INVESTIGATION OF MECHANICAL AND COMBUSTION CHARACTERISTICS OF CASHEW NUT AND MANGO SEED SHELLS COMPOSITE BRIQUETTES

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A thesis submitted to the Graduate School in partial fulfilment of the requirements of Master of Science Degree in Engineering Systems and Management of Egerton University

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DECLARATION AND RECOMMENDATION

DECLARATION

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

Huko Dickens Owino - BM12/2045/08

Signature……………………………………Date…………………………………………

RECOMMENDATION

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

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Department of Mechanical and Mechatronic Engineering,
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DEDICATION

To my late father, Jorim and mums Lorna and Sarah; My wife Elizabeth and children.

Special dedication to my late daughter Sarah Atieno Huko.

ACKNOWLEDGMENT

I'm thankful to GOD Almighty who granted me life and good health to be able to do this course and the research work. Thanks to Egerton University for registering me as a graduate school student and allowing me access and use of their facilities. To my supervisors, Dr David Kamau and Prof. Wilson Ogola their guidance and professional input played a big role in shaping this research work. Their concern, appreciation and encouragement enabled me to become a professional. They have been exemplary mentors and I thank them for guidance and insight in my project. I thank the Management and staff of Kenya Bureau of Standards both in the chemical and material testing laboratories for allowing me use of their facilities to carry out my experiments and tests. I would like to thank my class mates of for the helpful discussions and comments.

ABSTRACT

The ever increasing world energy demand, with over dependency on fossil fuel is hampered by adverse environmental effects due to global warming resulting from carbon dioxide emitted during combustion. Majority of Kenyans rely on biomass, whose sustainability is faced with diminishing forest cover, currently at 1.7 %. Hence, there is need to search for alternative environmentally friendly and accessible sources. Availability of mango seed and cashew nut shells, currently considered of no economic value, may be an option for alternative fuel. Although studies have been done on the mechanical and combustion characteristics of varieties of biomass, there is little information on composite briquette produced from the cashew nut and mango seed shells. This study focused on mechanical and combustion characteristics of cashew nut and mango seed shells composite briquette. Cashew nut and mango seed shells were collected, dried, hammer milled, carbonized in muffle furnace at 400^{o}C for 5 mins and cooled. The carbonized shell fines were mixed at varying ratios and particle sizes and bonded with banana peels before compacting at different pressures. Resulting composite briquettes were dried and mechanical and combustion characteristics determined. Density of the briquettes varied from 381.3 Kg/m^3, to 763.45 Kg/m^3 at the mango: cashew nut shell ratios 5:0, 4:1, 3:2, 2.5:2.5, 2:3, 1:4, 0:5. Moisture content, ash content and calorific value increased from 7.30 %, 5.28 % 16.47 MJ/kg to 11.27 %, 10.37 % and 26.61 MJ/kg respectively as the cashew nut fines in the mix ratios was increased. Durability index, compressive strength and carbon monoxide rose from 95.59 %, 7.44 KN/m^{2,}, 1.80 ppm to 99.1 % , 7.89 KN/m^2 and 5.96 ppm respectively. As the particle sizes increased from 3mm to 11mm, the density, moisture, ash content reduced from 729.08 Kg/m^3, 7.56 %, 5.94 % to 492.41Kg/m^3, 6.88 %, 5.93 % respectively but no significant effect on calorific value. Durability index, compressive strength and carbon monoxide reduced significantly with change in particle sizes from 98.41 %, 7.75 KN/m^2 and 5.64 ppm to 95.52 % , 6.37 KN/m^2 and 5.21 ppm respectively. As the compaction pressure increased from 5 MPa to 11 MPa, the briquette density changed from 492.41Kg/m^3 to 729.08 Kg/m^3 but no significant reduction of ash content from 5.94 % to 5.92 %. Calorific value, Carbon Monoxide and durability index increased from 21.60 MJ/kg, 5.21 ppm, 97.14 % to 25.74 MJ/kg, 5.64 ppm and 98.87 % respectively which could be attributed to increased bonding of particles at higher pressure. The resulting briquettes had similar mechanical and combustion characteristics to wood and charcoal, hence could serve as alternative source of energy.

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ACRONYMS

ASAE	American Society of Automotive Engineering
ASABE	American Society of Agricultural and Biological Engineers
ASTMI	American Society for Testing and Materials International
ANOVA	Analysis of Variance
CNS	Cashew Nut Shell
d.b.	dry basis
Ha	hectares
HDC	Horticultural Development Corporation
JICA	Japan International Cooperation Agency
KEBS	Kenya Bureau of Standards
KNBS	Kenya National Bureau of Statistics
LPG	Liquefied Petroleum Gas
LSD	Least Significant Difference
MPa	Mega Pascal
MSS	Mango Seed Shell
Mtoe	Million tons of oil equivalents
NAAQS	National Ambient Air Quality Standards
UNEP	United Nations Environmental Program
UN	United Nations
w.b.	Wet basis
SAS	Statistical Analysis Software
FAO	Food And Agricultural Organization
WHO	World Health Organization
OSHA	Occupational Safety and Health Act

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Biomass is the third largest global energy resource after oil and coal (Banpast *et al*, 1997). Its usage declined in the last 50 years due to increased usage of oil, but still provides 1250 million tons of oil equivalent (Mtoe) which constitute approximately 14 % of the world's annual energy consumption (Purohit *et al*, 2006). Biomass is considered a clean development mechanism for reducing greenhouse gases emissions (Li and Hu, 2003). Waste from wood and agro processing units are considered as relatively cheap source but the supply is limited. Countries that previously depended on nuclear energy are scaling down its use.

Sweden is scaling down nuclear energy production and oil usage while increasing biomass production for energy (Bjorheden, 2006). According to Sokhansanj and Fenton, (2006) and Mitchell *et al*, (2007) density of biomass ranges from 60-80 kg/m^3 for straws and grasses while that of woody biomass (wood and chips) is between 200-400 kg/m^3. They further reported that about 50 % world population, mostly from low income households in Africa, Asia and South America use woody biomass. The high cost of liquified petroleum gas (LPG) force most of these households to harvest wood from forests for use as firewood or charcoal, destroying the forest cover resulting in negative impact on environment and climate change (Mitchel *et al*, 2007). By compacting biomass, high density and energy concentrated solid material known as briquettes are produced which can supplement existing energy sources.

Close to 70 % of known as electricity supply in Kenya is hydro based. By June, 2014 approximately 2.6 million Kenyans had been connected to electricity supply benefitting about 20 % of 38.6 million Kenyan population (KNBS, 2009), leaving the rest of the population to seek alternative sources of energy. Similarly, wood accounts to about 70 % of total energy consumption in Kenya, benefitting 80 % of Kenyan population. It serves 90 % of rural households and 85 % of urban households (Mugo and Kituyi, 2002). About 47 % of Kenyan households use charcoal of which 82 % and 34 % are urban households and rural households respectively (UNEP, 2006). The total amount of charcoal produced from the forests annually stands at 2.4 million tones but with the current forest cover of 1.7 % (below the target of 10 %) there is need to search for sustainable energy sources (Mugo and Kituyi, 2002).

Densification of agricultural residue is one way of upgrading combustion and mechanical characteristics. Through briquetting of agricultural residues, the produced briquettes will supplement existing energy sources hence reduce the pressure on wood based biomass in the country. It is projected that with usage of improved energy conversion technologies, a reduction of 36.6 giga tones/yr of carbon dioxide ($CO_{2)}$ and conservation of 76,000 ha of woodlands will be realized by 2030. About 8.1 million tons of woody biomass, the equivalent of firewood and charcoal used per year will be saved in the same period (UNEP, 2006).

Studies that have been done on various low energy content agro residues molded into solid briquettes show that the resulting energy contents ranged between 14 to 16 kJ/kg and this was found to be influenced by process and material parameters such as moisture content, carbonization temperature and the composition of original materials (Sokhansanj and Fenton, 2006). According to a study by Chirchir *et al* (2013) energy content of carbonized saw dust, charcoal and wood pellets approximated to about 32 MJ/kg. Chichir *et al,* (2013) studied the use of molasses, cow dung and clay as binder and noted that physical and combustion characteristics are affected by the type of binder but little information exists on the use of banana as a binder despite of its availability.

Biomass waste briquettes have energy outputs similar to those from traditional fuels providing cheap method of converting agricultural residues into energy. This study produced briquettes at varying mix ratios of cashew nut shell and mango seed shell and their determined combustion and mechanical properties. It is anticipated that the resulting briquettes would supplement traditional fuels and save environmental degradation brought about by both deforestation and pollutants emission from combusting fossil fuels.

1.2 Statement of the Problem

Majority of Kenyan population rely on wood biomass as their source of energy, but with the increasing energy demand, the 1.7 % forest cover will not be able to sustain the wood biomass demand. There is therefore need to search for alternative sources of energy which would be sustainable. Conventional energy is not affordable to the larger Kenyan population. Previous research carried out on biomass fuels has little information on the optimum condition regarding mix ratios, particle size and compaction pressure if cashew nut shells and mango seed shells are briquetted using banana peels as binder.

1.3 Objectives

1.3.1 General objective

The main objective of this research was to determine the mechanical and combustion characteristics of cashew nut shells (CNS) and mango seed shells (MSS) composite briquettes bonded using banana peels.

1.3.2 Specific objectives

The specific objectives of this study were:

i. To determine the effect of varying MSS and CNS mix ratios on mechanical and combustion characteristics of the composite briquettes.
ii. To determine the effect of varying MSS and CNS particle sizes on mechanical and combustion characteristics of the composite briquettes.
iii. To determine the effect of varying compaction pressures on mechanical and combustion characteristics of the composite briquettes.

1.4 Research questions

i) How does varying MSS and CNS mixture ratio affect mechanical and combustion characteristics of the composite briquettes?

ii) How does varying MSS and CNS particle size affect mechanical and combustion characteristics of the composite briquettes?

iii) How does varying compaction pressure affect mechanical and combustion characteristics of the composite briquettes?

1.5 Justification of the study

Fossil fuel has been associated with increasing global warming hence there is need for alternative fuel which is environmentally friendly. The availability of agricultural residues such as cashew nut shells and mango seed shell present a feasible fuel option that can be developed through the process of briquetting. If briquettes can be produced from cashew nut shells and mango seed shells they would supplement the traditional sources of energy hence reduce pressure on already diminished forest cover. Other benefits of this alternative fuel include improved economy for the local population through the sales of shells, ease of transportation, and better utilization of wastes as well as cleaning the environment. The local population will also enhance planting of more cashew nut and mango trees and improve production of the mango fruit and the nuts.

1.6 Scope of the study

The study focused on mechanical and combustion characteristics of cashew nut shells and mango seed shells composite briquettes produced under the following conditions: The mould was a cylinder diameter 50 mm and length 100 mm. The particle size ranges were varied at 3 mm, 5 mm, 7 mm, 9 mm, 11mm while the compaction pressures values were 3 MPa, 5 MPa, 7 MPa, 9 MPa.11MPa. The values picked were for convenience of conducting the experiments and represented small and large particles for mix sizes while those for compacting pressures represented low medium and high for the material that was being tested. Five samples were made for each particle size and compaction pressure.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Global energy situation

The World has heavily relied on use of fossil fuel for energy with the figure rising to 86 % total energy production (El Saeidy, 2004; Kaliyan and Morey, 2009). Many countries have relied on raw coal to fuel industries and generate power, but without exploiting efficient use of agro and forest wastes. Both raw coal and biomass emit sulphur dioxide (SO_2) and nitric oxide (NO_X) with consequences of acid rain, global warming and climate change (Kim *et al*, 2002). Studies show that SO_2 and NO_X emissions cause respiratory and lung diseases to human (Tuladhar *et al,* 2002). The UN World Conference in Copenhagen, Denmark in December, 2009 discussed mitigation efforts against global warming (Oladeji and Lucas 2011). The proceedings from this conference created new thinking on alternative renewable energy forms to reverse global warming effects. Nearly half the world population live in energy deficient households in remote urban set ups and have traditionally relied on wood and charcoal for domestic cooking and heating needs. This trend has caused massive destruction of forest cover, with soil erosion, reduced farm fertility, environmental degradation and ground water contamination. In Kenya, the forest cover has gone down to less than 10 % land area currently from close to 30 % 40 years ago, with devastating effects on climate change and severe food insecurity (Kaliyan and Morey, 2009).

A lot of research work has been done on use of agro wastes and related residues for production of alternative fuel sources. Before this focus, a lot of such wastes were contributing to huge piles of solid wastes that ended up in open dumps, causing massive environmental hazards both to human health and environmental impacts from (GHG) emissions. Agricultural biomass can be used as feedstock for producing biofuel, but the residues have to be gathered, processed and densified, Adapa, 2009). Extensive wood fuel use cause deforestation, soil erosion, ground water contamination, floods and landslides. In 1992-95, Nepalese developed briquettes using local coal, lignite and various waste biomass using high pressure compression technology (Singh *et al,* 1996). Varied residual mass up to 30% proportion by mass of biomass, was blended with low grade coal to get briquettes, which were tested as cooking fuel, with results similar to wood fuel or animal dung and comparable to liquefied petroleum gas (LPG) (Singh *et al,* 2001). In Nigeria, a study was conducted to compare the performance of blended saw dust briquettes of *albiziazygia* against the traditional wood fuels from similar trees, having noted that wood accounted to 51% total energy consumption of the country (Aina *et al*, 2009). The results are shown in Table 2.1.

