UNIVERSITY OF NAIROBI

Faculty of Engineering

Optimization of Ceramic insulation of Cooking Stoves using Carbonized Organic Waste

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Project report submitted in partial fulfilment for the Degree of Master of Science in Energy Management.

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November 2022

Declaration

I **Esther Mwende Kyuvi** declare that this report is my original work, and except where acknowledgements and references are made to previous work, the work has not been submitted for examination in any other university.

Signature Date: 29th November, 2022

Approval by supervisors

I confirm that the study was carried out under our supervision and has been submitted for examination with our approval as University supervisors.

Prof. J. Nyang'aya Signature Date: 29th November, 2022

Dr. Aganda Alex A. Signature alex aganda Date: 29th November, 2022

Dedication

This thesis is dedicated to my family and Kenya Industrial Research and Development Institute (KIRDI) family for their unending support and encouragement throughout my studies.

Acknowledgement

I acknowledge my supervisors Prof. James Nyang'aya and Dr. Alex Aganda for the support and guidance throughout the study.

My sincere gratitude goes to my colleagues at Kenya Industrial Research and Development Institute specifically Mr. Benjamin Gituku, research scientist and head of cook stove centre, for guiding me through cook stove development and testing. Many thanks to the head of engineering development and service centre, who provided material support in fabrication of moulds for development of samples and ceramic lining. I wish also to thank Ms. Cecelia Mesa, Mr. Mbithi and Mr. Momanyi of cook stove testing centre for allowing me to use their facilities and guiding me through the stove testing process. I would also wish to thank Ms. Elizabeth Kimonge of Ministry of energy for providing invaluable information on cook stove lining manufacture.

Above all I acknowledge God for the strength, wisdom and care.

ABSTRACT

Many households and small hotels in Kenya source their energy from biomass; mainly wood and charcoal. For the urban poor, their energy source is basically charcoal. With increasing population, rural urban migration, tough economic times, the use of charcoal must be as efficient as possible. In cognizance of this need, development of energy efficient biomass (charcoal) cook stoves is paramount. The cook stoves with high efficiency will ensure that during cooking, most of the energy from the fuel goes to the cooking pan and heat losses are minimized.

The main objective of the project was to optimize the insulating properties of ceramic insulation used in ceramic cook stoves using carbonized organic waste as the burnout additive. Carbonized organic waste herein referred to as char was collected and ground to fine dust. The char was used as a burnout medium in the clay to create pores, reduce density and increase porosity thereby improving insulation properties of the fired clay. Optimization was achieved by using different ratios of clay to char.

Testing of biomass cook stove is provided for in ISO- 19867-0; the harmonized laboratory test protocol. Described in part 1 of the protocol is the standard test sequence for determination of emissions, performance, safety and durability. Adopted in this project were 410g of charcoal, 5 kg of water and a duration of 30min. The quantity of fuel used, rise in water temperature and amount water evaporated were measured. The real time emissions of Carbon monoxide (CO) and fine inhalable particles of up to 2.5 micrometers diameters ($PM_{2.5}$) were continuously monitored using sensors.

The results showed that the apparent porosity of the sample increased from 34% with no char to 87% when the sample had 50% char. On the other hand, the bulk density reduced from 2.8 g/cm^3 with no char to 1.2 g/m^3 with 50% char. The prototype thermal efficiency was better at 33% compared to the 25.8%.for the control cook stove. The prototype and control cook stove cooking power were 0.97kW and 0.71kW respectively. Another important outcome of this study was to do with emissions. The prototype $PM_{2.5}$ emissions estimated to be 76 mg/MJ_d and CO emissions at 21 g/MJ_d which were lower than the Kenya standard KS 1814:2019 maximum emission of 137 mg/MJ_d and 25 g/MJ_d respectively.

Fuel saving per month using the prototype for heating and cooking would be 112kgs of charcoal.

This study has shown that when clay was mixed with char, there was a significant increase in desirable characteristics, which results in increased efficiency of biomass (charcoal) cook stoves and lower emissions.

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ABBREVIATIONS AND ACRONYMS

KIRDI	Kenya Industrial Research and Development Institute
KEBS	Kenya Bureau of Standards
UNHCR	United Nations High Commission for Refugees
KCJ	Kenya Ceramic Jiko
LEMS	Laboratory Emission Monitoring System
Kshs	Kenya shillings
CO	Carbon Monoxide
$PM_{2.5}$	Particulate Matter of up to 2.5 micrometre
mg/MJ_d	Milligrams per Mega joules dry weight
LEMS	Laboratory Emissions Measurement System

CHAPTER 1

1.0 INTRODUCTION

1.1 Background

The development of cook stoves has evolved over time with improvements being done from the traditional three stone fire to highly efficiency cook stoves using more advanced insulation technologies.

The performance (higher thermal efficiency, low emissions and cooking power) improvement of biomass cook stove started in 1980s. Over the years the efforts have resulted into the specifications of the Kenya Ceramic Jiko (KCJ) as a standard cook stove. It is now widely produced locally by juakali artisans and more than half of urban population in Kenya use it. It has been found to be a relatively efficient charcoal cook stove. However its performance is not optimum and further improvement can be made. Cook stove performance is dependent on several factors including but not limited to stove design, properties of the stove construction material, fuel type and the type of insulation used. The cook stoves that have significantly high thermal efficiency are expensive because manufacturers use artificial insulation which is very efficient but costly. In recent months or years, other designs of charcoal cook stoves (from out of Kenya) have been introduced in the local market. Examples are EcoZoom, Burn and Envirofit. Although their efficiencies are superior, the KCJ is affordable and reliable. Hence the need for more studies to further improve the KCJ performance.

The need for energy efficient cook stoves continue to increase. Efforts to improve the cook stove has focused on improving the thermal efficiency and reduction of emissions. Since most insulating materials used for insulation are made from naturally occurring clays, determining the best performing clay mixture in terms of thermal resistivity will help in optimizing the insulation. In cook stove, heat is lost through conduction, radiation and convection. The use of ceramic insulation in metal charcoal cook stove conserves the heat lost through conduction.

Kenya ceramic jiko (KCJ) herein referred to as ceramic cook stove is widely adopted as the preferred charcoal cook stove due to its affordability and reliability. Currently more than half of all urban households in Kenya own the ceramic Jiko, and users cut across both the poor and affluent. [10]

The use of carbonized organic waste as the burnout additive is preferred because any organic matter can be carbonized through pyrolysis and can be found virtually everywhere and used where other filler materials are not available. Carbonized organic matter is much easier to reduce in size than raw organic waste. Most of the carbonized organic waste will burn out of the matrix during firing. Any remains, is both lightweight and insulative though care should be exercised in selection of the carbonized organic waste to ensure there is minimum ash content when combusted.

Carbonized organic matter (char) can be obtained using a carbonizer, a technology available in the market and locally manufactured in Kenya Industrial Research and Development Institute (KIRDI). Char is also a byproduct of gasifier cook stove. This is a double benefit because cooking or heating will be achieved at the same time forming the carbonized waste.

The quality of the cook stove is highly dependent on the choice of materials and the manufacturing method. Though several design options are available, it was noted that despite the success of many cook stoves in reducing the amount of fuel needed to cook, none are completely clean except for solar cookers.[1]

A typical cook stove includes the heat generator and a heat transfer structure. In designing the heat generator, consideration should be made on how to make most heat from the fuel. The heat transfer structure design should consider how to get most heat to the pot. [2]

Lower mass cook stove models with insulative ceramic tend to use less fuel hence significant fuel savings. Material choice for insulation lining has a significant effect on cook stoves. Since higher temperatures facilitate more complete combustion, the use of a more effective insulation material should be beneficial.

Cook stove performance is defined by thermal efficiency, emissions and cooking power. Design features of a cook stove affect both combustion and thermal efficiency. The geometry determines air flow in the heating chamber. Air circulation determines the burning rate of fuel hence the combustion efficiency. The more efficient the burning process, the less the emissions. Insulation combined with improvement of air flow contribute to improvement of thermal efficiency. In design improvement of stoves, more focus is on thermal efficiency. [1]

The aim of developing fuel efficient cook stoves is to make them consume less fuel during cooking hence slowing down deforestation. Fuel saving of up to 50 % can be achieved through design improvement of cook stoves. [3] The issues in the cook stove industry is not limited to the development of the stove itself but includes consideration of environmental sustainability, technological feasibility, economic viability as well as social acceptability. Improved thermal insulation reduces thermal dissipation hence increasing thermal efficiency and results in reduced fuel consumption.

