Original Research Article

Improvement Of Ceramic Insulation Of Cook Stoves Using Carbonized Organic Waste

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 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.

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 33% and 25.8% for the control cook stove. The prototype and control cook stove cooking power were 0.97kW and 0.71kW respectively. 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

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.

Key words: Cook stove, thermal efficiency, carbonized organic waste, emissions, ceramic insulation

Abbreviations

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
CO	Carbon Monoxide
$PM_{2.5}$	Particulate Matter of up to 2.5 micrometer
mg/MJ_d	Milligrams per Mega joules dry weight
LEMS	Laboratory Emissions Measurement System

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 improvement of biomass cook stove started in 1980s with the development of the Kenya Ceramic Jiko (KCJ); an improved Kenyan cook stove. It is now widely produced locally by informal sector 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 of such brands 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. Improvement has focused on increasing 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.

KCJ 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 KCJ, 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 has high insulation properties 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 carbonizing machine, a technology available in the market and locally manufactured in Kenya Industrial Research and Development Institute (KIRDI). Char is also a byproduct of pyrolysis. 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 ceramic insulation 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. Low density thin materials are used for stove design to save on energy. 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]. Okina et al used sawdust on the insulation layer of the combustion chamber of an improved cook stove to increase thermal efficiency.[9]

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 improving 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 an insulation 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. [10]. 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. [11]

The most prominent cook stove used in Kenyan households is KCJ with ownership of the ordinary metallic charcoal stove estimated at 4.2 million. [12] Use of clay has been proven in improvement of efficiency in stoves. [13] Design modification of cook stoves while maintaining familiarity has been found to be a key factor in ensuring acceptability [14] hence the reason why KCJ was selected.

1.5 Scope

The project scope is limited to 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.

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. [15]

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. [16]

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. [17]

2.3 Improving thermal efficiency using organic waste

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

Sani and Nziou 2019 experimented the use of agro waste in improving thermal propertied of fired ceramics. Thermal properties were improved with addition of agro waste in the clay. [18]

Silva et al 2022 did a review on the use of organic and inorganic waste in production of porous ceramics. Rice husk, Banana leaves, Sawdust, Active yeast Coffee waste, Cherrie seed, Olive stone flour, Grape seed and wheat straw were some of the organic wastes reviewed. Low thermal conductivity due to increased porosity was achieved by addition of organic waste in ceramics. [19]

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. [20] 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. [16] In 2016, Fgaier did an experimental study which was focused on improving thermal properties of ceramics using flax shives and starch. Optimal thermal performance with good mechanical strength was achieved. [21]. 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. [22]

Bories in 2014 developed clay bricks using bagasse and urban sludge as pore forming agents. Low weigh and low thermal conductivity was achieved. [23] 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. [24] 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. [17]

3.0 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

We sourced clay in 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

We used the clean clay to mix 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 gasification cook 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, we added water to create plasticity for molding. For each mixture, we molded three samples 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.

Once dried, we measured the shrinkage lines. We fired the samples systematically up to 900^{0}C and left them to cool overnight inside the furnace.

3.4 Shrinkage, Porosity and bulk density

We measured the shrinkage lines on the samples before and after firing. It was in these measurements that we computed firing shrinkage. We evened the surfaces of the fired samples using a sand paper to a standard size of 9.1cm diameter and 3cm thickness Porosity and bulk density was determined using the water immersion porosimetry (WIP) technique (ASTM Standard C 373-88 (2006). Referring to the standard, we saturated the mixture samples in water by boiling them for 2 hours and cooled thereafter for 12 hours after which we weighed and the pore volume was 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.

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

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

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, we adopted the following procedure. We made an opening of diameter 9.1cm through the door of a furnace and placed the samples 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. We set the furnace temperature at 500 ^{o}C. After every 5 min, we monitored and recorded the temperature of the outside surface of the samples 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.

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

Where (λ) is thermal conductivity of the material, which can be expressed as

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

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

We determined the compressive strength (kN/cm^2 or MPa) 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.

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

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 we fabricated a prototype. A standard KCJ cook stove cladding material were acquired. A clay molding tool was designed using the shrinkage factor of 1.1. The molding tool was then made using wood panels as shown in figure 1. Clay and charcoal dust were mixed according to selected ratio and molded 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 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 2.