Table 2.1 Combustion characteristics of blended sawdust briquettes

Properties	100% *Albiziazygia* briquettes	100% solid wood
Moisture content (%)	7.1	23.76
Heat value (kcal/kg)	4.723	4.014

(Source: Aina *et al*., 2009)

From these results it can be concluded that it is possible to produce briquettes with higher calorific value from saw dust of *albiziazygia* tree. According to the same study, demand for fuel wood in Nigeria was expected to rise to 213.4 million metric tons by the year 2030 (Adegbulugbe and Oladosu 1994) which must be reversed in order to save Nigeria's forest cover. Compared to wood based biomass, briquettes take less space for storage and are easy to transport (Olorunnisola, 2004).

2.2 Typical biomass resources

Some of the available biomass includes forest, agricultural waste, straw, peat, bagasse, wood processing waste, waste water and landfill (Susta and Sohif 2003). The typical characteristics of some biomass fuels are summarized in Table 2.2.

Table 2.2 Combustion characteristics of biomass fuel

Type of biomass	Moisture content (%)	Ash content (%)	Volatile matter (%)	calorific value MJ/kg
Charcoal	2-10	2.5	5-30	25.0
Wood	20-40	0.1 – 1.0	70-80	20
Rice husk	3-5	15-25	60	15
Coconut shells	25	0.8	79	20

(Source: Susta and Sohif, 2003)

2.2.1 Cashew nut and Mango farming in Kenya

Cashew nut farming is currently spread over Kwale, Kilifi, Malindi and Lamu within the Coastal strip of Kenya and is estimated to cover 30,921 hectares, producing approximately 60,000 tonnes nuts per year (Mrabu and Muniu 2001). According to (Das *et al*, 2004) Cashew Nut Shell is estimated to give a gross calorific value of 4.252 MJ/kg of energy when burned. Kenya has a potential to produce 200,000 tons of cashew nut per year (Mwangi *et al*, 2013).Cashew nut production in Kenya fell from 36,000 ha to 27,000 ha crop area in 1980 and 2006 respectively (Kithi,2006).

Table 2.3 Mango production 2011/2013 by County

	2011			2012			2013			%
county	Area Ha	Quantity MT	Value (Mill Sh.)	area	Quantity MT	Value (Mill Sh.)	Area (Ha)	Quantity MT	Value (Mill Sh.)	Share By value
Kwale	2136	43196	431	2636	52574	525	4135	91390	1365	18.3
Kilifi	5727	98309	983	5729	101655	1017	5793	106269	1093	14.7
Migori	1722	23888	532	1874	26055	645	2061	28898	741	9.9
Machakos	4520	41532	520	4825	54329	630	5133	51546	624	8.4
Meru	4097	45371	459	4176	46010	460	4135	48432	484	6.5
Makueni	9224	40038	361	10237	44482	398	10632	48494	473	6.3
Bungoma	919	17813	229	1155	22370	319	1258	24391	410	5.5
Embu	1857	9171	75	3290	27388	202	3605	39588	357	4.8
Tana River	1133	18540	185	1211	22054	242	1276	23204	256	3.4
Lamu	2158	31778	318	2187	32466	325	2189	24440	245	3.3
others	5874	83308	1205	6457	91049	1414	6764	94638	1409	18.9
total	**39367**	**452944**	**5298**	**43777**	**520432**	**6177**	**46980**	**581290**	**7459**	**100**

(Source HDC, 2013)

581,290 tons mango fruit was produced in Kenya in 2013, up from 452,944 tons in 2011. Coast region produced 245,303tons in 2013. Mango shell contains a tough inedible part which can’t be used as animal feed or as fertilizer. The shell is also known as endocarp and is rich in lignin which is associated with high energy content when heated (Mrabu and Muniu, 2001).

2.3 Biomass combustion

During photo synthesis, the plant (biomass) receives light energy from the sun which is stored. When biomass is combusted, the stored energy is released with byproducts of water and carbon dioxide. Combustion is a complex and rapid spontaneous chemical reaction which releases energy through an oxidation (reduction) process. The reaction mainly involves carbon and hydrogen elements of the fuels, the reducers and oxygen from the atmosphere. Biomass is combusted to transform the chemical latent heat of the reactants that is referred to as heating value into sensible heat. Some of the ways of this heat transformation involves direct radiation to the walls of the combustion chamber, convection using the reaction products as a heat carrier, and direct conversion into mechanical work during thermodynamic process. Today, biomass combustion is important aspect of environmental management as it plays a key role in controlling CO_2 gas emissions in the atmosphere (Demirbas and Sahin, 2004). Figure 2.1 shows combustion cycle

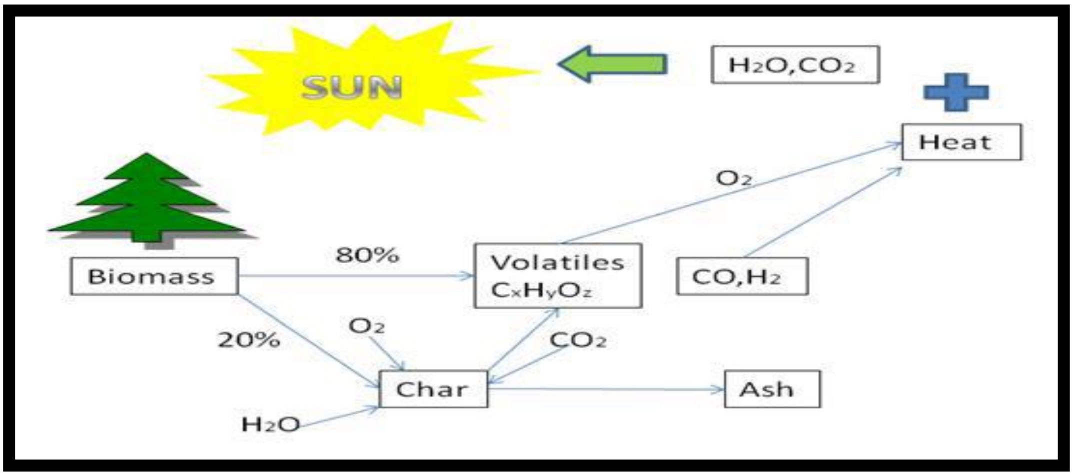

Fig. 2.1 Biomass combustion cycle (Ralph, 2003)

2.4 Methods of densifying biomass

There are various methods employed in biomass densification that include, bailing, pelletization, extrusion and briquetting. The use of bailer, pelletizer, screw, piston or roller presses technologies in densification have been extensively employed. Pelletization and briquetting are the most preferred for solid fuel applications. These two systems apply pressure in compaction and use either piston or screw press (Sokhansanj *et al*, 2006)

2.4.1 Briquetting machines

Briquetting is usually done by hydraulic, mechanical or roller presses. Density of produced briquettes ranges between 900-1300 kg/m^3 (Sokhansanj *et al*, 2006). As opposed to pellet mills, briquetting machines can handle larger particles sizes with wider moisture contents without adding binders. Briquetting can also be done by a simple hand operated wood press. Compressions are done at high pressure and temperatures causing the material to self-bond by thermoplastic flow and form briquettes. Lignin, which is a natural binder, is availed during the thermoplastic flow allowing formation of high density briquettes.

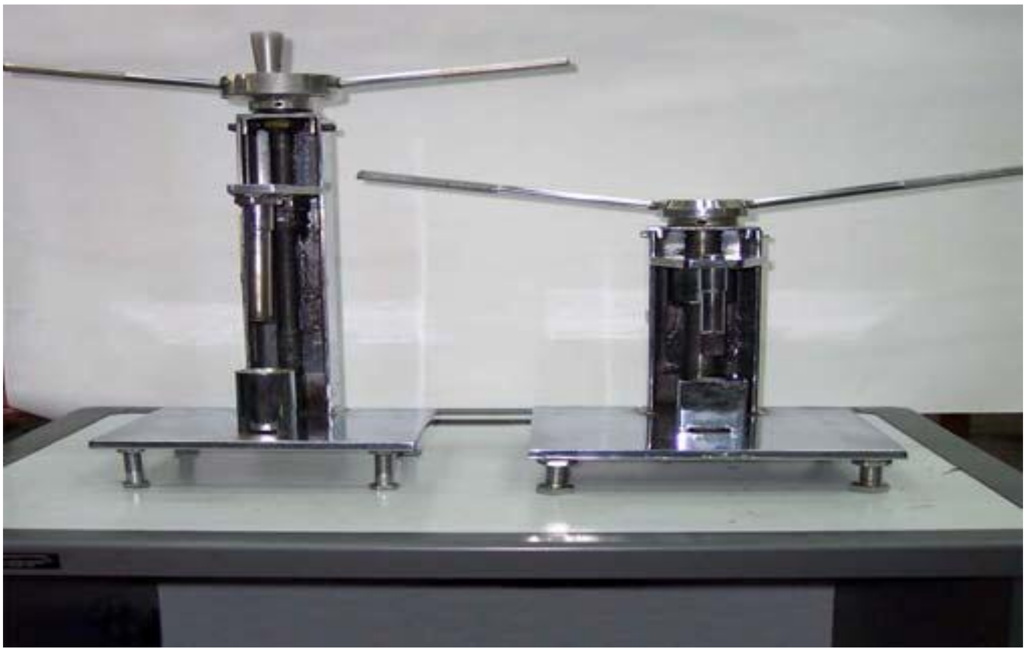

Plate 2.1 manual briquette machine (Source: Saptoadi, 2008)

From Plate 2.1 the upper wheel is turned clockwise, pushing the piston down to gradually compress the materials in the mould until a certain level of briquette compactness is achieved. It was established that briquette porosities are determined by particle sizes; similarly density increases with reduction in particle size while porosity increases with increase in particle size (Saptoadi, 2008). The density recorded ranged from 492.1 - 941.2 kg/m^3. Coarser rice husks briquettes were noted to expand more significantly shortly after being released from the machine (Saptoadi, 2008).

2.5 Densification system variables

The characteristics of densified briquette depend on process variables (die temperature, pressure, and geometry), feedstock variables (moisture content, particle size and shape) and material composition such as protein, cellulose, hemi celluloses and lignin. These are discussed in sub sections below.

2.5.1 Process variable

a) Pressure

Briquetting pressure has effect on the properties of briquettes. The density of chopped alfalfa pellets was found to vary proportionately with natural logarithm of applied pressure and also raising the pressure significantly raised the density (Butler and Mc Colly, 1959). It was however noted in another study that an optimum pressure exists beyond which fractures may occur in the briquette due to sudden dilation (Ndiema *et al,* 2002).

b) Retention time

It was found that briquette properties are also influenced by the length of time the materials are retained in the die. However, some studies also noted that certain levels of retention time (5-20s) had no significant effect on the quality, durability and stability; for oak saw dust briquettes at higher pressures (over 138 MPa) as compared to lower pressure (Al-Widyan *et al,* 2002). It was similarly observed that hold time also had little effect on briquette expansion rate. Hold time of about 10s could give about 5 % rise in log density while hold times above 20s had insignificant effect.

c) Relaxation time

Relaxation time influences the density of briquette materials. Final relaxed density of briquette and relaxation duration after the briquette is removed from the die depends on several factors notably: Die geometry, mode and level of compression, type and properties of feed material and storage condition. Studies have shown that upon removal from the die, after a high pressure compaction, the density of the briquette reduces with time to a relaxed density. For most materials the expansion rate is highest just after the removal from the die and reduces with time thereafter until a constant volume is attained (Carre *et al,* 1987). Relaxation characteristics are measured by percent increase in elongation. Increase in voidance depends on factors such as feed material and storage conditions such as relative humidity (Wamukonya and Jenkins, 1995. These authors established a multiple correlation equation as shown in 2.1

$$\mathrm{Y} = \alpha_0 + \alpha_1 \mathrm{P} + \alpha_2 t \qquad 2.1$$

Where Y is percent volume expansion

t is die temperature (℃),

P is die pressure (kg/m^3)

α_0, α_1 and α_2 are constants.

d) Die geometry and speed

Geometry refers to size and shape of die. Die geometry affects the properties of briquettes such as moisture content, density and durability. Rise in briquetting pressure increases the briquette length. Durability of briquettes was noted at smaller die (Tabil and

Sokhansanj, 1996). Die barrel temperature and screw speed significantly affected briquette density and hardness (Shankar *et al*, 2005). Ratio of length to diameter of the die and screw speed significantly affected the flow rate of mixtures during briquetting hence affect the resulting properties of briquettes (Shankar *et al,* 2008).

2.5.2 Feedstock variables

This includes moisture content, particle size, shape and distribution which are discussed in subsequent sub topic.

a) Moisture content

Moisture facilitates starch gelatinization, protein denaturization and fibre stabilization when densifying briquettes. Moisture is observed to increase the bonding via van der Waal's forces hence raising the contact area of the particle (Mani *et al*, 2006). A study by Li and Liu (2000) found that moisture content of about 5-10 % resulted in denser, more stable and durable briquette as opposed to those with higher moisture contents of about 15% and above. An optimum moisture content of about 8% was recommended for high density briquettes (Li and Liu, 2000),who also noted that under 4% moisture content created fragility of the pellets or briquettes within a few days due to absorption of moisture from the atmosphere. Li and Liu further recommended 5-12 % moisture content for production of good quality logs in terms of density and longtime storage properties from hardwood, softwood and bark, and further concluded that briquetting cellulosic material needs 8-12 % as optimum moisture content while those with starch and protein (mostly animal feed) need up to 20 % moisture content (Sokhansanj *et al*,2005) Mani *et al*,(2006) found that for moisture content at the range of 28-44 % (w.b), the briquettes density decreased with increase in moisture content. Kaliyan and Morey (2006) observed that for moisture content ranging between 6-25 % (w.b) the bulk density of compacted plant residues reduced with increase in moisture content.

b) Particle size, shape and distribution

Studies have shown that briquette density and durability is inversely proportional to particle size. It was also noted that straws with finer grind size produced denser and compact briquettes (Kaliyan and Morey, 2009). It was noted that low porosity in briquettes are attributed larger particle size which tend to hinder mass transfer: drying, devolatisation, and char burning during combustion process. This is caused by fewer free spaces for mass diffusion: water vapour, volatile matter, carbon dioxide outflows and simultaneous oxygen infiltration. Large particle size briquettes, burn for a period of 19.25 minutes while those from fine particles take up to 28 minutes. Also coarser material briquettes leave 16% unburned carbon while those made of finer particles leave 33% unburned carbon at the termination of combustion (Demirbas and Sahin 1998).

