations.

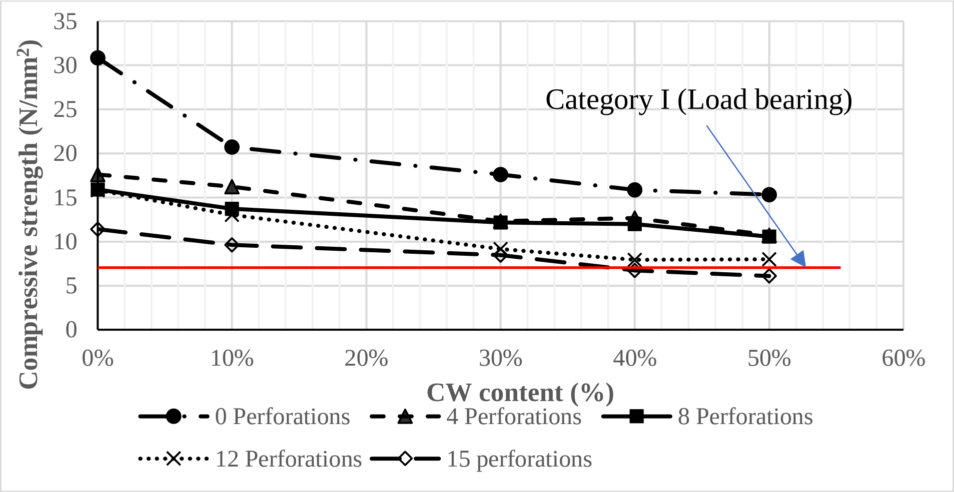


Figure 4.6: Perforated Clay Bricks Compressive Strength

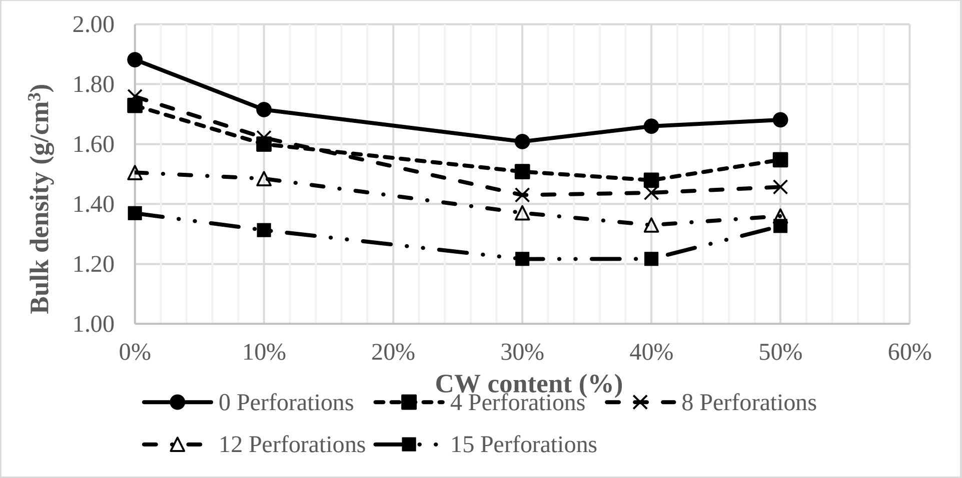


Figure 4.7: Perforated Clay Bricks Density

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were drawn from this research work;

5.1.1 Conclusions for Objective One

(1) Increase of charcoal waste led to increase in linear shrinkage of clay soil bricks due to the increase of calcium cation and reduction of magnesium cations in the soil. An optimum of 30% of charcoal waste was identified for linear shrinkage of clay soil bricks.

(2) Conclusions for objective two

(3) An increase in the number of perforations reduces the water absorption capacity of bricks however they don't meet the code requirement.

(4) An increase in number of perforations and charcoal waste result to higher abrasion of clay soil bricks. However, beyond 8 perforations amount of abraded material reduces due to effectiveness of burning of the bricks.

5.1.2 Conclusions for Objective Three

(1) Bricks having 12 perforations and below with 30% charcoal waste additive can be categorized as category I (load bearing) bricks.

5.2 Recommendations

The study recommends that:

(1) Clay bricks with charcoal waste content should be considered to be used in areas where water absorption is discouraged since with increase in charcoal waste it led to higher water absorption. However, when perforations are introduced in the clay bricks, durability is enhanced.

(2) A framework to choose the application of clay bricks in different construction applications need to be developed in order to optimize on the varied properties of charcoal additive in clay bricks.