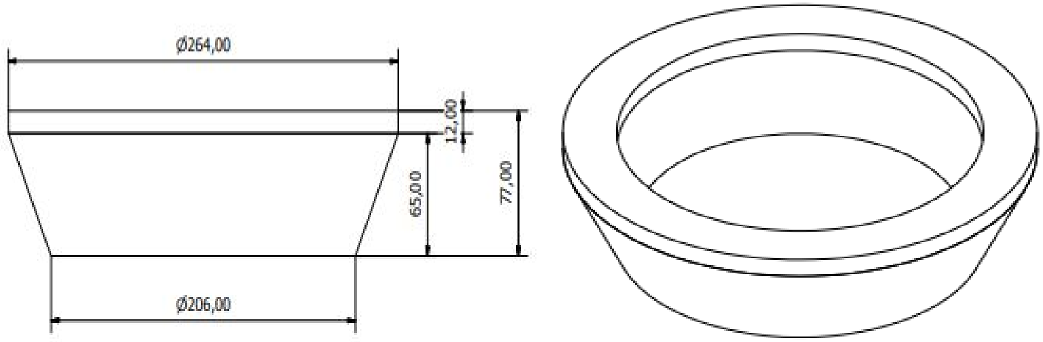

Figure 1: mould

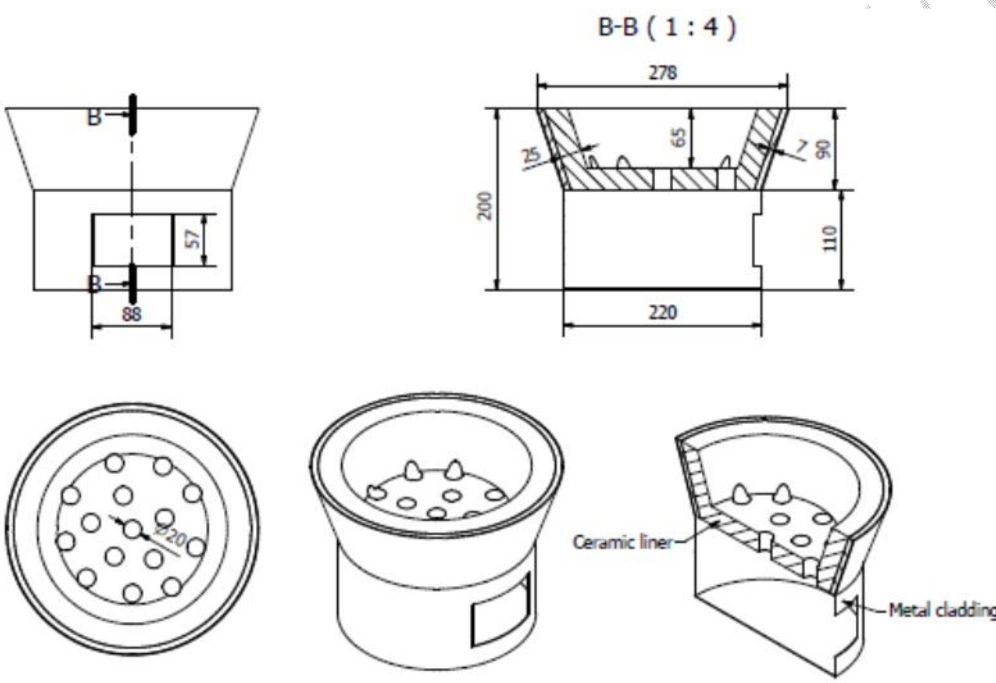

Figure 2: Dimensions of the prototype charcoal cook stove

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

We tested the assembled prototype cook stove 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 2. The procedure for testing included using 410g of charcoal with a known calorific value to heat 5kg of water for 35 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.

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. 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

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 1. Shrinkage along the thickness was not noticeable.

Table 1: Shrinkage of samples after drying and firing

% char dust in samples	Shrinkage line size			% shrinkage			
	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

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 2 shows the results of porosity and bulk density

Table 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 3 and 4 shows graphical presentation of porosity and bulk density respectively.