2.5.3 Feed composition

Chemical and biological composition of biomass provides better understanding in compositional changes that occur due to reactions in the densification process. Raw biomass has low molecular weight and macromolecular compositions which include substances such as cellulose, hemicelluloses and lignin (Mohan *et al*, 2006*)*. Starch, sugar, non-starch polysaccharides (NSP), fat, fiber, inorganic matter and water were found to influence densified biomass characteristics (Thomas *et al,* 1998).

a) Starch

Starch is a D - glucose polymer and has branched (amylopectin) or un branched (amylase) chains (Collado and Corke, 2003). Starch undergoes gelatinization at high processing temperature. Starch granules at high temperature and moisture content influence the texture of many foods and feeds (Shankar and Bandyopathyay, 2006). According to Collado and Corke (2003), starch acts as lubricating agent and facilitates smooth flow of materials during briquetting process.

b) Protein

During biomass densification process, the protein is heated and denaturizes, forming new bonds and structures with other proteins, lipids and starch available in the biomass, and improves the binding capacity (Thomas *et al*, 1998; Nyanzi and Maga, 1992).

c) Cellulose

This is tough; water insoluble substance found in plant cell walls, more so in stalks, stems, trunks and woody portions of the plant body and is considered to be the major source of carbon in biomass (Nelson and Cox, 2005). When wood material is hot pressed, the binding strength of wood based product cellulose is converted to an amorphous state and hence acts as binding agent (Zandersons *et al*, 2004).

d) Hemicelluloses

These are a combination of many sugars other than glucose (hetero saccharides) are also found in the cell walls. Their branching nature is the cause for their amorphous structure, and is more easily hydrolyzed or can be dissolved in alkali solution. It is believed that their adhesive degradation products may cause natural binding (Nyanzi and Maga, 1992).

e) Lignin

This is a random network polymer with various linkages based on phenyl propane units (Andersons and Akin 2008). Its molecule in plant is multi tasked and can act like glue to the cellulose fibres. Its presence allows briquetting without adding any binder. It has been found to show thermosetting properties at working temperatures above 140°C (Van Dam *et al*, 2004). Briquettes made from lignocellulose materials owe their strength to adhesive properties of thermally softened lignin (Granada *et al*, 2002).

f) Use of binders for densification of biomass

Binders possess the following properties that qualify their use as additives in briquetting: lubrication for wear reduction on production equipment, abrasion resistance of the fuel, adhesion for improving binding of the materials and toughness of the material textures hence product durability.

2.6 Characteristics of briquettes

2.6.1 Determination of density

The density of briquettes is determined immediately it is removed from the mold by equation below:

$$\rho = \frac{\text{mass of briquette}}{\text{volume of briquette}} \qquad 2.2$$

The mass of the briquette can be determined by weighing the sample in digital weighing scale while the volume can be evaluated through linear measurement of the diameter and height of the briquette. The volume is then calculated. The ratio of mass to volume gives the density.

2.6.2 Proximate analysis

The proximate analysis of solid fuel can be determined by using standard procedures, Solid fuel comprises of moisture content, ash content, volatile matter and fixed carbon which sum up to 100 %. The volatile matter, ash content and fixed carbon are determined using ASTM standard D 5373-02 (2003).

2.6.3 Flame propagation rate

Flame propagation rate was highlighted by Musa, (2007) where a piece of oven dried briquette is graduated. It is then ignited and burnt using a Bunsen burner in laboratory condition. Flame propagation time is calculated as;

$$\text{Flame Propagation rate (cm/sec)} = \frac{\text{distance (cm) burned}}{\text{time taken (seconds)}} \qquad 2.3$$

2.7 Effect of material characteristics on briquettes performance

Chirchir *et al*, (2013) found that varying binder types and ratios and particle sizes gave varying physical and combustion properties of composite rice husk and bagasse briquettes. Novakova and Brozek (2008) studied the effect of varying material compositions and binders on density and compressive strength as shown in Figure 2.2. Direct correlation was noted between the density of briquettes and compressive strength though sample condition also had influence. From fig.2.2 Sample no. 15 recorded the highest compressive strength; no. 14 recorded the least compressive strength. The densities obtained were averagely above 1000 kg/m^3, but ranged 900-1400 kg/m^3 which compares with the ASTM D5373-02, 2003 standard.

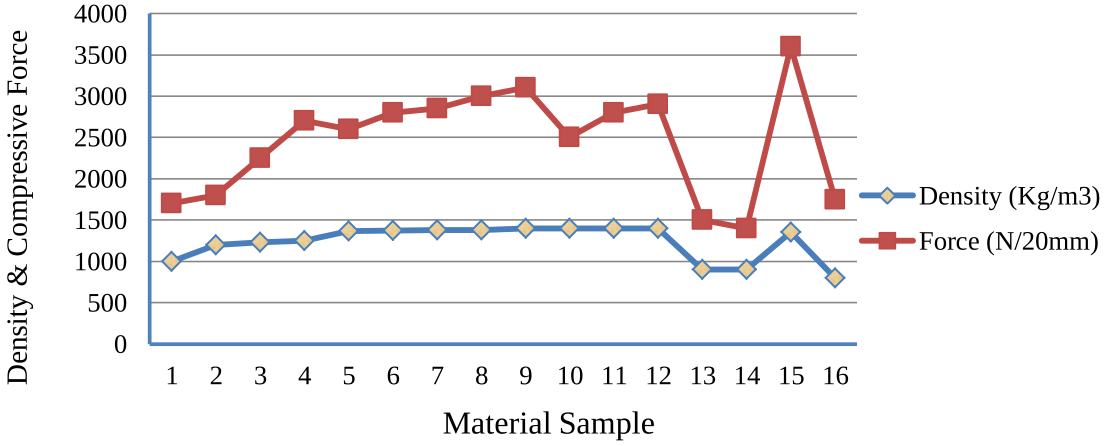

Fig. 2.2 Material composition vs. density and compressive strength of briquette

Source: (Novakova and Brozek, (2008)

Itodo *et al*, (2011) studied combustion characteristics of saw dust and coal dust blend briquettes and found that the blended briquettes took 26 minutes to boil 2 liters of water while the pure saw dust briquette took 30 minutes. Coal char – saw dust briquette reduced moisture content of briquettes and raised the ash content (3.14% to 13.98%) and shear stress (76.0 to 265KN/m^2), raising the residence time for combustibility. Oladeji and Lucas (2011) studied the physical and combustion of corn cob and rice husks and obtained results for the characteristics for both, as shown in Table 2.4

Table 2.4 Physical and Combustion properties of corn cob and rice husks

Properties	Corn cob	Rice husk
Moisture content (%)	13.47	12.67
Density (Kg/m^3)	650	524
Relaxation ratio (%)	1.71	21.83
Flame propagation rate (cm/s)	0.12	0.10
Volatile matter (%)	86.53	67.98
Heating value (MJ/kg)	20.89	13.389
Compressive strength (N/m^2)	2.34	1.07

Source: (Oladeji and Lucas 2011)

From the table, corn cob and rice residues produced good biomass fuels but corn cob briquettes are more superior to rice husk in term of heating value (Oladeji and Lucas 2011). The slow flame propagation rate recorded show that the briquettes will ignite easily burn with intensity for a long time. The average value of energy of 20,890 kJ/kg obtained can provide enough domestic cooking energy and supply small industrial cottages. It was also concluded that the low sulphur and nitrogen contents of 0.82 % and 0.38 % respectively makes corncob briquettes suitable as fuel due to minimal environmental pollution effects (Oladeji and Lucas 2011).

2.8 Effect of binders and binder ratios on properties of briquettes

Various binders have different gluing properties hence have varying effects on briquette physical and combustion characteristics. Some types of binders that have been tested in the past include: starch, clay, sugar molasses, wood tar, cassava and waste cement (Hollingdale *et al,* 1991). Heat treatment (250-300^{o}C) could be used to soften the lignin of un carbonised biomass to achieve self-bonding (Erikson and Prior, 1990).Lignin has the disadvantage of low melting point of 140^{o}C hence when heated; it melts and exhibits thermosetting properties (Van Dam *et al*, 2004).Clay binders also make briquettes burn longer than starch. Starch burns more efficiently and faster than clay (Olorunnisola, 2004).

2.9 Effect of particle size on briquette properties

A research by Saptoadi (2008) showed that varying particle size influences change in properties like density, strain, volume, burning time and unburned content

Table 2.5 Variation of briquette properties with increase in particle size

Briquette size(microns)	150	180 -212	212 - 250	250 - 300	300 - 425
mass (g)	2.926	2.629	2.691	2.539	2.798
Height (mm)	15.95	18.00	18.30	20.75	23.90
Diameter (mm)	15.75	16.00	16.60	17.10	17.40
Volume (mm)^3	3108.8	3620.6	3962.2	4767.3	5685.4
Density (kg/m^3)	941.2	726.1	679.2	532.6	492.1
Strain (%)	32.92	38.46	40.77	48.21	70.71
Reacted mass (g)	1.963	2.148	2.159	2.137	2.332
Unburned mass (%)	32.91	18.30	19.77	15.83	16.65
Combustion time (mins,)	28.0	25.5	24.0	22.0	19.25

(Source: Saptoadi, 2008)

2.9.1 Effects of varying compaction pressures on compressive strength

Saptoadi (2008) studied effect of varying compaction pressure on briquette properties; the result is shown in Fig. 2.3 ,using six pressures in steps of 1 KN/m^2 ranging from 3 to 8 KN/m^2, applied to see the effects of pressure on density, moisture content, bending and compressive strength of the briquettes. The result showed rise in compressive strength with increase in compaction pressure.

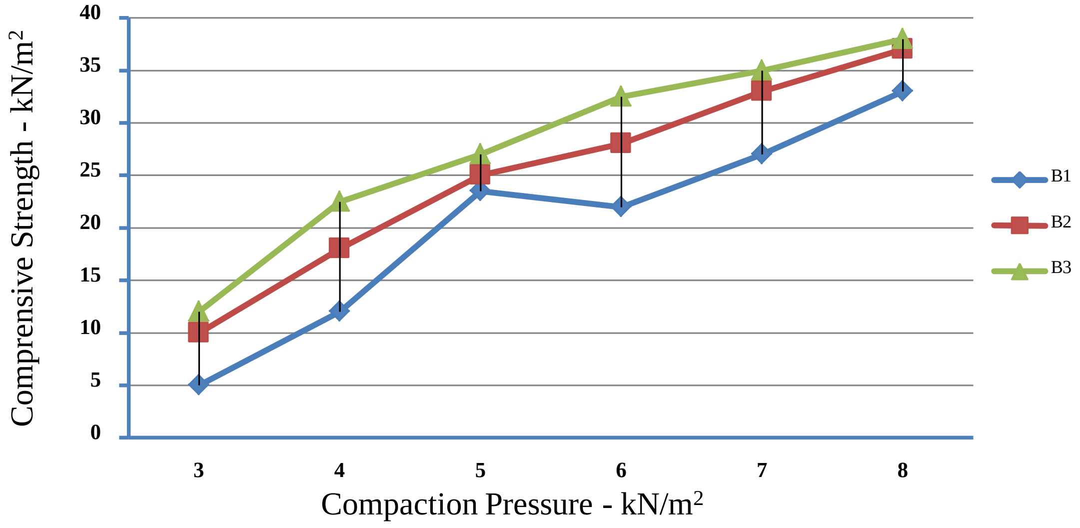

Fig. 2.3 Compaction pressure on compressive strength (Source: Saptoadi, 2008)

2.9.2 Knowledge gap

From the literature review, very little information exists on mechanical and combustion characteristics of cashew nut and mango seed shells composite briquettes produced using banana peels as binder. The research sought to determine the optimal physical and combustion characteristics of the composite of varied compaction pressures, particle sizes and mix ratios of cashew nut and mango seed shells while using banana peel as binder. The study result can provide sustainable renewable energy forms for rural and urban low income households, and reduce the practice of felling trees for charcoal and firewood that increasingly impact negatively on our forest cover.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Production of the briquettes

Cashew nut shells (CNS) were procured from Kilifi Cashew Nut factory while Mango seed shells (MSS) from Mango fruit processing plant at Mtwapa with moisture content of about 28 %. Banana peels which were used as a binder were obtained from the local markets in Njoro. Mango seed shells and Cashew nut shells were chosen due to their availability and the fact that they are discarded as waste with no other economic value after fruit extraction.