When optimizing design of cook stoves, acceptability by the user should be considered. After technical analysis on performance, input by the user through customer feedback mechanisms should be incorporated to enable design adoption. Organic matter use in clay mixtures has been found to improve thermal performance though decrease in mechanical strength has been observed. To achieve durability, a careful balance should be ensure in mixing clay with organic matter. [4]

Clay has been mixed with sand, cow dung, ash, cement, organic matter by stove builders in the effort of trying to enhance strength and performance. From a report by United Nations High Commission for Refugees (UNHCR), mixing ratios varied from place to place and the need for experimentation and further investigation was expressed. The concerns shown were clay mixture not holding together, not sufficiently malleable, cracking and lack of resistance to thermal shocks. [5]

Challenges experienced using different clay mixtures like clay not holding together, clay not being sufficiently malleable, cracking and lack of resistance to thermal shocks were reported hence prompting for further investigation in mixing clay with other substances in order to enhance strength and performance. [5]

In stove design, the thermal properties of the material to be used are density, thermal conductivity and specific heat capacity. Thick materials absorb more energy than thin ones during heating up. It is recommended that low density thin materials are used for stove design to save on energy. In stove design, proper ventilation ensures that adequate air flows in to the combustion chamber for complete combustion of fuel. This increases fire power. Insulation of the combustion chamber reduces heat losses. [6]

Making ceramic materials lighter by creating air cavities has been found to be the most effective way of increasing thermal technical properties. Jiri et al recommended the use of small dimensions for relieving process so as to maintain good thermal properties.[7].

Organic materials have been used to create porosity in clay materials usually bricks hence improving insulation properties and consequently reducing weight. Porosity is usually created by adding a combustible material to the raw material mixture. Pore forming agents have been used in brick manufacture to reduce bulk density and increase porosity hence improving the insulation properties. [8]

Reports from several cook stove tested in KIRDI cook stove testing centre show that despite several attempts made to improve stove performance in terms of efficiency and emissions, most stoves do not meet the requirements stated by KEBS standard for ceramic cook stove.

This project aims at improving the efficiency of cook stoves by optimizing the ceramic insulation properties using organic waste as the burnout agent.

1.2 Problem statement

The main problem to be addressed by the project was performance improvement of ceramic cook stoves in Kenya. The heat loss from the char cook stove and the combustion of the biomass still render the stove overall efficiency and emissions poor. This project seeks to contribute towards reducing the heat loss by developing a better insulating material.

1.3 Objectives

1.3.1 Main objective

The project aims at optimizing the insulating properties of ceramic insulation used in ceramic cook stoves using carbonized organic waste.

1.3.2 Specific Objectives

i. To develop materials with different ratios of clay and organic waste and conduct tests to obtain porosity, bulk density and compression strength.

ii. From the tests, identify the optimum mixture and make a lining for the purpose of insulating the prototype cook stove

iii. To assemble the lining with a standard cook stove cladding and test performance.

1.4 Justification

Population growth and urbanization has increased demand for charcoal. Annual consumption is about 2.5 million of charcoal. People prefer charcoal as a fuel compared to un-carbonized biomass because of its higher calorific value per unit mass and less moisture content. Charcoal is durable due to resistance to moisture, can be sold in small quantities and can be burned in any stove model makes it most preferred energy source. [9]. 82% of urban households use charcoal as the primary source of energy. Making and selling of charcoal is a source of income to 66% of households in rural areas. [10]

The most prominent cook stove used in Kenyan households is KCJ with ownership of the ordinary metallic charcoal stove estimated at 4.2 million. [11]

Use of clay has been proven in improvement of efficiency in stoves. [12]

1.5 Scope

The project scope is limited to Kenya Ceramic Jikos (KCJ). Only the insulation of the KCJ will be altered. The stove design considered is the one that is widely used in Kenya of medium size which is mostly preferred by users. Clay preparation, stove preparation and testing will all be done within KIRDI premises. The organic waste to be used is available in the KIRDI cook stove pilot plant which is a byproduct of gasifier stoves.

CHAPTER 2

2.0 LITERATURE REVIEW

A lot of research has been done on use of organic waste in improvement of insulating properties of clays. Most available literature on application of such clays is in the manufacture of insulating bricks. The following is a brief review of clay use in cook stoves.

2.1 Clay as a natural insulator

Clay is a naturally occurring soil material that is fine grained. Its plasticity, heat resistivity, poor conductivity among other properties makes it suitable for use in making ceramic insulation. The nature of clay is determined mostly by the composition of parent rock and the physical and chemical environment in which the alteration takes place.

Fired clay produces is used in combustion chambers of cook stoves. The insulting properties of clay can be improved by use of fluxes like wood ash. [13]

2.2 Cook stove design

Design optimization and people participation in stove design process has been found to be effective in improving thermal efficiency and producing acceptable stove designs. [14]

Jetter analyzed the design on several cook stoves widely used in Africa. It was noted that the KCJ design model is widely adopted across Africa and its thermal efficiency is high compared to traditional cook stoves. The stove has metal cladding which holds the cooking pot and houses the ceramic lining. It has an opening on the lower side which creates a natural draft for combustion of the fuel. [15]

2.3 Improving thermal efficiency using organic waste

Insulating cook stoves with clay has been proven to improve thermal efficiency.

Three traditional charcoal cook stoves tested by Boafo showed that the cook stove insulated with a ceramic liner performed better in terms of thermal efficiency. [16]

Material analysis by Schreiner showed that use of straw in clay mixture improves thermal efficiency. [4]

Experimentation was done by Honkalaskar using clay, rice husk and cattle dung in the manufacture of insulation. . The results showed that there was reduction in fuel consumption, cooking time and soot accumulation. [14]

In 2016, Fgaier did an experimental study which was focused on improving thermal properties of ceramics using flax shives and starch. Optimal thermal performance withb good mechanical strength was achieved. [17]. Demir 2008 used saw dust, tobacco residues and grass as burn out agents for the manufacture of construction bricks. Porosity was increased, bulk density decreased and thermal properties improved. [18]

Bories in 2014 developed clay bricks using bagasse and urban sludge as pore forming agents. Low weigh and low thermal conductivity was achieved. [19]
Wheat straw and husks of sunflower seeds in quantities of 5 % mass and 3 % mass were used as pore forming agents in brick production. Decreased thermal conductivity and increased porosity was observed keeping acceptable compression strength. [20]

Jetter et al tested a variety of cook stoves which included KCJ. Comparison was done with cook stoves without ceramic insulation. The test results showed improvement in thermal efficiency. [15]

CHAPTER 3

3.0 MATERIALS AND METHODS

This project was concerned with improving the insulation characteristics of cook stove clay lining. Although a lot of efforts have gone towards increasing the thermal resistance of clay and therefore enhancing cook stove efficiency, this is yet to be optimized. Different types of clay and the blending are still being tested to improve the efficiency even further. In this project, clay from a specific area in Kenya was blended with carbonized organic waste and prepared as a stove lining. It was tested in a cook stove as to its thermal and other characteristics suitable for stove lining. Presented in this chapter are the procedures and materials used in determining the best clay and organic waste mixture which results in higher cook stove efficiency.

3.1 Clay preparation

The source of clay used in this project is an area known as Mukurwe-ini 0.5609° S, 37.0488° E, 117 kms NE of Nairobi. The raw clay usually comes with sand and other impurities. In the clay preparation, the first task was to remove as much impurity as possible. It involved mixing the clay with water and then employing a plunging machine in separating the clay from sand and other impurities. The clean mixture of clay in water was then open air dried on a cloth for seven days. The dried clay was first crushed by a jaw crusher and then by steel ball mill into the required particle size.