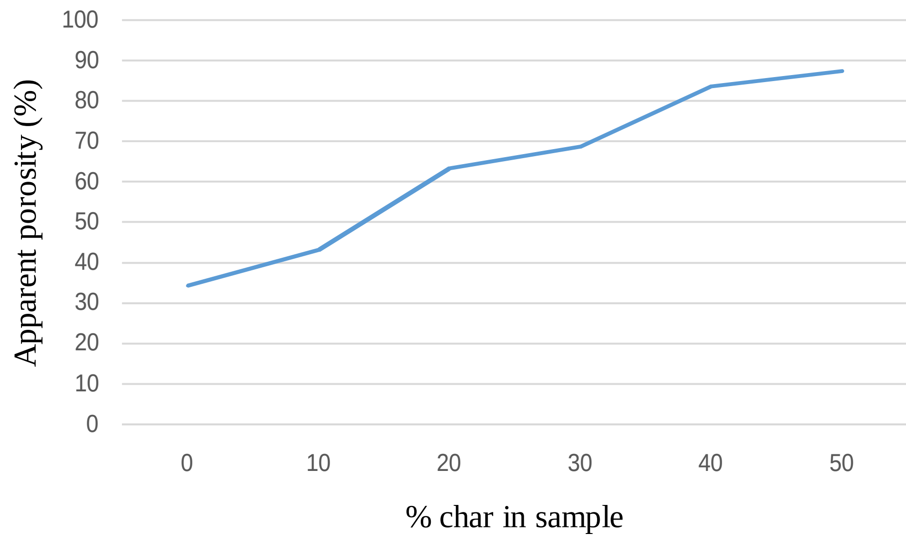

Figure 3: Samples apparent porosity

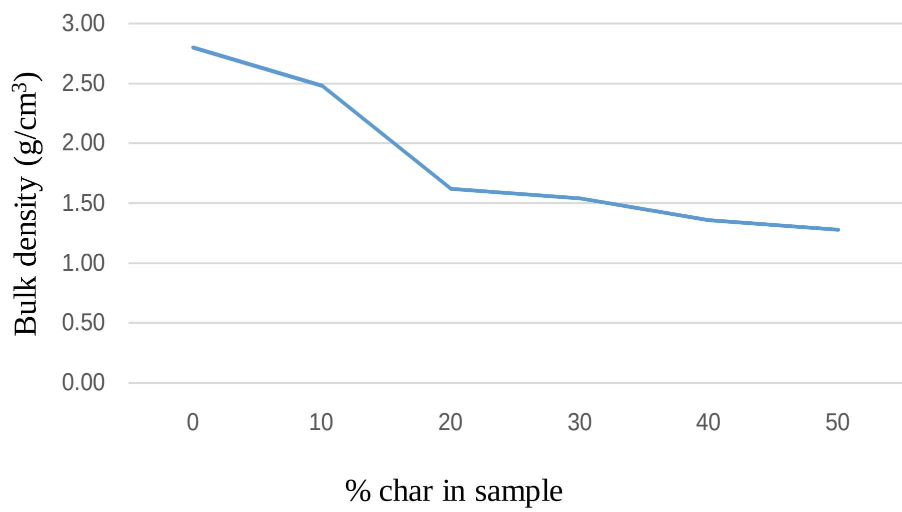

Figure 4: Samples bulk density

Figure 3 shows that porosity increased as the proportion of char in the sample increased, while Figure 4 shows that bulk density decreased as the proportion of char in sample increased.

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

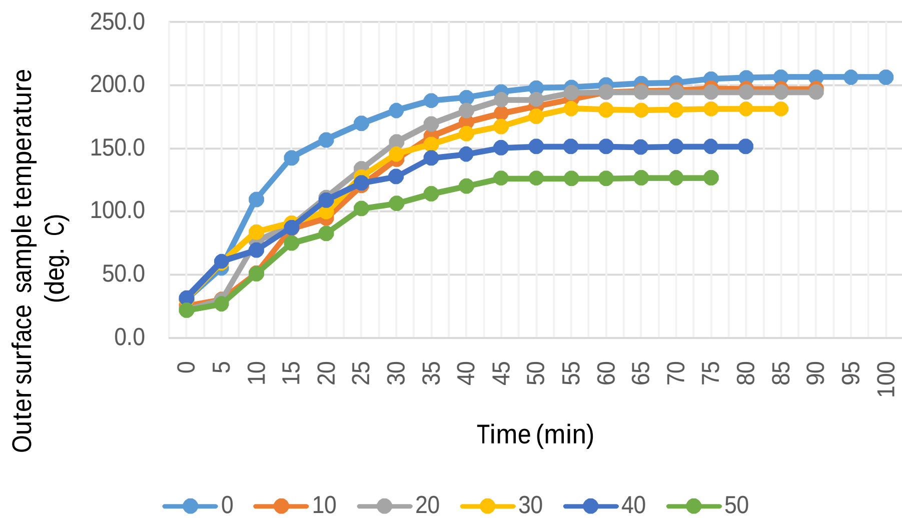

Figure 5: Variation of outer sample surface temperature with time

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 3.