Hammer mill and screening were done in the Department of Agricultural Engineering at Egerton University. The shells were carbonized in a muffle furnace in the Department of Animal Science at Egerton University at a controlled temperature of 400^oC for 5 mins in accordance with ASTM D 2677 standard, to improve the carbon yield for higher heat value. The produced carbon fines were then mixed with the binder and compacted in the Departments of Industrial and Energy Engineering workshop. The produced briquettes were left to dry in the same place after which they were packed and labeled then transported to Kenya Bureau of Standards in Nairobi.

Mechanical characteristics determined were density, durability index and compressive strength since these affect packaging, handling, transportation, storage and usage of solid fuels. Combustion characteristics determined were calorific value, ash content and flue gases due to their importance on quality of fuels. The equipment used were Parr 6200 bomb calorimeter, muffle furnace, flue gas analyzers improvised stove (KEBS),oven drier, desiccators, digital weighing scale and Vanier caliper which were available in the Department of Animal Science.

3.1.1 Preparation of raw materials

Cashew nut shells and mango seed shells collected were sun dried separately to approximately 5% moisture content and hammer milled before carbonizing at 400^oC for 5 minutes in the muffle furnace according to Gimba and Turoti (2008). The carbonized materials were then cooled to room temperature in the desiccator. After cooling, the materials were sieved to different particle sizes of 3 mm, 5 mm, 7 mm and 10 mm as recommended by Zhang *et al.* (2012). The sieved materials were packed and sealed in separate labeled plastic bags to avoid absorption of moisture from the atmosphere. The mould used was 50 mm in diameter and 100 mm by length.

Portions of MSS and CNS were taken separately from their containers, weighed on digital weighing scales then mixed in water with banana peel paste inside a mortar followed by pounding using a pestle until fine paste was achieved. Total sample weight was 50g. Weight of binder was kept at 50% weight of sample mix, which was reached at by trial and error, and which also agrees with findings of Davies and Davies,2013 for best binder ratio.

3.1.2 Preparation of moulds and dies

Cylindrical mould of 50 mm diameter by 100 mm in length was fabricated from mild steel cylindrical bar section. The cylindrical solid bar of 75 mm diameter by 100 mm length was clamped in a lathe machine and drilled at the center to produce an internal bore of 50 mm. The surface finishing of the internal bore was smoothened using fine emery paper to reduce the friction during briquetting process. The compaction arrangement was as shown in the drawing in Appendix D (Plate D3).

3.2 Effect of mix ratios on mechanical characteristics of briquettes

For this process Mix ratio of MSS: CNS of 2:3 and 3 mm particle size was used.

a. Density

This is one of the most important mechanical and combustion characteristics which determine handling, storage, and transportation characteristics of solid fuel. Density of briquette was determined according to ASAE S269.4 standards. Since density is property of mass against volume, the process of determining density of briquette was accomplished as follows. Both the height and diameter of a briquette were measured at six positions at 90^0 to each other using Vanier calipers. The average of the measurements were computed and treated as the height (h) and diameter (d) in each case. Density of briquettes was then determined using equation 3.1.

$$\rho = \frac{m}{v} \tag{3.1}$$

Where $\rho =$ is density (g/cm^3)

m = is the mass (g)

v = is the volume of the briquette (cm^3)

b. Durability index tests

The durability of the briquettes was determined in accordance with the chartered index described by Suparin *et al.* (2008). The briquette samples were dropped repeatedly from a height of 1.5 m onto a solid base. The fraction of the briquette retained was used as an index of briquette breakability. Upon dropping the sample from 1.5m height part of the sample crumbled. The remaining portion was then reweighed. Durability rating of the briquette was expressed as a percentage of the material remaining on the metal plate to the initial mass.

$$I_n = \langle \frac{m1 - m2}{m1} \rangle * 100\% \qquad 3.2$$

c. Compressive strength test

The compressive strength is a criterion of briquette durability (Richard, 1990). The compressive strengths of the briquettes were determined using an Instron Testing Machine with an accuracy of ± 0.5 % and a maximum force of 50 kN according to ASTM D 2166-85.The flat surface of the briquette sample was placed on the horizontal metal plate of the machine. A 2 kN- load was applied at a constant rate of 0.5 N/s until the briquette failure by cracking occurred. The compressive strength was computed using the force and the cross sectional area at the cracking point. Five samples obtained from each experiment were tested and average values determined. The compression was done as illustrated in Figure 3.1 and Plate D4 in Appendix section.

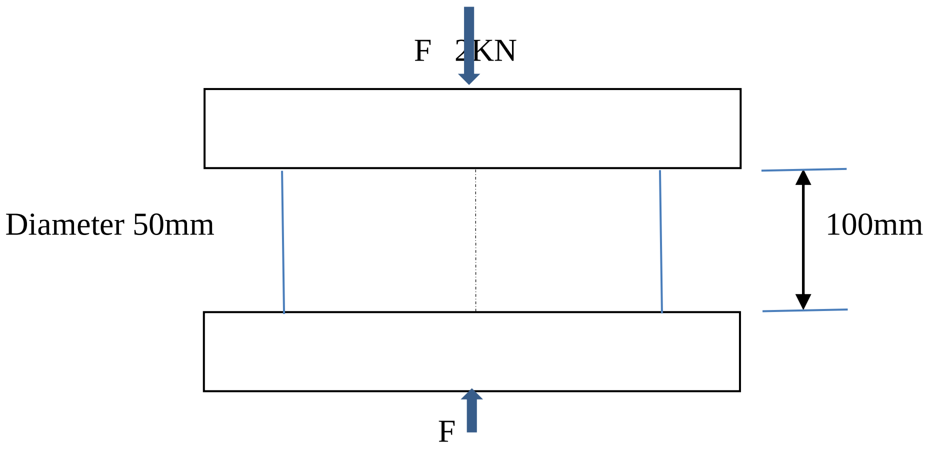

Fig. 3.1 compressive strength test arrangement

3.2.2 Effect of mix ratios on combustion characteristics of briquettes

In order to ascertain the quality of the briquettes as a fuel, the key combustion characteristics tested were moisture content, calorific value and flue gas emissions.

a. Determination of moisture content

Moisture content was determined as per ASTM D3173-11 standard. Empty crucibles were heated to 105℃ for a duration of 1 hr. They were then removed from the oven, covered and cooled immediately in a desiccant for 30 minutes. One gram of each of the samples was weighed, put in the crucibles then dried in an oven at 105℃ for 24 hrs. The crucibles were cooled in desiccators to room temperature then weighed again. Difference in mass is the moisture content. This was expressed in wet basis as shown in equation 3.3

$$\text{Moisture content } = \left(\frac{wet\ weight - dry\ weight}{wet\ weight} \right) \times 100\%. \qquad 3.3$$

b. Determination of calorific value

Calorific (heating) value of biomass is indicative of the energy content of the fuel. A Parr 6200 oxygen bomb calorimeter (Parr Instrument Company, Moline, IL) was used to determine the gross calorific value of the briquettes. One gram was placed in a stainless steel crucible, and the material in the vessel (bomb) ignited by a cotton fuse. The vessel was filled with oxygen and surrounded by a water jacket. Upon ignition, the released heat transferred to the water jacket. The temperature rise in the water jacket was used by the calorimeter to calculate the heating value of the sample. Tests on each sample were replicated five times. ASTM Standard D5865-03 (ASTM 2003b) test method for gross calorific value was referred to in this experiment.

c. Determination of ash content

Ash refers to the residue after burning of biomass. The determination of ash content was done in accordance with the standard (ASTM E 830-87) where one gram of the sample was placed into a weighed crucible. The crucible with sample in it was placed into the muffle furnace and gradually heated to 725^{o}C and kept inside the furnace for a period of 1 hour. The crucible was removed and put in desiccator to cool to room temperature. It was then weighed and difference in weight is the ash content, determined using equation 3.4

$$\text{Ash content (\%) } = \left(\frac{A - B}{C} \right) \times 100\% \qquad 3.4$$

Where

A is the mass of the crucible ash and residues (g)
B is the mass of empty crucible (g)
C is the mass of the sample used (g)

d. Determination of emissions tests

To evaluate emission tests, three pieces of briquettes weighing about 100g were placed over a charcoal stove ignited in the combustion enclosure located in the petroleum laboratory at KEBS, until steady flame was observed. Two flue gas analyzers, having been calibrated, were placed next to the stove to record the flue gases emitted from the combustion process. The two were: a CO_2 and CO analyzer; an analyzer for SO_2,NO_x, HCl, H_2S. Both analyzers had systems to record temperature and amount of emissions for each gas as captured by the inbuilt probes. The data was suitably captured in the inbuilt computer systems for the analyzers and recorded. This was replicated for other mix ratios and particles sizes.

3.3 Effect of particle sizes on mechanical and combustion characteristics of briquettes

Briquettes made from particle sizes of 3 mm, 5 mm, 7 mm and 10 mm at different mix ratios at 50% banana peels binder were produced at 5 MPa and mix ratio 2:3 using a cylindrical mould of 50 mm in diameter by 100 mm length. The produced briquettes were dried then placed in labeled plastics bags before mechanical and combustion characteristics were determined. Mechanical characteristics of density, durability index and compressive strength were then determined based on the standards described in section 3.2

Combustion tests parameters were moisture content, calorific value, ash content and emissions carried out for briquettes prepared using varied particle sizes as explained in section 3.2

3.4 Effect of varying compaction pressures on mechanical and combustion characteristics of briquettes

Once the mix ratios were weighed, the mixture was poured into plastic container, and then the banana paste mixed with it. Stirring of the mixture and binder was carried out till good mould was obtained at 12 % moisture content. The mixture was then fed into the prepared mould of 50 mm diameter by 100 mm height and compacted using hydraulic press at ambient condition to varying pressures of 3, 5, 7, 9, 11MPa, selected to represent low, medium and high pressure conditions during compaction. It was held under pressure for 5 minutes before being withdrawn then dried in the oven to 8 % moisture content and packed in plastic bags to keep from moisture. For each compaction pressure, five samples were prepared. Thereafter, mechanical and combustion characteristics of the briquettes were determined and results tabulated as shown in Table 3.3 in Appendix B3.The particle sizes were maintained at 5mm and binder ratios was 50 % by mass of the mix as recommended by Oladeji and Lucas (2011),and which also agrees with Davies and Davies,2013 for best binder ratio. Calorific value, moisture content, ash content and flue gas emissions were tested on the produced briquettes as explained in subsection 3.2 above.

3.5 Data analysis

Randomized Complete Design was used for this study. The study involved six mixture ratios, five particle sizes and five compaction pressures of composite briquettes. Five samples were analyzed for each condition. The analysis of variance, Duncan Multiply Range Tests and descriptive statistics were used. All the analyses were carried out with SAS statistical software. For separation of means, Least Significant Difference method LSD was at $\alpha = 0.05$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Production of briquettes

The briquettes were produced from the blend of mango seed shells and cashew nut shells that were crushed and carbonized at 400^0C as per ASTM D2677standard.The carbonized fines were then bonded using 50 % banana paste before briquetting, also recommended by Davies and Davies, 2013 for best binder ratio. The produced briquettes were then dried, sealed in labeled plastics bags before mechanical and combustion characteristics were tested.

4.2 Effect of mixture ratios on mechanical and combustion characteristics of briquettes

Briquettes at different mixture ratios were subjected to combustion and mechanical tests. The compacting pressures and particle size were maintained at 5 MPa and 3 mm respectively. Results are as tabulated and discussed below.

4.2.1 Mechanical Characteristics

a) Density

Density is an important characteristic of fuel. It is an indication of energy density. The results (Table 4.1) show the density of briquettes at varying mixture ratios. From the results, the density was 381.31 Kg/m^3 for 5:0 mix ratios of MSS: CNS but increased to 763.45 Kg/m^3 for 0:5 mix ratios. This could be attributed to characteristics of original materials which were the mango seed shells and cashew nut shells. This shows that the density of cashew nut shells is higher than that of mango seed shells, and agrees with findings of Chirchir *et al* (2013) who found that varying ratios of materials have direct impact on densities.

Table 4.1: Density (Kg/m^3) of briquette at different mix ratios at 5 MPa and 3mm

Mixture ratios (MSS:CNS)	Mean density (Kg/m^3)
5:0	381.31^g
4:1	392.85^f
3:2	492.41^e
2.5:2.5	557.68^d
2:3	583.58^c
1:4	729.07^b
0:5	763.45^a
Mean	562.37

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 5.1867

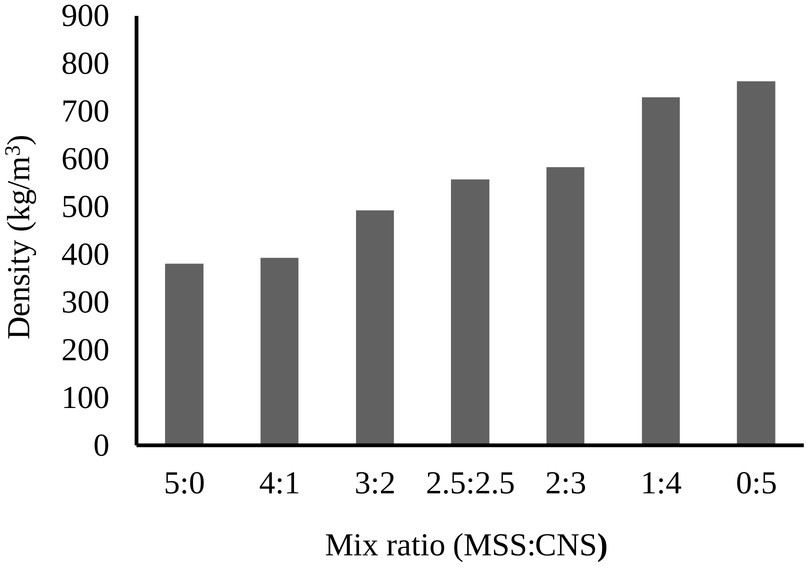

Fig. 4.1: Effect of mix ratios on the density

From Table 4.1 and Fig 4.1 it is evident that the density differs significantly at all mix ratios with LSD being 5.186 and correlation factor of 0.9657

b) Durability index

The durability index of the briquette is expressed as a percentage of the initial mass of the material remaining on the metal plate. It indicates how the particle bonded during briquettes process. From results, the durability index varied between 95.6 % to 99.01%. The mix ratios had no significant effects on the durability index except at the mix ratio of 5:0.