3.2 Carbonized organic waste preparation

The prepared clay was mixed with various quantities of carbonized waste. The carbonized waste increases the porosity of the resulted clay. In turn the thermal conductivity is reduced and hence an increase in the insulation characteristics. The carbonized waste was sourced from Kenya Industrial Research and Development Institute (KIRDI). At this institute is a gasifier stove which generates carbonized waste. For the purpose of this project the waste was carefully selected to ensure consistency of the raw material for uniformity. The waste was then crushed using steel ball mill to reduce the particle size. The fine waste was passed through a standard test sieve of 1.18mm to ensure evenness and removal of any foreign material like unburnt wood and stones. The carbonized organic waste dust was mixed with clay at different ratios and fired to create a mixture of various porosity.

3.3 Sample preparation

The prepared clay and waste dust were mixed to form a series of clay/carbonized dust mixtures. The ratios of dust to clay were (dust:clay) 0:100, 10:90, 20:80, 30:70, 40:60 and 50:50 by weight. For each mixture, water was added to create plasticity for moulding. For each mixture, three samples were moulded into cylindrical shapes of diameter 10 cm and 3 cm thickness. Shrinkage lines of length 8cm were drawn on the samples. The samples were air dried under a shade for seven days. After which they were oven dried to remove more moisture (Fig.3.2).

Once dried, the shrinkage lines were measured and recorded. The samples were then fired in a furnace in three stages; each at controlled temperature. At first, the temperature was raised up to 120 ^{o}C. The furnace was switched off and the door slightly opened to allow any steam formed to escape (soaking process). This ensured that any water content remaining in the dried samples was evaporated. After one hour, the door was closed and the furnace switched on. The furnace temperature was increased to 750 ^{o}C and maintained at that temperature for the next 2 hours. This is the temperature at which carbonized organic waste starts to burn. The two hours allowed the pore forming agent to burn progressively until pores are formed. The temperature was then raised to 900 °C which is the firing temperature for clay products and for complete combustion of any remaining pore forming agent. On reaching the firing temperature, the furnace was switched off and the samples allowed to cool inside the furnace until room temperature was achieved. The fired samples were removed from the furnace and kept in open air for a day (24 hours).

3.4 Shrinkage, Porosity and bulk density

The shrinkage lines on the samples had been measured before and after firing. After firing these lines were measured again. It was in these measurements that firing shrinkage was computed. The surfaces of the fired samples were evened using a sand paper to a standard size of 9.1cm diameter and 3cm thickness. Identification marks were then made. Porosity and bulk density was determined using the water immersion porosimetry (WIP) technique (ASTM Standard C 373-88 (2006). Referring to the standard, the mixture samples were saturated in water by boiling them for 2 hours and cooled thereafter for 12 hours. They were then weighed and the pore volume calculated from the weight difference between the fully saturated and dehydrated states. The total volume was determined using the Archimedes' principle - (Measurement of displaced water on immersion)

Equations 3.1 and 3.2 were used to calculate porosity and bulk density respectively.

$$P, \% = \frac{[W-D]}{V}\ X100 \qquad (3.1)$$

$$B = \frac{D}{V} \qquad (3.2)$$

Where P = Porosity expressed as a percentage

B = Bulk density

W = saturated weight

D = dry weight

V = saturated weight minus suspended weight.

3.5 Relative thermal conductivity

For the purpose of determining the relative thermal conductivity of the clay mixture samples, the following procedure was adopted. An opening of diameter 9.1cm was made through the door of a furnace. The samples were placed in this opening so that the inside surface of the cylindrical sample was in contact with heated air inside the furnace while the outside surface was in contact with ambient air. The furnace temperature was then set to 500 ^{o}C. After every 5 min, the temperature of the outside surface of the samples was noted using an Infra-Red thermometer until a steady state was reached.

To determine the insulating properties of the samples relative to the 100% clay sample, Fourier’s law was applied.

$$Q = \leftthreetimes \cdot \frac{\Delta \mathrm{T} \cdot \mathrm{A}}{\Delta \mathrm{x}}$$

Where ($\leftthreetimes$) is thermal conductivity of the material, which can be expressed as

$$\leftthreetimes = Q \cdot \frac{\Delta \mathrm{x}}{\Delta \mathrm{T} \cdot \mathrm{A}} \qquad (3.3)$$

The relative thermal conductivity (λ) of each sample were determined using equation 3.3. It was tabulated relative to that of the unmixed clay – i.e. 100% clay.

3.6 Compressive strength

Compressive strength (kN/cm^2 or MPa) was determined by testing the maximum load (failure load) applied to the samples (kN), using a compression testing machine, per cross-sectional area (cm^2) of the samples as shown in equation 3.4.

$$\mathrm{P} = \frac{\mathrm{F}}{\mathrm{A}} \qquad (3.4)$$

Where P = compression strength

F = Maximum load

A = area of the sample

3.7 Selection of optimal clay to charcoal dust mixture and development of a ceramic lining and cook stove

The sample with desirable properties was that considered as having the optimum proportion of char. It is from such sample that a prototype is fabricated. A standard KCJ cook stove cladding material were acquired. A clay moulding tool was designed using the shrinkage factors shown in Table 4.1. The moulding tool was then made using wood panels as shown in figure 3.7. Clay and charcoal dust were mixed according to selected ratio and moulded into a cook stove liner. The mould was left to dry under shed for a week. Firing and cooling was done using the same procedure followed for the cylindrical sample blocks.

The ceramic lining shown in figure 3.8 was joined to the metal cladding using mortar made with crushed ceramic and sodium silicate. The overall dimensions of the prototype were taken and illustrated by figure 3.10.