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APPENDICES

Appendix I: Soil Properties

Table 1: Specific gravity of clay soil mixed with charcoal waste

								4/28/2022		
Sample No.	0% Charcoal		10% Charcoal		30% Charcoal		40% Charcoal		50% Charcoal	
Bottle No	31	30	45	35	43	3	38	34	150	20
Wt of Bottle only m_1, (g)	53.24	62.94	37.42	44.3	39.42	52.94	47.2	45.02	45.34	46.54
Wt of Bottle + Dry Soil, m_2 (g)	103.62	113	87.44	94.12	90.14	102.98	97.46	95.4	95.5	96.5
Wt of Dry Soil = Ws (g)	**50.38**	**50.06**	**50.02**	**49.82**	**50.72**	**50.04**	**50.26**	**50.38**	**50.16**	**49.96**
Wt of Bottle + Soil + Water, m_3 (g)	181.94	188.92	171.16	174.64	172.54	183.96	173.64	173.86	169.72	170.72
Wt of Bottle + Water, m_4 (g)	152.6	159.36	141.54	146.5	145.68	156.64	147.64	147.94	144.24	145.14
Wt of water equal to solids, Ww (g)	**21.04**	**20.50**	**20.40**	**21.68**	**23.86**	**22.72**	**24.26**	**24.46**	**24.68**	**24.38**
Specific Gravity	2.39	2.44	2.45	2.30	2.12	2.20	2.07	2.06	2.03	2.05
Test water temperature (°C)	22	22	22	22	22	22	22	22	22	22
Correction Factor to 20°C	0.9993	0.9993	0.9993	0.9993	0.9993	0.9993	0.9993	0.9993	0.9993	0.9993
Specific Gravity at 20°C	**2.39**	**2.44**	**2.45**	**2.30**	**2.12**	**2.20**	**2.07**	**2.06**	**2.03**	**2.05**
Average Specific Gravity at 20°C	**2.42**		**2.37**		**2.16**		**2.06**		**2.04**	

Table 2: Clay soil moisture content

Moisture Determination										
MC on arrival	date	4/25/2022								
Sample No.	0% Charcoal		10% Charcoal		30% Charcoal		40% Charcoal		50% Charcoal	
Tin No	13	28	33	20	38	35	37	39	8	12
Tin + Wet Soil m_a, g	120.50	140.00	196.00	112.00	183.00	176.00	146.00	138.00	97.00	111.00
Tin + Dry Soil m_b, g	118.46	137.72	192.38	110.22	179.36	172.54	142.90	135.28	94.66	108.36
Tin only m_c, g	9.50	9.50	34.00	9.50	30.00	30.00	29.50	27.50	9.50	9.50
Moisture Content %	1.87	1.78	2.29	1.77	2.44	2.43	2.73	2.52	2.75	2.67
Average MC (%)	**1.83**		**2.03**		**2.43**		**2.63**		**2.71**	

Table 3: Loss on ignition (LOI)

CW Percentages (%)	ASH (%)	Loss on organic LOI (%)=100 - ASH (%)
0%	99.35	0.65
10%	90.74	9.26
30%	86.08	13.92
40%	84.00	16.00
50%	81.40	18.60
100%	18.02	81.98

Table 4: Shrinkage and water absorption of bricks

		SHRINKAGES MEASUREMENT							Water absorption			
Mixture	**SN**	**Length after forming (cm)**	**Length after drying (cm)**	**Length after firing (cm)**	**Drying shrinkage (%)**	**Firing shrinkage (%)**	**Total shrinkage (%)**	**Average by mixture (%)**	**W1**	**W2**	**W.A**	**Average by mixture (%)**
0%	1	10.00	9.50	9.30	5.00	2.11	7.00	**6.7**	158	177	10.7	**11.6**
	2	10.00	9.60	9.30	4.00	3.12	7.00		150	171	12.3	
	3	10.00	9.60	9.40	4.00	2.08	6.00		149	169	11.8	
10%	1	10.00	9.70	9.50	3.00	2.06	5.00	**4.3**	145	160	9.4	**12.4**
	2	10.00	9.70	9.60	3.00	1.03	4.00		142	171	17.0	
	3	10.00	9.70	9.60	3.00	1.03	4.00		149	167	10.8	
30%	1	10.00	9.80	9.60	2.00	2.04	4.00	**3.7**	122	138	11.6	**17.2**
	2	10.00	9.90	9.70	1.00	2.02	3.00		132	166	20.5	
	3	10.00	9.80	9.60	2.00	2.04	4.00		135	168	19.6	
40%	1	10.00	9.80	9.60	2.00	2.04	4.00	**3.3**	122	151	19.2	**18.3**
	2	10.00	9.90	9.70	1.00	2.02	3.00		125	154	18.8	

	3	10.00	9.90	9.70	1.00	2.02	3.00		118	142	16.9	
50%	1	10.00	9.80	9.70	2.00	1.02	3.00	**2.7**	112	144	22.2	**18.7**
	2	10.00	9.80	9.70	2.00	1.02	3.00		117	139	15.8	
	3	10.00	9.90	9.80	1.00	1.01	2.00		109	133	18.0	

Plate 1: Stabilized clay soil Atterberg limit

(a) Weighing CS and CW mixture **(b)** oven drying of the mixture at 105^{0}C

(c) Particle size distribution of the CS and CW mixture

Appendix II: Moulding and Testing of Blocks

IIA: Moulds and block making

(a) Different mechanical molds

Feeding the soil in

Compressing the

Extruding the

(b) The brick extrusion/moulding work by Manual extruder machine

(a) Transport/Arrival of CW&CS mixtures and brick samples at JKUAT main campus from Rwanda.

(b) Weighing and loading bricks into the electrical furnace at JKUAT engineering laboratory.

(c) Offloading fired bricks from the furnace

(a) Measuring block sizes

(b) compression strength testing of the blocks