This signifies that the bonding effect of the adjacent particle was not significantly influenced by the composition ratios since the briquetting pressure was maintained at 5 MPa and the particle size was kept at 3mm. Densification of biomass under high pressure brings about mechanical interlocking and increased adhesion between the particles, forming intermolecular bonds in the contact area. Table 4.2 and Fig. 4.2 shows the effects of mix ratios on the durability index

Table 4.2: Durability index (%) of briquette at different mix ratios 5 MPa and 3 mm

Mixture ratios	mean durability index (%)
5:0	95.58^{e}
4:1	97.41^{d}
3:2	97.90^{cd}
2.5:2.5	98.32_{bc}
2:3	98.73^{ab}
1:4	98.87^{ab}
0:5	99.10^{a}
Mean	97.95

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different $\alpha=0.05$ using LSD-0.6129

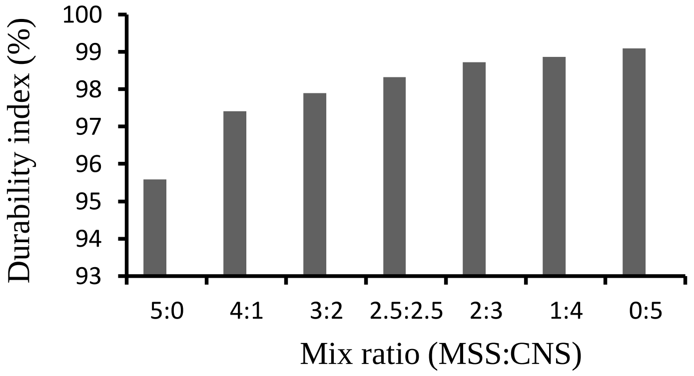

Fig 4.2: Effects of mix ratios on durability index (%) of briquette

Briquette strength has impact on the briquette durability, because when the strength increases the absorption of atmospheric humidity decreases. Sotande *et al*. (2010) discovered that increasing in binder proportion and types of binder have significant effect on the durability index of the briquettes. It was also reported that durability index of 98.74 % obtained in gum Arabic bonded briquettes was higher than 83.26 % obtained in starch bonded briquettes and the values were statistically significant at 5 % probability level which agrees with the results obtained in this study. The mean durability index obtained in the study was 97.95 % which is comparable to that of Gum Arabic binder. This suggests that banana binder has some strong gluing effects.

c) Compressive strength

Compressive strength is a measure of the ability of a briquette to withstand mechanical handling. It is an important parameter to be considered for transportation processes and feeding fuel to the combustion equipment. From the results obtained, the compressive strength increased with the increase in the proportion of cashew nut shells content in the briquette. From Table 4.3, the compressive strength for the mix ratios of MSS:CNS of 5:0, 2.5:2.5 and 0:5 were 7.44 N/mm^2, 7.68 N/mm^2 and 7.89 N/mm^2 respectively. The compressive strength of this briquette is within the range of 7.44N/mm^2 to 7.89N/mm^2, which can withstand mechanical disintegration (Sotande, *et al*, 2010).

Table 4.3: Compressive strength (kN/m^2) of briquette at different mix ratios 5 MPa and 3 mm

Mix ratios	Compressive strength (KN/m^2)
5:0	7.44^{d}
4:1	7.47^{cd}
3:2	7.48^{bcd}
2.5:2.5	7.68^{abc}
2:3	7.68^{abc}
1:4	7.71^{ab}
0:5	7.89^{a}
Mean	7.63

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD=0.2354

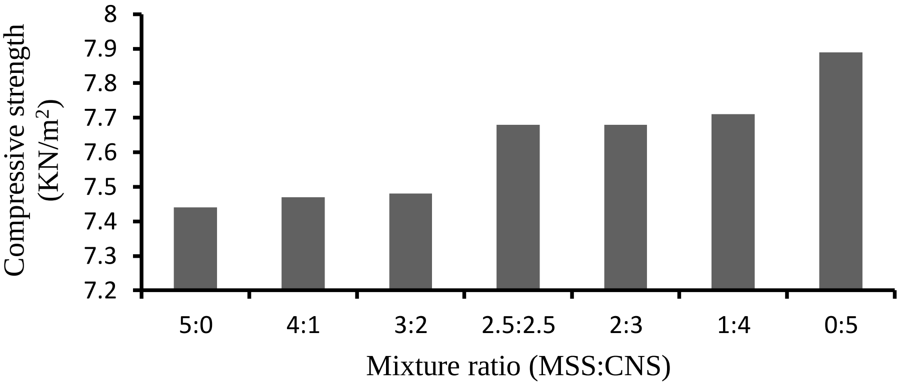

Fig 4.3: Effects of mix ratios on compressive strength of briquette

From the data analyzed, the mixture ratios had no significant effects on the compressive strength with the LSD of 0.2354 at $\alpha = 0.05$

The results obtained confirmed the findings of other studies on fuel briquettes produced under different conditions such as mixture ratios to have different handling characteristics. Besides, these characteristics were also found to be strongly affected by raw material properties (Kaliyan *et al*, 2009). Compressive strength is one of the most important characteristics of a briquette that determined the stability and durability (Kaliyan *et al*, 2009). It is also the major quality index for fuel briquettes. The values of compressive strength obtained were in agreement with those reported by Chin and Siddiqui (2000).

4.2.2 Combustion Characteristics

a) Moisture content

Moisture content affects the combustion characteristics of the fuel. High moisture content is not desirable as more heat will be consumed in drying of the fuel. From the results obtained, the moisture content was 7.30 % at MSS:CNS 5:0 mix ratio but increased to11.27 % at ratio of 0:5. The optimum moisture content of input raw material is between 4 - 10 % when the best mechanical properties of briquettes are attained. However, for some raw materials the upper limit of moisture is at 6-8 %. The critical moisture content is that at which the formation of briquettes is still possible, but crack failures usually appear on their surface and the briquettes lose their market value. The critical amount of water is within 10 - 15 %. Moisture of briquettes depends mainly on the initial moisture of raw material and it changes during the briquetting process, when the temperature increases by compression, some amount of moisture evaporates. High moisture content of briquettes leads to their bed consistency, increased number of crumbles, low energy value and consequently low price (Li and Liu, 2000). Table 4.4 and Fig 4.4 show the trends

Table 4. 4: Moisture content (%) of briquette at different mix ratios 5 MPa and 3 mm particle size.

Mix ratios	Moisture content (%)
5:0	7.30^{g}
4:1	7.56^{f}
3:2	7.85^{e}
1:2.5	8.56^{d}
2:3	9.53^{c}
1:4	9.92^{b}
0:5	11.27^{a}
Mean	8.79

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.0414

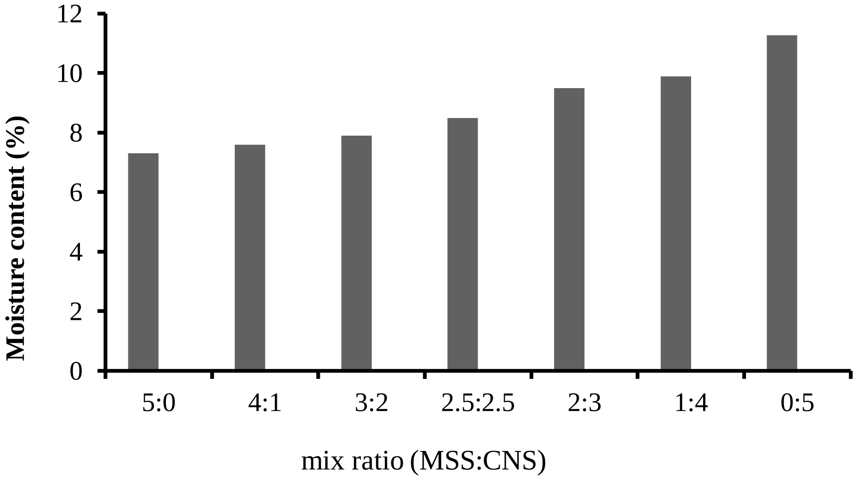

Fig 4.4: Effects of mix ratios on moisture content (%) of briquette

From the Table 4.4 and Figure 4.4, the moisture content varied significantly with the mix ratios with LSD of 0.0414 and the regression coefficient of 97.14 %. The mean moisture content of the briquettes was 8.786 %. This is within the acceptable operating moisture content of 8 – 12 % for making briquetting, consistent with the findings of Li and Liu,(2000) of range between 6 -12 %. This also agrees with findings of Kaliyan *et al,* 2006 of optimal moisture ratios between 8-12 % for good quality briquettes. However, the moisture content of some materials can be up to 20% and such materials can be densified in a piston press.

b) Ash content

Higher ash content reduces the burning efficiency of the briquettes and imposes fire management problems such as frequent ash removal from the stove. From Table 4.5 the ash content was 5.28 % at the mixture ratios of MSS:CNS of 5:0 but increased with increase in the cashew nut shells content in the composite briquettes. In the briquettes produced from cashew nut shell alone (0:5), the ash content was 10.37 %. This showed that the ash content is a characteristic of the original material. Table 4.5 and Fig. 4.5 show the ash contents at varied mixture ratios. This agrees with a study by Chirchir *et al,* 2013 that briquette quality depends on material used.

Table 4.5: Ash content (%) of briquette at different mix ratios 5 MPa and 3 mm

Mix ratios	Mean ash content (%)
5:0	5.28^{g}
4:1	5.94^{f}
3:2	6.93^{e}
2.5:2.5	7.29^{d}
2:3	8.93^{c}
1:4	9.24^{b}
0:5	10.37^{a}
Mean	7.635588

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.049

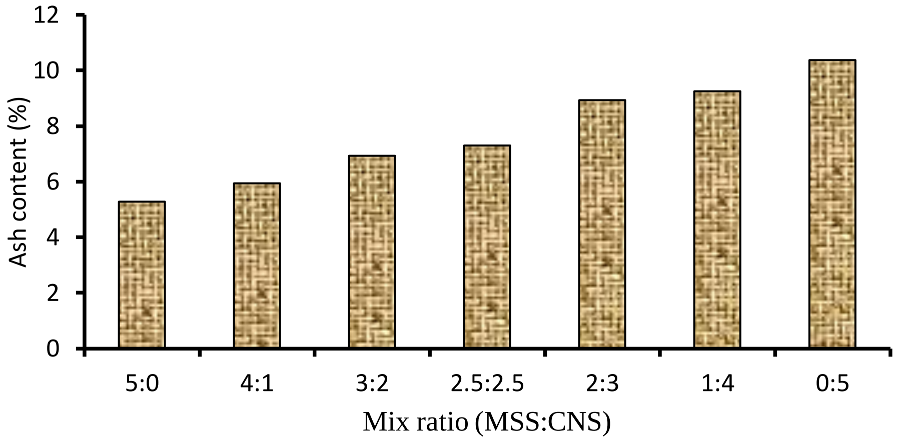

Fig 4.5: Effect of mix ratios on the ash content

Statistically, the mix ratios had significant effect on the ash content with the LSD being 0.049. This suggests that, the amount of ash content in fuel is contributed significantly by the characteristics of the original materials. Higher ash content is not desirable in the fuel because it lowers calorific value of the fuel.

c) Calorific value

The calorific value (or heating value) is the standard measure of the energy content of a fuel. It is defined as the amount of heat evolved when a unit weight of fuel is completely burnt and the combustion products are cooled to 298 K. Table 4.6 and Fig. 4.6 shows the effects of mix ratios on the calorific values

Table 4.6: Calorific value (MJ/kg) of briquette at different mix ratios 5 MPa and 3 mm

Mix ratios	Mean calorific value (MJ/kg)
5:0	16.47^{g}
4:1	19.04^{f}
3:2	21.60^{e}
2.5:2.5	22.11^{d}
2:3	23.73^{c}
1:4	25.74^{b}
0:5	26.61^{a}
Mean	22.35

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD= 0.096

From Table 4.6 and Fig. 4.6, the calorific value varied with the mixture ratios. At 5:0, 2.5:2.5 and 0:5 mix ratios the calorific values were 16.45 MJ/kg, 22.11 MJ/kg and 26.61 MJ/kg respectively. These suggest that Mango shell had lower calorific value than cashew nut shell

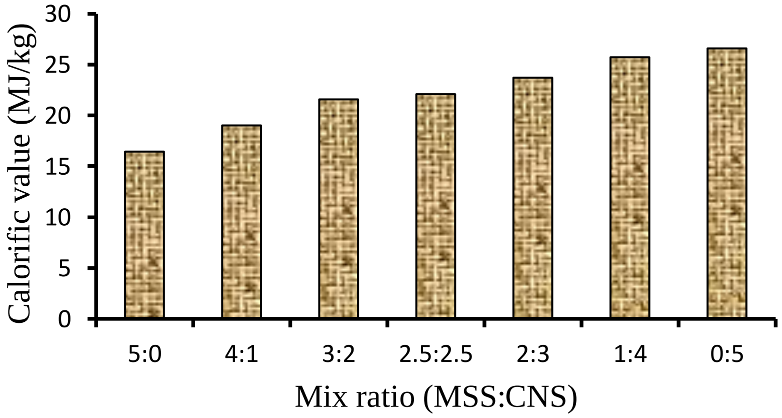

Fig. 4.6 Effects of mix ratios on the calorific value of the briquettes

From the analyzed data, the mix ratios of the Mango seed shell and the cashew nut shell had significant effect on the calorific values with the LSD being 0.096 and the mean calorific value was 22.35 MJ/kg. Based on the finding above, it was found that all briquettes produced fulfill the minimum requirement of calorific value for making commercial briquette (>17500 J/g), except at mix ratio of 5:0

Based on the previous studies on the calorific value, the results obtained for the rice husk was 13,389 KJ/kg while that of corncob briquette was 20,890 KJ/kg. These energy values are sufficient enough to produce heat required for household cooking and small scale industrial cottage applications. They also compare well with the value obtained in this research. For examples, groundnut shell briquette- 12,600 kJ/kg (Musa, 2007), cowpea-14,372.93 kJ/kg, and soybeans-12,953 kJ/kg (Enweremadu, *et al.*,2004) of which the obtained heating value of briquette produced are higher than indicated. Hence from these results MSS cv at 16.47 MJ/kg and CNS cv at 26.61 compare well with results researched from other agricultural wastes

d) Carbon monoxide

Combustion of briquettes contributes significantly to air pollution resulting in potential risks to human health. 1 cubic meter of fuel wood emits 61-73 kg of carbon dioxide (CO_2) equivalents as well as other toxic and greenhouse gasses over its life cycle. Prolonged exposure to emission such as carbon monoxide (CO), Sulphur Oxides (SOx) and Nitrogen oxide (NOx) may cause human health complications (Raymer, 2006).