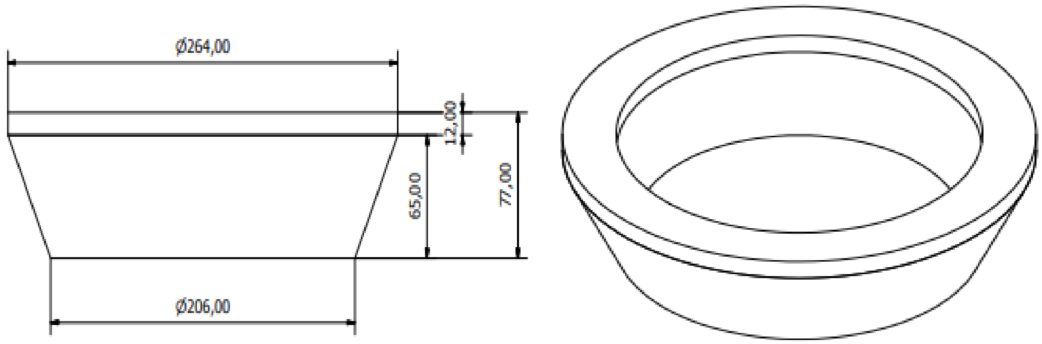

Figure 3.1: mould

Figure 3.2: ceramic lining

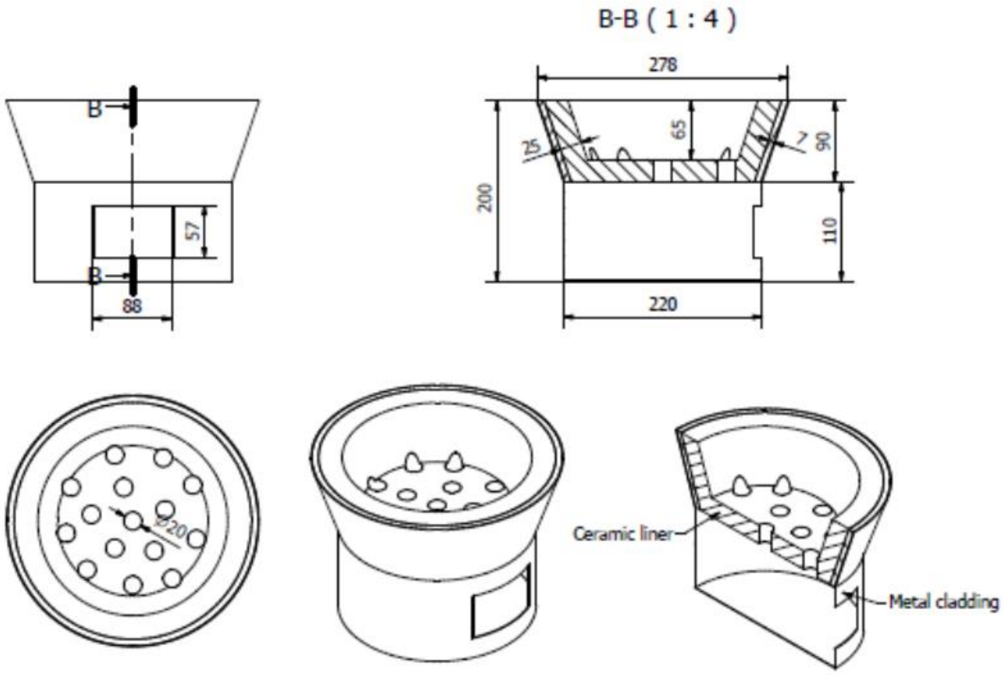

Figure 3.3: Dimensions of the prototype charcoal cook stove

Figure 3.4: prototype charcoal cook stove

3.8 Testing performance of prototype cook stove compared to a standard KCJ as the control

The now assembled prototype cook stove was tested at KIRDI cook stove testing laboratory to establish its performance compared to a standard KCJ cook stove as the control.

The ISO 19867-1 test method was followed. The cook stove was set up in a LEMS as shown in figure 3.13. The procedure for testing included using 410g of charcoal with a known calorific value to heat 5kg of water for 30 min. Amount of fuel used, rise in water temperature and amount water evaporated were measured. CO and $PM_{2.5}$ sensors took real time measurements of emissions.

The dependent variables were: thermal efficiency, firepower, cooking power, PM2.5 and CO emissions.

The Kenya standard KS 1814:2019 requirements are that; for charcoal ceramic cook stove, thermal efficiency and cooking power shall not be less than 30% and 0.85kW respectively. Using gravimetric method which determines the weight of emissions discharged during the burning process; $PM_{2.5}$ and CO emissions shall be less than 137 mg/MJ_d and 25 g/MJ_d respectively.

Five tests were carried out for each cook stove at both high power and medium power levels. To operate at high power, the doors of the cook stove were left completely open. For medium power, the doors were folded to reduce the air entry opening by half.

The performance of the stoves was calculated using the equations in appendix 3.

T-test at 95% level of confidence were carried out to compare the means of the performance variables. The computation equations used are in appendix

CHAPTER 4

4.0 RESULTS AND DISCUSSION

A cook stove lining is key in reducing heat loss and thereby enhancing thermal efficiency and power. In this project, a lining consisting of clay and carbonized organic waste was made. Different ratios of the clay to carbonized waste (char) were tested to obtain the optimum ratio that lead to high efficiency and power. Presented and discussed in this chapter are the results from the experiments conducted with various mixtures of clay and char. The results included, the clay shrinkage, bulk density, compression strength, porosity, thermal conductivity and cook stove power. The results were compared with those of the standard KCJ cook stove.

4.1 Clay Shrinkage

Clay soil swells when wet and shrinks when dry. The amount of minerals in the soil determines the shrinking capacity. The type and source of clay soil also determines the shrinkage capacity. Ball clay used in pottery is extremely plastic and fine grained. The challenge in its use is high shrinkage. The shrinkage factor is an important parameter to consider in pottery design because it determines the final size of the fired product.

On average, shrinkage along the lengths of the samples developed using ball clay mixed with char was 10 – 11.3% after firing as shown by Table 4.1. Shrinkage along the thickness was not noticeable.

Table 4.1: Shrinkage of samples after drying and firing

	Shrinkage line size			% shrinkage			
% char dust in samples	before drying (cm)	after drying (cm)	after firing (cm)	after drying	after firing	Original sample diameter (cm)	Final sample diameter (cm)
0	8	7.5±0.1	7.1±0.2	6.3	11.3	10	9.18
10	8	7.5±0.1	7.2±0.1	6.3	10.0	10	8.92
20	8	7.4±0.0	7.1±0.1	7.5	11.3	10	9.02
30	8	7.4±0.2	7.1±0.2	7.5	11.3	10	9.19
40	8	7.7±0.1	7.2±0.1	3.8	10.0	10	9.3
50	8	7.6±0.1	7.1±0.1	5.0	11.3	10	9.17

The shrinkage of the samples after firing was approximately 11%. The diameter of the liner moulding tool was therefore designed by multiplying the diameter of the metal cladding by 0.11.

Research on shrinkage has been done using clay mixed with organic waste.

Ugwu and Famuyibo compared the shrinkage, porosity and bulk density of pure clay with that blended with rice husk. The shrinkage for pure clay was higher than blended clay showing that blending clay with rice husks lowers the shrinkage factor of clay. [21]

Djafri and Chelouah evaluated the effects of increasing amounts of ground date pits on clay brick properties. They observed addition of ground pits in clay mixture lowers the shrinkage factor in comparison to pure clay.[22]

This shows that different types of clay have different shrinkage factors and addition of organic waste in clay mixtures lowers shrinkage factor.

4.2 Porosity and bulk density

Porosity is an important parameter in determining thermal conductivity in blended clays. The more porous the clay, the lower the thermal conductivity. The bulk density for insulation bricks need to be low because they are not weight bearing and they need to be as light as possible so as not affect the overall load in construction. In KCJ design, the insulation does not bear the weight of the cooking pot. The overall weight of the cook stove should be as low as possible for portability.

Table 4.2 shows the results of porosity and bulk density

Table 4.2: Samples porosity and bulk density

% char in sample	Dry weight (D) in grams	Suspended weight (S) in grams	Saturated weight (W) in grams	Apparent porosity (%)	Bulk density (g/cm3)
0	350	268	393	34.4	2.80
10	315	243	370	43.3	2.48
20	256	198	356	63.3	1.62
30	222	177	321	68.7	1.54
40	187	163	301	83.6	1.36
50	163	147	274	87.4	1.28

Figure 4.1 and 4.2 shows graphical presentation of porosity and bulk density respectively.