Table 3: temperature profiles after 65 min

% char dust in samples	Inside furnace set temperature (°C)	Outer surface sample temperatures (°C)			AVG	STDEV	Temperature gradient i.e. ΔT (°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)

Table 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) ($cm/(^oC \times cm^2)$)	Relative thermal conductivity λ
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

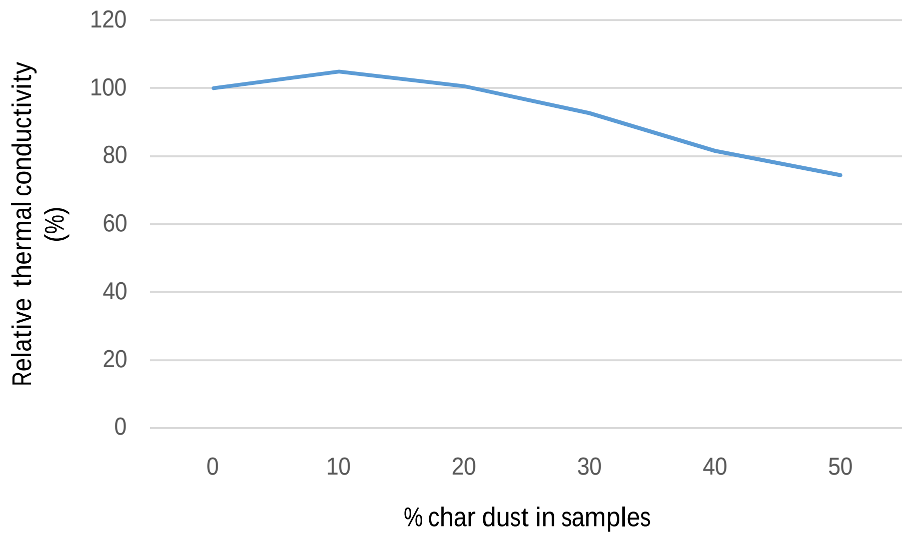

Figure 6: Thermal conductivity of samples versus the % of char

Samples with a higher proportion of char showed lower steady state outer surface temperatures (figure 6). Table 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 and Figure 6

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 5 shows the maximum loads the samples and the calculated compression strengths

Table 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

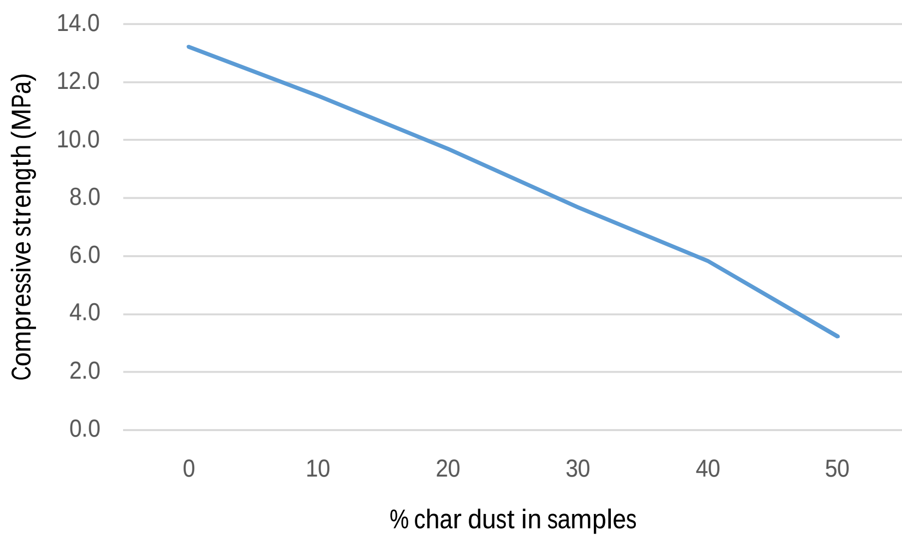

Figure 7: Variation of compressive strength among samples

Samples with a higher proportion of char showed a lower compressive strength as shown by Table 5 and Figure 7. The higher the amount of char, the lower the compression strength.

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.

a. 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 6.

Table 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 6. The prototype had a significant increase in water temperature compared to the control cook stove for the test period of 35 minutes.

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

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 a reduction in both thermal conductivity and bulk density to increase cook stove efficiency

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.

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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