Table 4.7: CO (ppm) of briquette at different mix ratios 5 MPa and 3 mm

Mix ratios	Mean CO (ppm)
5:0	1.80^{f}
4:1	3.31^{e}
3:2	5.21^{d}
2.5:2.5	5.24^{d}
2:3	5.46^{c}
1:4	5.64^{b}
0:5	5.96^{a}
Mean	4.83

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.1191

From Table 4.7 the CO ranged between 1.80 ppm and 5.96 ppm. It increased significantly with increase in the amount of Cashew nut shells. This could be attributed to chemical composition of the cashew nut. This conforms to emission levels recorded by Banzaert (2013) of 5-7 ppm comparable to other wood biomass levels.

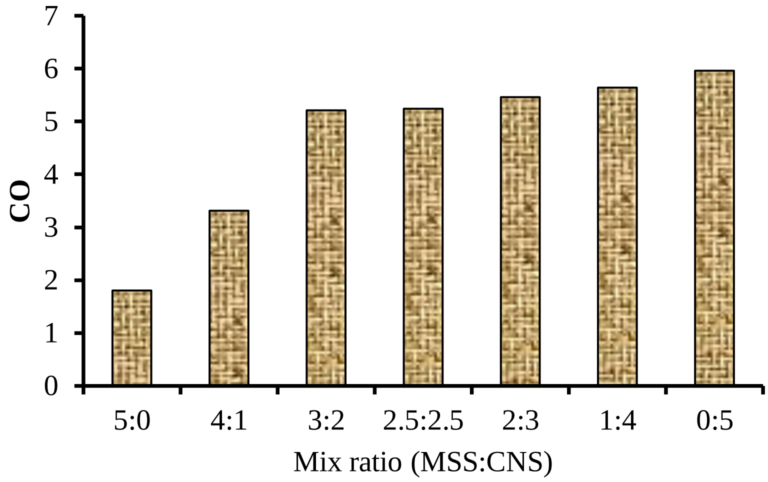

Fig 4.7: Effects of mix ratios on carbon monoxide (%) of briquette

4.3 Effects of Particle Size on Mechanical and Combustion Characteristics of Briquettes

The particles sizes were varied from 3mm to 11mm, but the compacting pressure were held constant at 5 MPa. while mix ratios were maintained at 1:4 and results of the study were as discussed below.

4.3.1 Mechanical characteristics

a) Density

The results tabulated in Table 4.8 show that density reduced with increase in particles size. At 3mm, the density was 729.08 kg/m^3 but reduced to 492.41kg/m$^{3.}$. This could be attributed to increased mechanical interlocking and adhesion between the particles, forming intermolecular bonds as the smaller the particle means higher surface area. Another important binding mechanism is van der Waals' forces. These are prominent at extremely short distances between the adhesion particles. This compares with findings of Mitchual *et al* (2012) that coarser particles produce weaker bonds than finer ones hence less denser.

Table 4.8: Density (d) of briquette at different particle size at 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean d (Kg/m^3)
3	729.08^a
5	629.01^b
7	583.58^c
9	557.68^d
11	492.41^d
Mean	609.84

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.0519

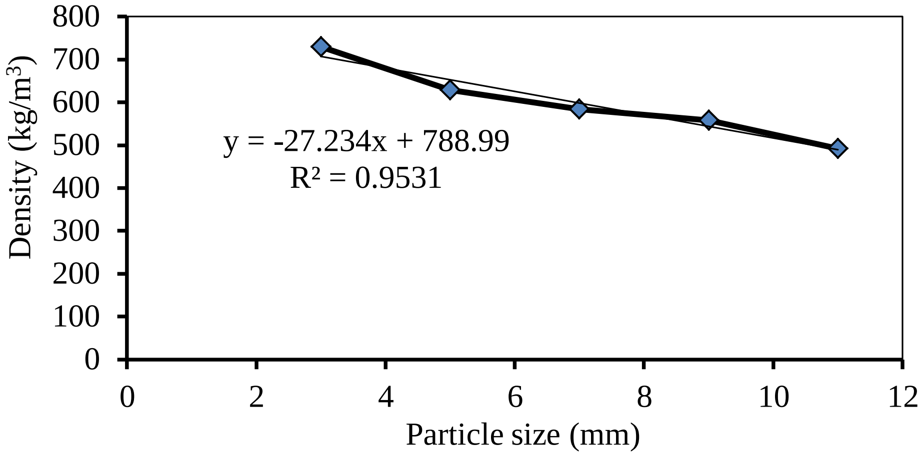

Fig 4.8: Effects of particle size on density of briquette

Statistical analysis, showed that as the particle sizes increases, this had significant effect on the density at all particle sizes. The correlation coefficient was 95.3 % at α=0.05 and least significant difference of 0.0519.

b) Durability index

From the results in Table 4.2, the durability index at particle size of 3 mm was 98.41 % but reduced to 95.52 % at particle size of 11mm. This showed that durability (mechanical strength) of briquettes are inversely proportional to particle size since smaller particles have greater surface area resulting in increased gelatinization and better binding. Therefore, the major contributing factors to the bond formed during this densification may be the mechanical interlock of the fibres of the biomass and adhesive force between the particles resulting in the formation of a stronger bond. The result agrees with previous findings by Habib *et al,*2014 who found that coarser coal particles reduce its durability.

Table 4.9: Durability index (%) of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean di (%)
3	98.41^{a}
5	97.61^{ab}
7	96.75^{bc}
9	96.19^{c}
11	95.52^{c}
Mean	96.90

Means followed by the same letter(s) (a,b,c,) in same column are not significantly different α=0.05 using LSD = 0.3745

From the analyzed data, the least significant difference was 0.6378 at α=0.05 and at all particle sizes the difference was significant suggesting that particle sizes has effect on the durability properties of the briquettes.

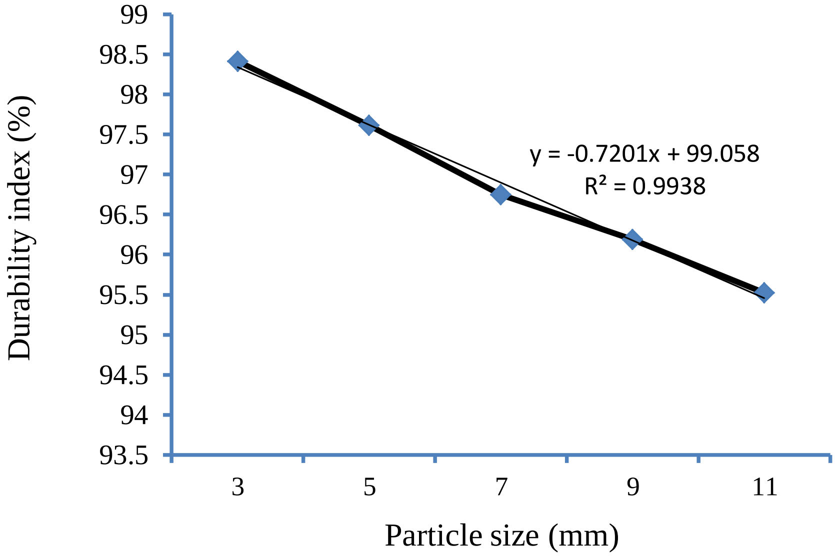

Fig. 4.9 Effects of particle size on durability index (%) of briquette

c) Compressive strength

As shown in Table 4.10 and Fig 4.10, the compressive strength of briquette reduced with increase in particle sizes. The compressive strength was 7.75 KN/m^2 and 6.37 KN/m^2 at particle sizes of 3mm and 11mm respectively. This agrees with findings of Mitchual *et al,* (2013) that finer particles produce stronger bonds hence more durable briquettes.

Table 4.10 Compressive strength (kN/m^2) of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean cs (kN/m^2)
3	7.75^a
5	7.74^a
7	6.93^a
9	6.68^a
11	6.37^a
Mean	7.03

Means followed by the same letter(s) (a,b,c,) in same column are not significantly different α=0.05 using LSD = 0.0369

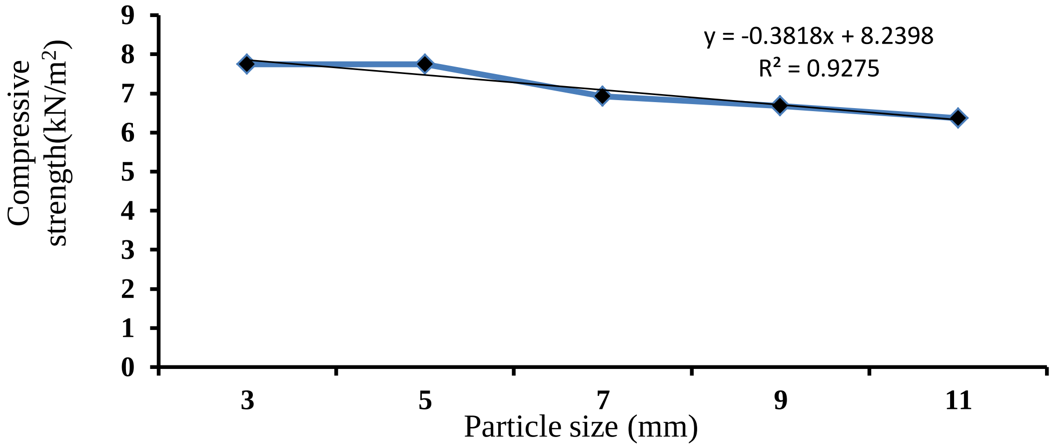

Fig. 4.10: Effects of particle size on compressive strength of briquette

4.3.2. Combustion characteristics

a) Moisture content

Moisture content is important combustion characteristics. From the results obtained in Table 4.11, it showed that there was indirect correlation between the particle sizes and the moisture content. The moisture content was 7.56 % at particle size of 3mm and reduced to 6.88 % at particle size of 11 mm. From statistical data, it showed significant different at smaller particles sizes unlike for the particle sizes of 9 mm and 11 mm.

Table 4.11: Moisture content (mc) of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean mc (%)
3	7.56^{a}
5	7.36^{b}
7	7.27^{c}
9	7.16^{d}
11	6.88^{d}
Mean	7.25

Means followed by the same letter(s) (a,b,c,d) in same column are not significantly different α=0.05 using LSD = 0.0431

The results in Fig 4.11 showed the reduction in moisture content as particle sizes increased with the correlation coefficient of 86.1 %

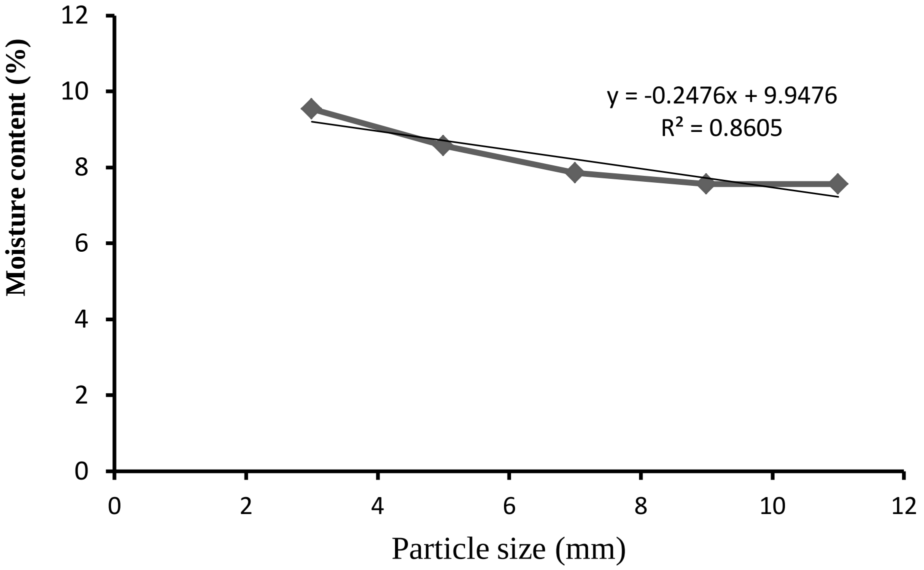

Fig. 4.11: Effects of particle size on moisture content (mc) of briquette

From studies by Li and Liu (2000) it has been found that when the feed moisture content is 8-10 %, the briquettes will have 6-8% moisture. At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. But when the moisture content is more than 10%, the briquettes are poor and weak.

b) Calorific value

From the results obtained in Table 4.12, it shows the calorific values at particle size of 3 mm was 25.64 MJ/kg but increased insignificantly to 25.740 MJ/kg for 11 mm particle size. This suggests that the caloric value of a fuel does not vary significantly with particle size.
The small variations in CV are due to other extraneous experimental factors since CV is dependent of chemical composition of the material and should remain constant irrespective of the particle size. A study by Tokan *et al*, (2014) however got the following results after combusting corn cob briquettes from varying particle sizes:
Size 300 µm = 16.63 MJ/kg; size 2000 µm = 17.51 MJ/kg hence higher particle sizes gave higher calorific values due to improved combustion resulting from increase in surface area allowing more and easy flow of oxygen to support the combustion process.