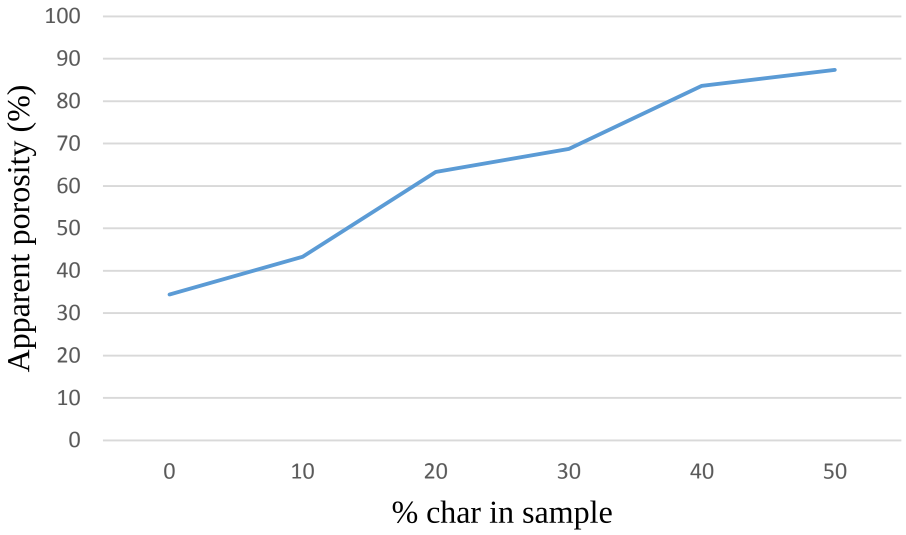

Figure 4.1: Samples apparent porosity

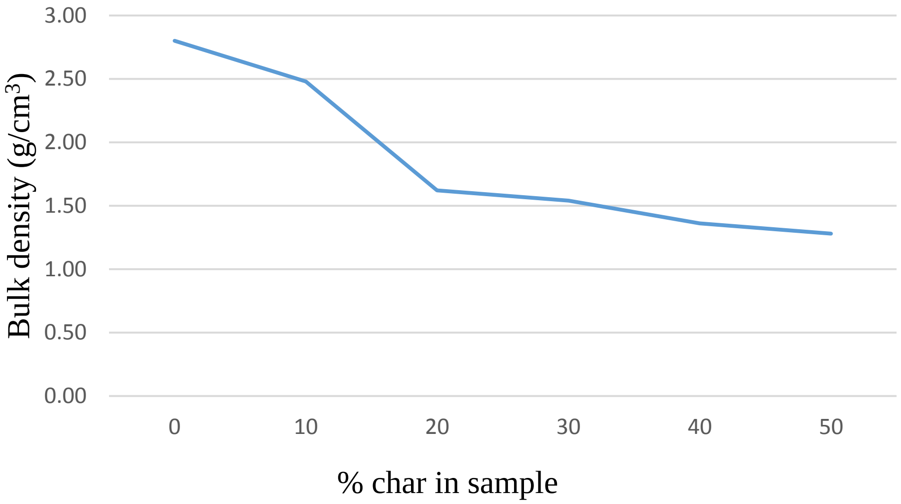

Figure 4.2: Samples bulk density

Figure 4.1 shows that porosity increased as the proportion of char in the sample increased, while Figure 4.2 shows that bulk density decreased as the proportion of char in sample increased.

From experimentation by Ugwu and Famuyibo, apparent porosity for blended clay was almost double of the one of pure clay. Bulk density reduced when clay was blended with organic waste. This therefore shows that blending of clay increases apparent porosity and reduces bulk density. [21]. Georgiev, Yoleva and Djambazov used wheat straw and sunflower seed husks to create pores in the clay mixture. Addition of pore forming agents increased the apparent porosity. [20]

Comparing these reports with the results obtained in the current study, it was found that the apparent porosity of the sample with 50% char was 87% and that with no char was 34%. The bulk density of the sample with 50% char was 1.28 g/cm^3 and that with no char was 2.8 g/cm^3. Hence this shows that apparent porosity increases and bulk density decreases with increase in organic waste in clay mixtures.

This shows that char was very effective in creating void spaces in the clay making it more porous and reducing its bulk density.

4.3 Relative thermal conductivity

Insulation materials should have low thermal conductivity.

Figure 4.3 shows how temperature increased with time for different samples when a constant heat source of 500 ^{0}C was applied.

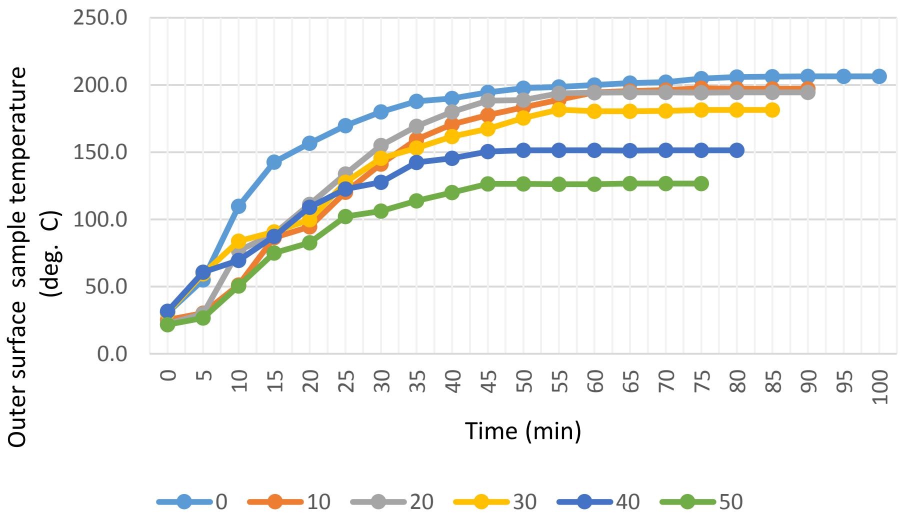

Figure 4.3: Variation of outer sample surface temperature with time

The outer surface sample temperature reached a steady state after approximately 65min.

The steady state temperature profiles were summarized and tabulated as shown on table 4.3.

Table 4.3: temperature profiles after 65 min

% char dust in samples	Inside furnace set temperature (^{o}C)	Outer surface sample temperatures (^{o}C)			AVG	STDEV	Temperature gradient i.e. ΔT (^{O}C)
		Test 1	Test 2	Test 3			
0	500	196.9	196.4	196.1	196.5	0.4	303.5
10	500	195.5	195.4	195.1	195.3	0.2	304.7
20	500	194.7	194.3	194.4	194.5	0.2	305.5
30	500	180.6	180.3	180.1	180.3	0.3	319.7
40	500	151.7	151	150.5	151.1	0.6	348.9
50	500	126.6	126.4	126.8	126.6	0.2	373.4

The relative thermal conductivity of the samples was calculated and tabulated. (Table 4.4)

Table 4.4: Samples relative thermal conductivity compared to 100% clay sample

% char dust in samples	Thickness Δx (cm)	Cross sectional area A (cm^{2})	Δx/ (ΔT. A) (cm/(^{o}C x cm^{2})	Relative thermal conductivity ⋋
0	3.14	66.15	0.000156393	100
10	3.12	62.46	0.000163939	105
20	3.07	63.87	0.000157342	101
30	3.07	66.30	0.000144842	93
40	3.02	67.89	0.000127488	82
50	2.87	66.01	0.000116439	74

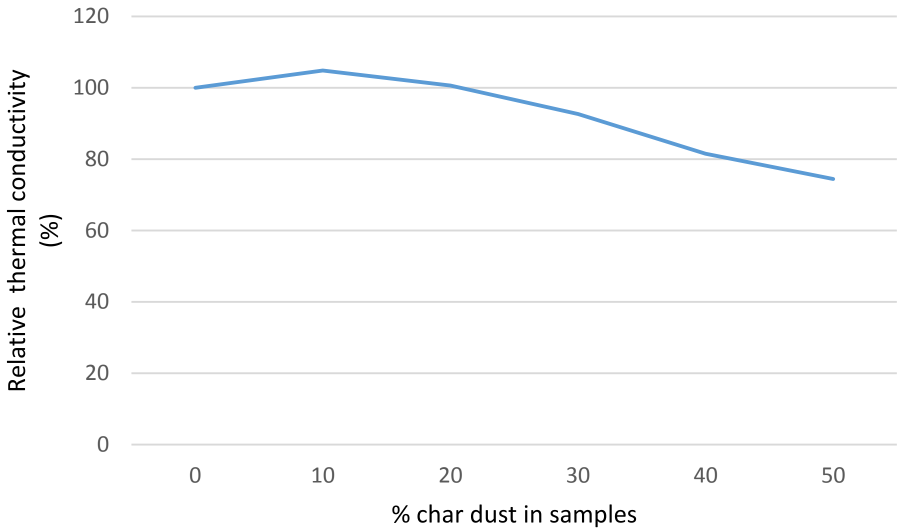

Figure 4.4: Thermal conductivity of samples versus the % of char

Samples with a higher proportion of char showed lower steady state outer surface temperatures (figure 4.3). Table 4.3 shows the sample with 50% char had the highest temperature gradient between the inner and outer surfaces.

The relative thermal conductivity therefore reduced with increased proportion of char in sample as shown by Table 4.4 and Figure 4.4.

Experimentation by Djafri and Chelouah using ground pits in clay mixture found that thermal conductivity of the clay brick samples considerably decreased with the increase in the percentage and diameter of the Ground Date Pits (GDP) in blended clay. [22]

Table 4.4 shows that the thermal conductivity of the sample with 50% char by weight in the blend was 26% lower compared with sample with 0% char dust in blend. The current study therefore confirms that higher the proportion of air in the clay mixture, the higher the thermal insulation since air is a good insulator.

4.4 Compressive strength.

Addition of organic waste in clays lowers the compression strength. This is because after the organic waste burns out during firing, voids are created. The voids act as points of weakness hence lowering the compression strength.

Table 4.5 shows the maximum loads the samples and the calculated compression strengths

Table 4.5: Compressive strength of samples

% char dust in samples	Maximum load (kN)	Cross-sectional area (cm^2)	Compressive strength (MPa)
0	86	0.0065	13.2
10	75	0.0065	11.5
20	63	0.0065	9.7
30	50	0.0065	7.7
40	38	0.0065	5.8
50	21	0.0065	3.2

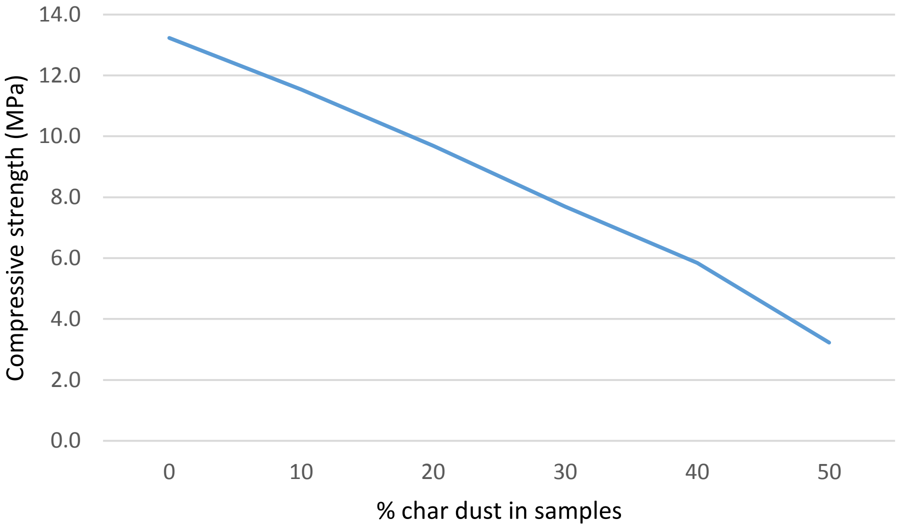

Figure 4.5: Variation of compressive strength among samples

Samples with a higher proportion of char showed a lower compressive strength as shown by Table 4.5 and Figure 4.5. The higher the amount of char, the lower the compression strength.

Djafri and Chelouah found that increasing the diameter of ground date pits decreases the compression strength.

The compressive strength of samples without burnout material (no GDP) was approximately was higher than samples with ground date pits. [22]

This was also observed in the current study where compressive strength decreased from 13.2 MPa for sample with no char in blend to 3.2 MPa for sample with 50% char dust in blend. It was observed that the sample with 50% char dust in blend did not have sufficient strength and broke easily. The sample with 40% char that had a compressive strength of 5.8 MPa was selected for development of the ceramic liner since it had sufficient strength and good insulation properties. It is worth noting that the ceramic liner does not bear weight in the ceramic cook stove design hence the compression strength is not a major factor when determining the right mixture.

4.5 Performance of prototype compared to control cook stove

The performance of the cook stoves was determined using the ISO 19867-1 test method. The major parameters considered in performance analysis were Water temperature, Dry fuel consumed, Thermal efficiency ,Fuel burning rate, Firepower ,Cooking power, PM 2.5 mass per useful energy delivered, PM 2.5 mass per time, CO mass per useful energy delivered and CO mass per time. The results obtained were as shown in table 4.6.

The raw data on performance of the KCJ prototype and the control is tabulated in appendix 1 and 2 respectively.

Table 4.6: Average performance of the cook stove

	KCJ (Control)		Prototype	
	Mean	STDEV	Mean	STDEV
Water temperature at 30 min (deg C)	72.2	5.0	87.3	6.6
Dry fuel consumed (g)	174	12	184	24
Thermal efficiency (%)	25.8	1.1	33.3	1.9
Fuel burning rate (g/min)	5.76	0.41	6.12	0.80
Firepower (kW)	2.72	0.19	2.89	0.38
Cooking power (kW)	0.71	0.07	0.97	0.13
PM 2.5 mass per useful energy delivered (mg/MJ)	75.42	25.00	75.81	14.76
PM 2.5 mass per time (mg/min)	3.25	1.34	4.35	0.58
CO mass per useful energy delivered (g/MJ)	23.93	2.53	21.34	4.38
CO mass per time (g/min)	1.02	0.15	1.21	0.19

The thermal efficiency and cooking power of the prototype cook stove was 25.8% and 33.3% as shown by table 4.6. The prototype had a significant increase in water temperature compared to the control cook stove for the test period of 30 minutes.

Emissions of PM2.5 and CO between the prototype and KCJ control cook stove were not significantly different.

A T – test at 95% confidence was calculated and tabulated as shown in table 4.7

Table 4.7: T-test for Equality of Means

	t	Degrees of freedom	Significance (2-tailed)	Mean Difference	Std. Error Difference
Water temperature at 30 min (^oC)	4.054	8	0.004	15.080	3.720
Dry fuel consumed (g)	0.896	8	0.396	10.830	12.082
Thermal efficiency (%)	7.788	8	0.000	7.460	0.958
Fuel burning rate (g/min)	0.896	8	0.396	0.359	0.401
Firepower (kW)	0.896	8	0.396	0.170	0.189
Cooking power (kW)	3.794	8	0.005	0.254	0.067
PM 2.5 mass per useful energy delivered (mg/MJ_d)	0.031	8	0.976	0.398	12.985
PM 2.5 mass per time (mg/min)	1.674	8	0.133	1.097	0.655
CO mass per useful energy delivered (g/MJ_d)	-1.147	8	0.285	-2.593	2.261
CO mass per time (g/min)	1.807	8	0.108	0.195	0.108

T-critical is 2.306 at 95% confidence level. There is therefore significant differences between the prototype and KCJ control cook stove in thermal efficiency, cooking power, and rise in water temperature (Table 4.7).

The mean thermal efficiency and mean cooking power were plotted for both cook stoves. (Figures 4.6 and 4.7).

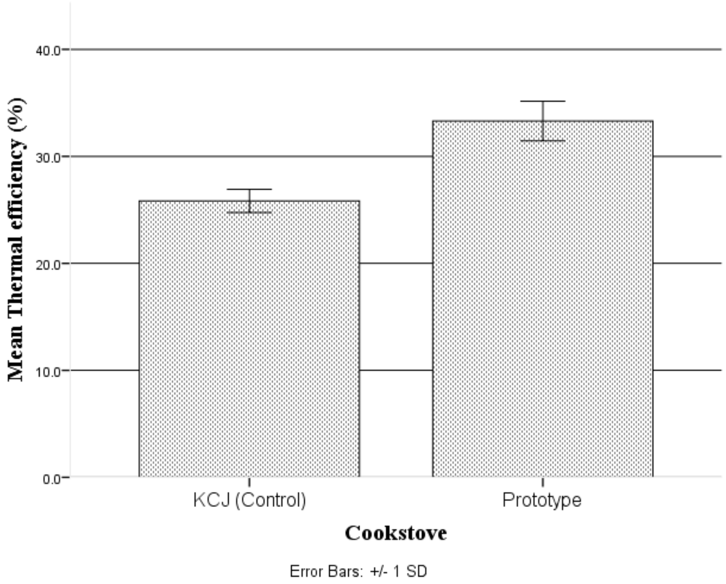

Figure 4.6: Thermal efficiency between prototype and control cook stove

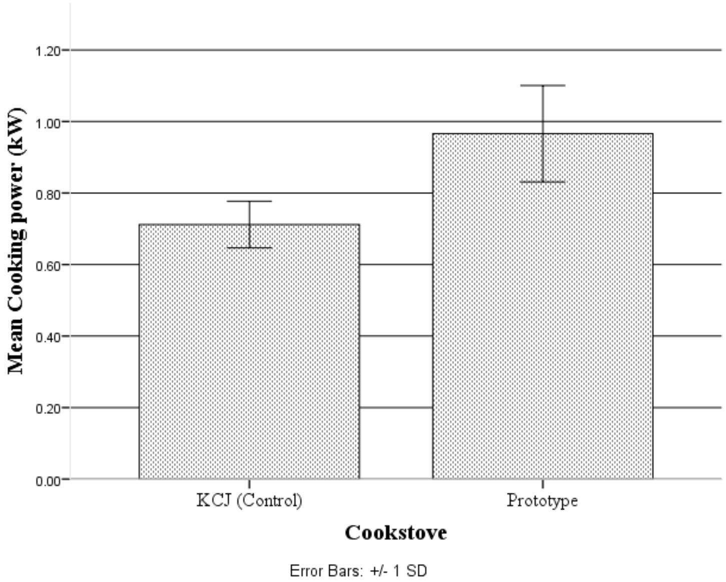

Figure 4.7: Cooking power between prototype and control cook stove

From figures 4.6 and 4.7, the prototype has a high range of both thermal efficiency and cooking power compared to the control cook stove.