Table 4.12: Caloric value (cv) of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean cv (MJ/kg)
3	25.64 ^{c}
5	25.68 ^{bc}
7	25.69 ^{bc}
9	25.71^{ab}
11	25.74^{a}
Mean	25.68

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.0495

Fig 4.12 show the graphical view of the variation of the calorific value with the particle sizes. Even though there was rise of the calorific value with increase in particle sizes, statistical analysis at α = 0.05 indicated that the changes of calorific value was insignificant.

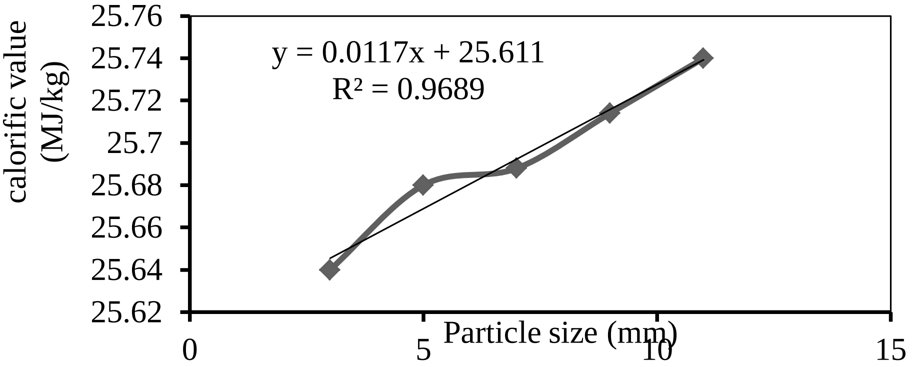

Fig. 4.12: Effects of particle size on calorific value (cv) of briquette

Based on the DIN 51731 Standard on minimum calorific value for making commercial briquette (>17.500 KJ/Kg), the results obtained are comparable to those from a study by Habib *et al, (*2014).

c) Ash content

The ash content of different types of biomass is an indicator of slagging characteristics of the biomass. Generally, the greater the ash content, the greater the slagging effect. The temperature of operation, the mineral compositions of ash and their percentage combined determine the slagging characteristics. Ash content is hence dependent on chemical composition of the material and should remain constant irrespective of the particle size.

The results in Table 4.13 show that there was no significant effect of the ash content as the particle size was varied from 3 mm to11 mm. At 3 mm the ash content was 5.94 % while at 11 mm particle size it increased insignificantly up to 5.93 %.

Table 4.13: Ash content (ac) of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean mc (%)
3	5.94^{a}
5	5.94^{a}
7	5.93^{a}
9	5.93^{a}
11	5.93^{a}
Mean	5.81

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column row are not significantly different α=0.05 using LSD = 0.0519

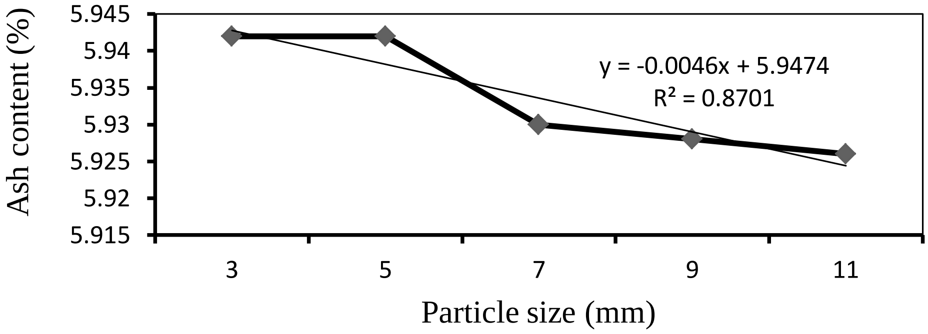

Fig. 4.13: Effects of particle size on ash content (ac) of briquette

The results obtained are comparable with those from a study by Tokan *et al*,(2014) who got ash content values from combustion of corncob briquettes of varying particle sizes as follows Size 300 µm – ash 36.36 % ; size 2000 µm – ash 9.09 % and after burning saw dust briquettes Size 300µm – ash 45.45 % and size 2000 µm – ash 7.69 %

d) Carbon Monoxide

The carbon monoxide was 5.64 ppm at particle size of 3 mm and 5 mm but slightly reduced to 5.21 ppm at particle size of 11mm. Even though there was slight reduction as the particle was increased, the effect was insignificant. This could be attributed to the fact that the amount of carbon monoxide is a function of the air infiltration during combustion process which is affected by particle size of the briquettes.

The results are consistent with those of Banzaert, (2013) averaging 5-7 ppm for combustion tests done on other agricultural wastes in a laboratory.

Table 4.14: Carbon monoxide ppm of briquette at different particle size 5MPa and MSS:CNS 1:4

Particle size (mm)	Mean CO (ppm)
3	5.64^{a}
5	5.64^{a}
7	5.46^{b}
9	5.24^{c}
11	5.21^{c}
Mean	5.44

Means followed by the same letter(s) (a,b,c,d,e.f,g) in same column are not significantly different α=0.05 using LSD = 0.0929

The Fig. 4.14 show the trend of carbon monoxide as the particle size was varied. Even though there was reduction,

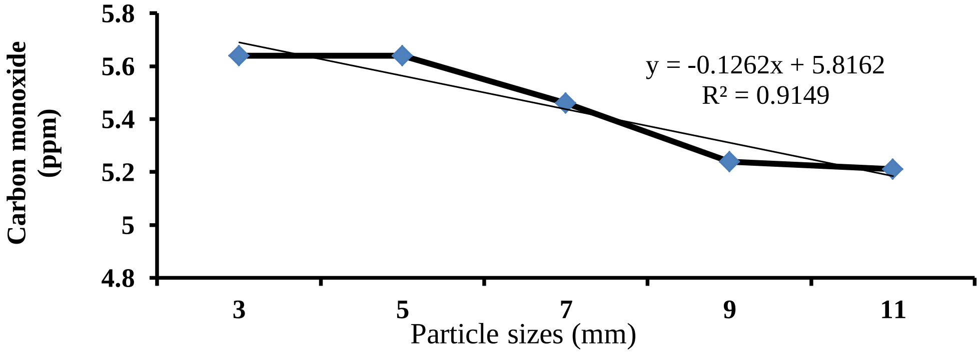

Fig. 4.14: Effects of particle size on carbon monoxide ppm of briquette

4.4: Effect of compaction pressures on mechanical and combustion characteristics

The briquettes were produced at varied compaction pressure but the particle size and mix ratio were maintained at 3mm and 2:3 respectively. Mechanical and combustion characteristics are discussed below.

4.4.1 Mechanical characteristics.

a) Density

Briquettes density increased with increase of the compaction pressure. At 5 MPa the density were 492.41 kg/m^3 and increased to 729.08 kg/m^3 at 11 MPa. This could be attributed to increased interlocking of adjacent particle as the pressure was increased. Table 4.15 and Fig 4.15 show the results obtained

Table 4.15: Density (kg/m^3) of briquette at different compaction pressure 3mm and 1:4

Pressure (MPa)	Mean d (kg/m^3)
5	492.41^d
7	557.68^c
9	583.58^b
11	729.08^a
Mean	590.69

Means followed by the same letter(s) (a,b,c,d,) in same column are not significantly different α=0.05

using LSD =

6.2925

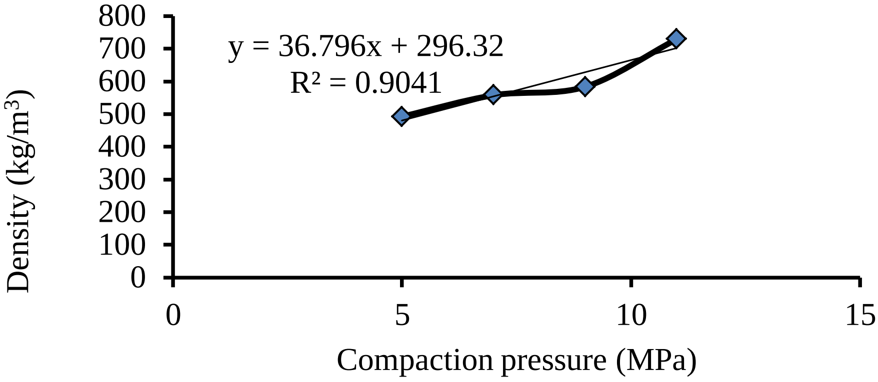

Fig. 4.15: Effects of compaction pressure on density of briquette

The maximum density obtained at pressure of 11 MPa is more than the minimum value of 600 kg/m^3 recommended by Musa, (2007) for efficient transportation and safe storage.

b) Compressive strength

Briquettes' compressive strength is one of the indices used to assess its ability to be handled, packed and transported without breaking. Tables 4.16 show the compressive strength of the briquette produced at different compaction pressures. The compressive strength was 7.47 KN/m^2 and 7.71 KN/m^2 at 5 MPa and 11 MPa respectively. The increase in the compressive strength with the compacting pressure could be attributed to particles of biomass material being closely packed due to reduction of void ratio and plastic deformation. The compressive strength values obtained are however lower than those of another researcher, Katimbo *et al* (2014) who obtained values between 16.7 and 34 kN/m^2 using other binders for mango waste briquettes.

Table 4.16: Compressive strength (KN/m^2) of briquette at different compaction pressure 3mm and 1:4

Pressure (MPa)	Mean cs (KN/m^2)
5	7.47^a
7	7.68^a
9	7.68^a
11	7.71^a
Mean	7.64

Means followed by the same letter(s) (a, b, c, d,) in same column are not significantly differentα=0.05 using LSD = 0.3098

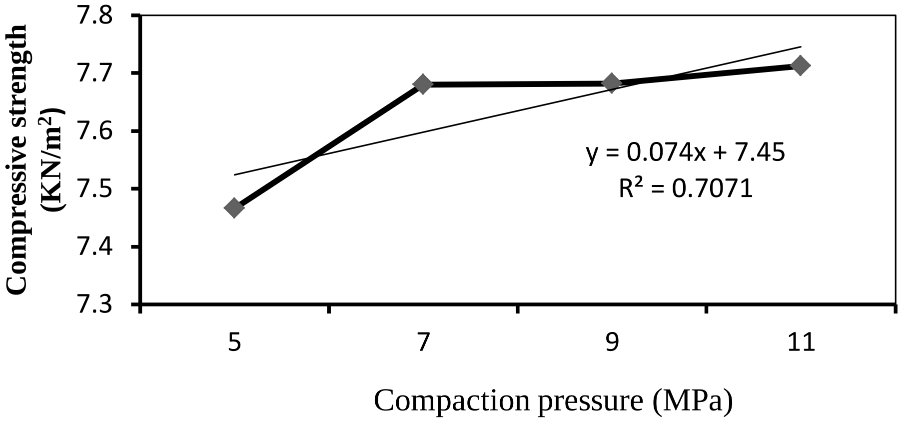

Fig. 4.16: Effects of compaction pressure on compressive strength of briquette

Compacting pressure was found to have a very strong positive significant correlation with the compressive strength of the briquettes produced (LSD=0.3098, α = 0.05). These results suggest that the compressive strength of the briquettes produced increases with increasing compacting pressure.

c) Durability index

Durability index which is a measure of the briquettes to resist abrasion increased directly with increase in pressure. At 5 MPa, the durability was 97.4 % while at 11 MPa it went up to 98.87 % which was significant. This was caused by van der Waals' forces, or interlocking of the particles. Table 4.17 and Fig 4.17 show the results obtained

Table 4.17: Durability index of briquette at different compaction pressure 3mm and 1:4

Pressure MPa	Mean di (%)
5	97.41^{c}
7	97.89^{bc}
9	98.32^{ab}
11	98.87^{a}
Mean	98.13

Means followed by the same letter(s) (a,b,c,d,) in same column are not significantly different α=0.05 using LSD = 0.7244

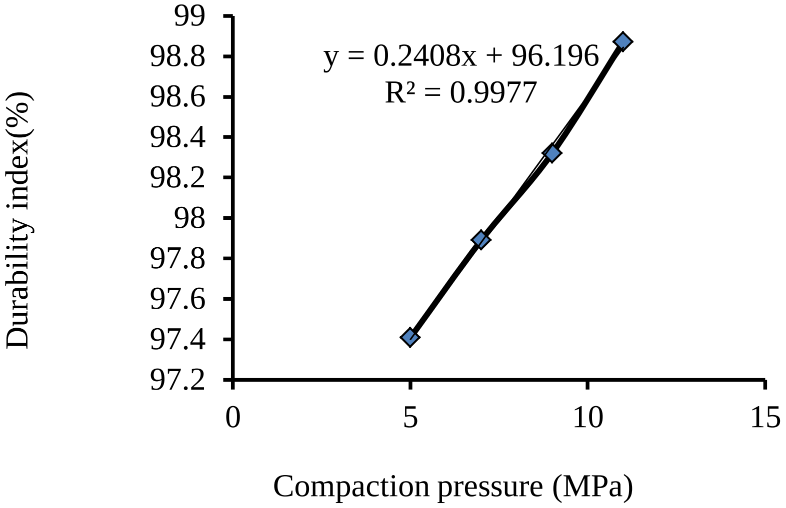

Fig. 4.17: Effects of compaction pressure on durability index (di) of briquette

Briquette strength has impact on briquette durability, because when the strength increases the absorption of atmospheric humidity decreases. The results obtained, show direct correlation between the compacting pressure and the durability, agreeing with previous study Wakehaure and Mani,2009. The LSD was 0.7244 at *α=0.05* and the correlation coefficient was 99.7 %.