Jetter et al tested a variety of commonly used charcoal cook stoves across Africa. Thermal efficiencies of Gyapa, Jiko ceramic, KCJ standard, and Kenya Uhai were comparable with the outcome of the control cook stove test results. [15]

The prototype had a thermal efficiency of 33% while that of the control cook stove was 25.8%. The thermal efficiency (33%) and cooking power (0.97kW) of the prototype was also higher than that provided by Kenya standard KS 1814:2019 of 30% and 0.85kW respectively. $PM_{2.5}$ emissions (76 mg/MJ_d) and CO emissions (21 g/MJ_d) were also less than 137 mg/MJ_d and 25 g/MJ_d respectively, set by the standard.

4.6 ANALYSIS OF THE COSTS AND BENEFITS

4.6.1 Cost of production of liner

Requirements and cost

Clay@ Kshs 4000 per tonne

Water @Kshs 4000 per 10000 litres

Charcoal @Kshs 70 per 1.5kg

labour @Kshs 500 per day

Firewood @Kshs 200 per 20kg bundle

100 liners require 150kgs of clay, 800litres of water, 200kgs of charcoal, 4 days labour and firewood of 150kgs.

This translates to Kshs 6980 per 100 liners

The kiln carries a total load of 300 liners per batch

Cost of production for 300 liners will be Kshs 20,940

Therefore the cost of production of one liner will be approximately Kshs 70.

The market cost for a liner is Kshs 50

4.6.2 Cost of production of cook stove

Medium size control cook stove is Kshs 300

Medium size prototype is Kshs 320

4.6.3 Cost saving analysis

From appendix 1 the average water temperature for high power for the prototype (assuming cooking will be done with the ventilation door open) was 85.25 ^{0}C while from appendix 2 the control cook stove average water temperature was 67.24^{0}C for high power boiling test of 30 minutes.

The difference in water temperature is

85.26 – 67.24 = 18.02 ^{0}C

To raise the temperature of water by 18.02^{0}C using the control cook stove, it will require (18.02 x30 /67.24) = 8.04 minutes

This implies that in actual cooking, the prototype will cook faster than the control cook stove by 8.04 minutes

From appendix 2, the average fuel burning rate at high power of the control cook stove was 5.464g/min

For 8.02 minutes, the fuel consumed = (8.02 x 5.464) = 43.93g = 0.4393kg

Hence the fuel saved in 30 minutes boiling period using the prototype = 0.4393kg

In a normal day energy consumption where households depend entirely on charcoal for cooking and heating, the time breakdown is as follows;

Cooking breakfast – 15min

Boiling bathing water for a household of 4 people – 60 min

Boiling drinking water - 60 min

Cooking lunch – 60 min

Cooking supper – 60 min

Total time taken = 255min

For every 30 minutes, 0.4393kg of charcoal is saved if cooking is done using the prototype.

In 255min total fuel saving will be 0.4393 x255/30 = 3.734kgs

In the open market, 1.5kg container of charcoal is sold at Kshs 70

Savings in a day using the prototype = 3.734 x70/1.5 = Kshs 174

On a day when cereals are to be boiled, the cooking time will increase by approximately 180 minutes. The total cooking and heating time will be 435min

Fuel savings in such a day will be 0.4393 x435/30 = 6.37kgs

Money saved = 6.37 x 70/1.5 ≈ Kshs 297

In a month, fuel saved using the prototype would be 3.734kgs x 30 = 112kgs of charcoal.

Cost saving will be 112.02 x 70/1.5 = Kshs 5227

If the household will be boiling cereals every day, the total fuel savings = 30 x 6.37kgs = 191kgs

The cost savings will be 191x 70/1.5 = Kshs 8913 which is equivalent to USD 74 at an exchange rate of kshs 120 per USD.

4.6.4 Benefits

Summary of benefits of using the prototype cook stove in comparison with the control cook stove include;

1. Cost savings
2. Thermal shock resistance
3. Light weight hence better handling
4. Affordable
5. Easy to manufacture
6. Reduced fuel needs
7. Less CO mass per useful energy delivered hence less air pollution
8. Health benefits as a result of less air pollution and less cooking time
9. Less fuel consumption hence reduced pressure on forests

The impact of the new technology include

1. Creation of jobs for liner manufacturers hence better livelihoods

2. Improved health for the users
3. Higher revenues from sales for liner manufacturers due to higher demand on the new product.

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

This project was an attempt to develop a cook stove lining made of clay and carbonized organic waste that when applied would lead to high cook stove performance. This means a reduction in both thermal conductivity and bulk density. The findings of the project are summarized in the followings sections.

5.1 Conclusions:

The cook stove lining was a mixture of clay and carbonized organic waste in various ratios. It was found that the apparent porosity of the sample with 50% char was 87% with a bulk density of 1.28 g/cm^3. With no char, the clay apparent porosity was 34% and the bulk density was 2.8 g/cm. Clearly, the char was very effective in creating void spaces in the clay making it more porous and reducing its bulk density. It was observed that the optimum ratio of clay to carbonized organic waste was 60:40. At this ratio, the porosity was highest, the bulk density lowest and the shrinkage after firing of 0.11.

The tests on the prototype cook stove showed that the thermal efficiency was 33% compared with 30% required by Kenya standard KS 1814:2019. The corresponding cooking power was 0.97kW for the prototype cook stove, higher than that provided by Kenya standard KS 1814:2019 of 0.85kW. Further, there was remarkable reduction in emissions. The $PM_{2.5}$ emissions were 76 mg/MJ_d and CO emissions were 21 g/MJ_d compared with 137 mg/MJ_d and 25 g/MJ_d respectively of the standard cook stove.

In cost matters, savings of 74 US dollars per month could be realized if the prototype is used for cooking and heating.

This project has shown that carbonized organic waste when used in development of ceramic insulation improves thermal efficiency and cooking power of cook stoves.

5.2 Recommendations:

Carbonized organic waste (char) from wood has been proven to improve efficiency in ceramic insulation for cook stoves. The cook stove design could also be improved to maximize on energy saving. More research is necessary to establish the performance of other carbonized organic waste materials. Other insulation applications could also be investigated.

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Appendix 1 – Performance data for prototype cook stove

		Prototype Test 1		Prototype Test 2		Prototype Test 3		Prototype Test 4		Prototype Test 5	
Performance variable	Units	High power	Medium power	High power	Medium power	High power	Medium power	High power	Medium power	High power	Medium power
Water temperature at 30 min	degC	92.1	90.6	93.4	91.5	89.6	92.5	79.9	89.5	71.3	82.1
Dry Fuel consumed	g	205	218	198	197	182	185	176	191	136	158
Thermal efficiency	%	34%	30%	36%	35%	34%	37%	30%	33%	32%	34%
Fuel burning rate	g/min	6.81	7.22	6.56	6.52	6.05	6.15	5.83	6.33	4.51	5.23
Fire power	kW	3.22	3.41	3.10	3.08	2.86	2.90	2.76	2.99	2.13	2.47
Cooking power	kW	1.09	1.02	1.11	1.07	0.97	1.07	0.82	0.99	0.68	0.84
PM2.5 temperature-corrected total mass	mg	157.67	75.23	95.10	140.78	49.96	257.78	119.44			144.52
mass per fuel mass	g/kg	0.77	0.35	0.48	0.72	0.27	1.39	0.68			0.92
mass per fuel energy	mg/MJ	0.03	0.01	0.02	0.03	0.01	0.05	0.02			0.03
mass per useful energy delivered	mg/MJ	81.00	40.95	48.02	73.45	28.72	133.08	81.53			94.93
mass per time	mg/min	5.26	2.51	3.17	4.69	1.67	8.59	3.98			4.82
CO temperature-corrected total mass	g	24.57	30.26	32.21	47.01	40.55	37.63	31.60	51.45	31.09	37.66
mass per fuel mass	g/kg	119.75	139.11	163.01	239.07	222.30	203.12	179.79	269.46	228.83	238.80
mass per fuel energy	g/MJ	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
mass per useful energy delivered	g/MJ	12.62	16.47	16.26	24.53	23.31	19.43	21.57	28.95	25.50	24.74
mass per time	g/min	0.82	1.01	1.07	1.57	1.35	1.25	1.05	1.72	1.04	1.26
CO2 temperature-corrected total mass	g	319.27	300.76	347.06	311.72	333.35	326.85	282.06	379.00	246.28	282.04
mass per fuel mass	g/kg	1555.89	1382.50	1756.36	1585.16	1827.55	1764.36	1604.90	1984.79	1812.85	1788.48
mass per fuel energy	g/MJ	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06
mass per useful energy delivered	g/MJ	164.02	163.69	175.24	162.63	191.61	168.74	192.53	213.22	202.05	185.26
mass per time	g/min	10.64	10.03	11.57	10.39	11.11	10.89	9.40	12.63	8.21	9.40
		Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp
Surface temp. (deg C.)		474.00	135.00	422.00	143.00	413.00	142.00	476.00	130.00	482.00	100.00

Appendix 2 - Performance data for KCJ control cook stove

		KCJ Test 1	Control	KCJ Test 2	Control	KCJ Test 3	Control	KCJ Test 4	Control	KCJ	Control Test 5
ISO FORMAT	Units	High power	Medium power	High power	Medium power	High power	Medium power	High power	Medium power	High power	Medium power
Water temperature at 30 min	degC	74.0	78.5	63.5	71.9	77.0	75.8	71.2	78.1	50.5	81.2
Dry Fuel consumed	g	179	189	161	174	181	181	177	185	126	183
Thermal efficiency	%	26%	25%	23%	26%	27%	27%	25%	28%	21%	29%
Fuel burning rate	g/min	5.92	6.27	5.33	5.77	6.02	6.02	5.86	6.15	4.19	6.08
Fire power	kW	2.80	2.96	2.52	2.73	2.84	2.84	2.77	2.90	1.98	2.87
Cooking power	kW	0.733	0.726	0.589	0.697	0.779	0.764	0.706	0.837	0.434	0.850
PM2.5 temperature-corrected total mass	mg	79.82		53.86	119.88	163.39		94.19	109.12	47.21	64.78
mass per fuel mass	g/kg	0.45		0.34	0.69	0.90		0.53	0.59	0.37	0.35
mass per fuel energy	mg/MJ	0.02		0.01	0.02	0.03		0.02	0.02	0.01	0.01
mass per useful energy delivered	mg/MJ	60.33		50.94	95.24	117.02		75.16	73.57	61.72	42.83
mass per time	mg/min	2.66		1.80	4.00	5.45		3.14	3.64	1.57	2.16
CO temperature-corrected total mass	g	25.53	30.32	20.80	30.31	38.23	36.34	30.12	34.67	20.28	38.85
mass per fuel mass	g/kg	142.93	160.39	129.56	174.36	210.69	200.28	170.45	187.16	160.47	211.91
mass per fuel energy	g/MJ	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
mass per useful energy delivered	g/MJ	19.29	22.91	19.67	24.08	27.38	26.36	24.03	23.37	26.51	25.69
mass per time	g/min	0.85	1.01	0.69	1.01	1.27	1.21	1.00	1.16	0.68	1.30
CO2 temperature-corrected total mass	g	270.00	222.70	182.54	212.08	251.30	228.19	279.57	330.66	203.43	349.70
mass per fuel mass	g/kg	1511.73	1178.00	1136.98	1219.93	1384.97	1257.58	1582.18	1784.94	1610.03	1907.28
mass per fuel energy	g/MJ	0.05	0.04	0.04	0.04	0.05	0.04	0.06	0.06	0.06	0.07
mass per useful energy delivered	g/MJ	204.08	168.28	172.64	168.49	179.98	165.50	223.09	222.92	265.97	231.20
mass per time	g/min	9.00	7.42	6.08	7.07	8.38	7.61	9.32	11.02	6.78	11.66
		Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp	Inside temp	Outside temp
Surface temp. (deg C)		360.00	108.00	397.00	117.00	301.00	182.00	432.00	161.00	477.00	177.00

Appendix 3: Computation of various cook stove performance variables

Thermal Efficiency	Eq. (1): $TE = \frac{Q1}{BQnet.fuel - CQnet.char}\ x\ 100\%$ Where: *TE* is the cooking thermal efficiency with energy credit for remaining char, %; Eq. (2): *Q1* is the useful energy, $kJ = 4.18 \times G1(T2 - T1) + (G1 - G2)2260$ Where: *G1* is the initial mass of water in the cooking vessel, kg; *G2* is the final mass of water in the cooking vessel, kg; *T1* is the initial temperature of water in the cooking vessel,℃; *T2* is the temperature of the water in the cooking vessel,℃; *2260* is the latent heat of water vaporization at the boiling point, kJ kg^{-1}; *4.18* is the specific heat of water, kJ/ kg^{-1} $℃^{-1}$; *B* is the mass of the fuel, kg; *Qnet.fuel* is the lower heating value of fuel, kJ kg^{-1}; *C* is the mass of the remaining char, kg; *Qnet.char* is the lower heating value of remaining char, kJ kg^{-1}.
Fire-power	Eq. (3): $FP = \frac{BQnet.fuel - CQnet.char}{60\ x\ (t2 - t1)}$ Where: FP is the ratio of wood energy consumed by the stove per unit time, kW *t2* is the final time at end of test; *t1* is the initial time at beginning of test.
Cooking-power	Eq. (4): $P_c = \frac{Q1}{(t2 - t1)}$ Where: P_c is the cooking-power, kW
PM2.5 and CO Emissions per Energy Delivered to cooking pot	Eq. (5): $ER = \frac{Mi}{Q1}$ Where: *ER* is the pollutant emission per energy delivered, mg MJ_d^{-1} and g MJ_d^{-1} *Mi* is the total mass of pollutant emissions during the test, mg and g Eq. (6): $Mi = \frac{Qtunnel}{Qsample}\ x\ msample$ Where: *Qtunnel* is the volumetric flow rate of gas in the dilution tunnel, $m^3\ s^{-1}$; *Qsample* is the volumetric flow rate of gas in the sample stream, $m^3\ s^{-1}$; *msample* is mass of pollutant e.g. fine particulate matter collected on the filter, mg or g;
PM2.5 and CO Emission Rate	Eq. (7): $ER = \frac{Mi}{(t2 - t1)}$ Where: *ER* is the pollutant emission rate, mg s^{-1} and g s^{-1}

Appendix 4: Computation of t-statistic

To Test the null hypothesis that the means of the two cook stove are not different, the t-test statistic was computed as follows:

$$t = \frac{Difference\ between\ group\ (means)}{Normal\ variability\ within\ the\ group\ (or\ standard\ error\ SE)}$$

$$t = \frac{M_x - M_y}{SE}$$

$$t = \frac{M_x - M_y}{s\sqrt{(1/n_x - 1/n_y)}} \qquad (3.5)$$

Where M_x and M_y are the sample means of independent samples with equal variances,

SE = mean standard error

s = standard deviation

n = number of samples.

The computed t statistic (t_{stat}) was compared with the tabulated t critical (t_{crit}) shown by table 4.1. Where $t_{stat} > t_{crit}$, there's likely an actual difference. If not, the difference is "not significant."

Table 0.1: Abbreviated t table (2-tailed)

Degrees of freedom	Confidence level	
	0.95	0.99
2	4.303	9.925
3	3.182	5.841
4	2.776	4.604
5	2.571	4.032
8	2.306	3.355
10	2.228	3.169
20	2.086	2.845
50	2.009	2.678
100	1.984	2.626