4.4.2 Combustion characteristics

a) Moisture content

From Table 4.18 and Fig 4.18, as the compaction pressure was increased, the moisture content reduced significantly. At 5 MPa the moisture content was 9.53 % but reduced to 7.56

% at 11 MPa. This could be attributed to reduction of voids which could have trapped the water pocket. The results obtained are within the accepted limits since when material moisture content is very low or very high (8-18 %), material elements are poor quality and briquette is falling to pieces. When the moisture content is very high, the vaporization of surplus water tears the briquette to pieces. When the material moisture content is very low (4 %), for briquette quality is poor due to rapid combustion in the furnace (Li and Lui, 2000).

Table 4.18: Moisture content (%) of briquette at different compaction pressure 3mm and 1:4 mix ratio

Pressure (bar)	Mean mc (%)
5	9.53^a
7	8.56^b
9	7.85^c
11	7.56^d
Mean	8.38

Means followed by the same letter(s) (a,b,c,d,) in same column are not significantly different α=0.05 using LSD = 0.0382

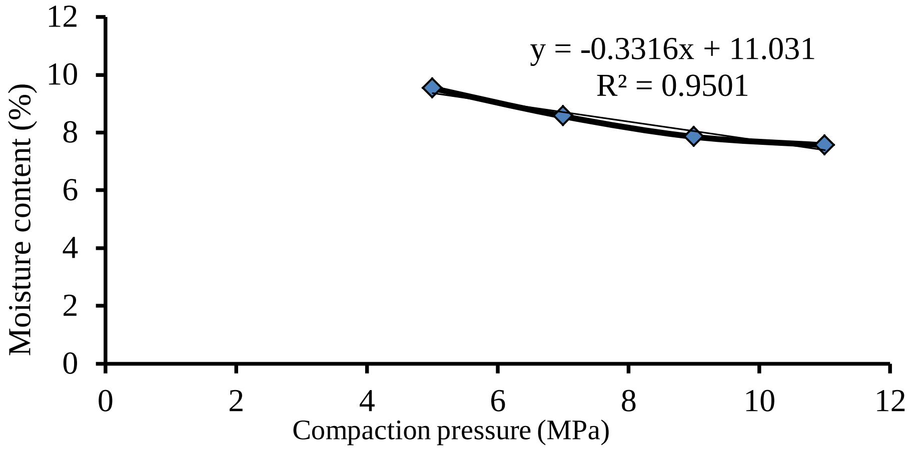

Fig. 4.18 Effects of compaction pressure on moisture content (%) of briquette

The correlation between the compaction pressures and moisture content for the briquettes obtained were 95.01 % (adjusted $R^2 = 0.9501$). This suggested that as the compaction pressure was increased the moisture content reduced.

b) Ash content

Ash content is dependent on the chemical composition of the material and is not expected to vary with compaction pressures. However, other extraneous factors may cause very slight variations in different samples. From Table 4.19 and Fig 4.19, the ash content varied insignificantly at all compacting pressure. At 5 MPa, the ash content was 5.94 % and reduced to 5.92 % at compaction pressure of 11 MPa. This suggested that the ash content in fuel depend on the chemical composition and not compaction of the fuel. This agrees with previous studies by Tokan *et al* 2014. The slight variations are due to other extraneous factors and not compaction pressures.

Table 4.19: Ash content (%) of briquette at different compaction pressure 3mm and 1:4

Pressure (bar)	Mean ac (%)
5	5.94^a
7	5.93^a
9	5.93^a
11	5.92^a
Mean	5.93

Means followed by the same letter(s) (a, b, c, d,) in same column are not significantly different α=0.05 using LSD = 0.0382

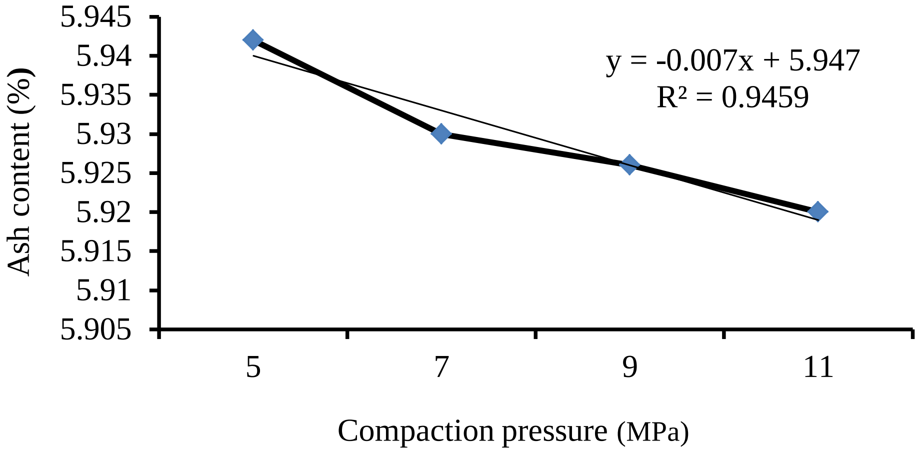

Fig. 4.19: Effects of compaction pressure on ash content (%) of briquette

c) Calorific value

The heating value is the most important combustion property for determining the suitability of a material as fuel. It gives the indication of the quantity of fuel required to generate a specific amount of energy. The heating value ranged from 21.6 MJ/Kg to 25.74 MJ/Kg for compaction pressure of 5 MPa to 11 MPa. The increase of calorific value could be attributed to the reduction of moisture content at higher compaction pressures. High moisture content causes increase in combustion remnant in the form of ash which lowers the heating value of briquettes. The result compares with those of previous studies carried out by Chirchir *et al* 2013 whose results showed better CV with higher compaction pressures. Table 4.20 and Fig 4.20 show the results.

Table 4.20: Calorific value (MJ/kg) of briquette at different compaction pressure, 3mm and 1:4

Pressure (MPa)	Mean CV (MJ/kg)
5	21.60
7	22.11
9	23.73
11	25.74
Mean	23.29

α=0.05 using LSD = 0.0614

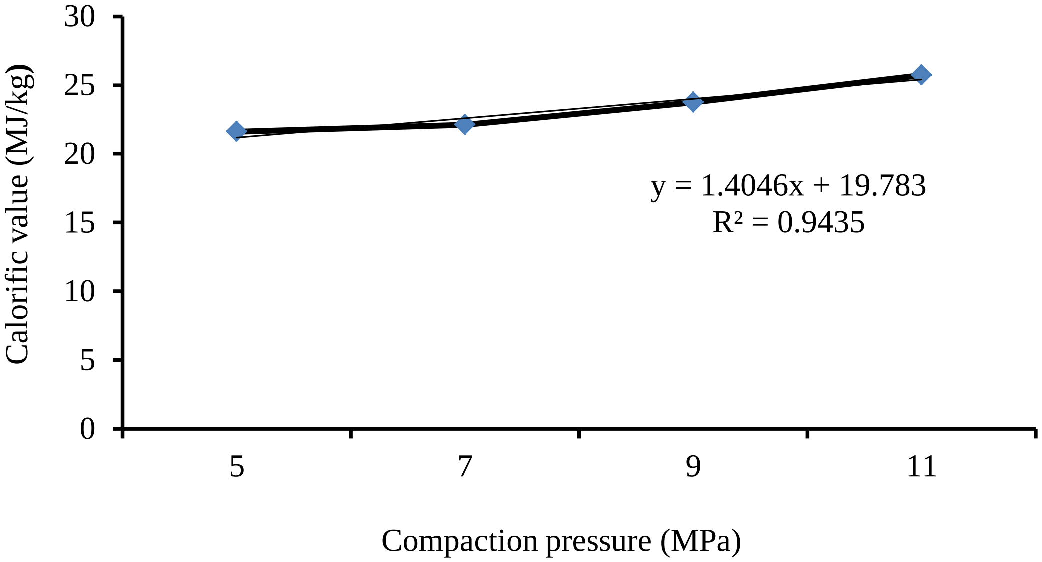

Fig. 4.20: Effects of compaction pressure on calorific value of briquette

d) Carbon monoxide

From the results shown in Table 4.21 and Fig 4.21 the carbon monoxide content was 5.21ppm at compaction pressure of 5 MPa, but increased significantly to 5.64 ppm at 11 MPa. The increase in the amount of carbon monoxide could be attributed to reduction of the surface area of the particle at higher pressure which hampered penetration of oxygen during the combustion process. The results agrees with those of previous studies by Mohammed and Olugbade,2015 whose results showed reduced burning rate at higher compaction pressures because of lower penetration by Oxygen to support combustion hence rise in CO emissions.

Table 4.21: Carbon monoxide of briquette at different compaction pressure, 3mm and 1:4

Pressure (MPa)	Mean CO (ppm)
5	5.21^d
7	5.24^c
9	5.46^b
11	5.64^a
Mean	5.39

Means followed by the same letter(s) (a, b, c, d,) in same column are not significantly different α=0.05 using LSD = 0.0989

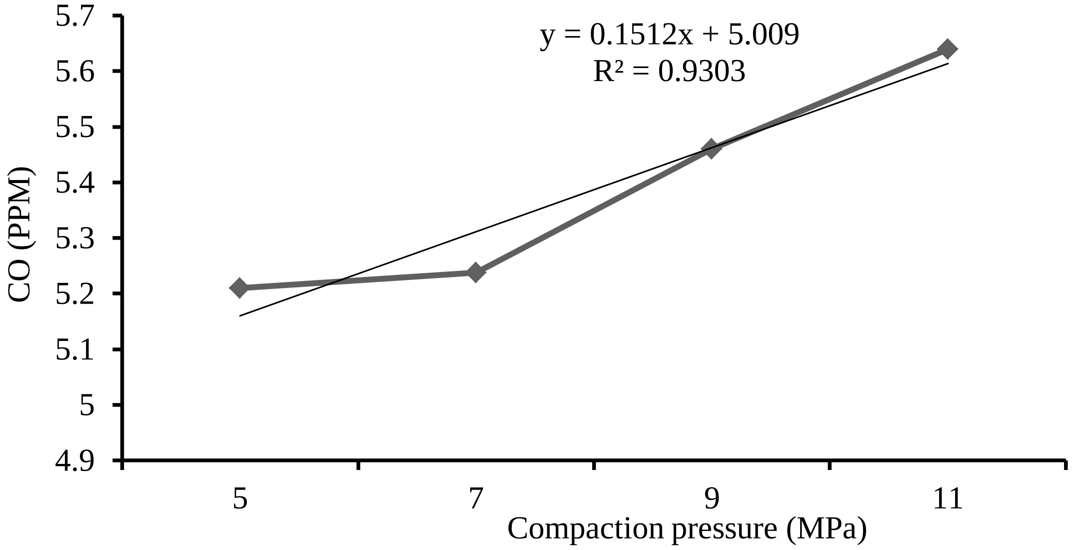

Fig. 4.21: Effects of compaction pressure on carbon monoxide (ppm) of briquette

The moisture content is however below the maximum exposure level of 9 ppm recommended for indoor air quality standard by the WHO and OSHA Act 2007, and NAAQS of US

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

From the research conducted, the effect of varying mango seed shells and cashew nut shells mixture ratios was done and mechanical and combustion characteristics of composite briquettes were determined.

The optimal mix ratio was MSS:CNS 1:4 being the highest in CV and also co emissions below the 9 ppm maximum exposure limit stated by the OSHA 2007 Act on indoor air quality emission levels.

The finding showed that the density of the briquettes increased from 381.30 Kg/m^3 to 763.45 Kg/m^3 at the ratios of 5:0, 4:1, 3:2, 2.5:2.5, 2:3, 1:4 to 0:5 (MSS:CNS); durability index, compressive strength increased from 95.58 % and 7.44 KN/m^{2,} to 99.09 % and 7.88 KN/m^2 respectively as the cashew nut shell was increased. Similarly there was increase of moisture content, ash content ,calorific value and carbon monoxide from 7.30 %, 5.28 % ,16.47 MJ/kg and 3.31 ppm to 11.27 %, 10.37 % ,26.61 MJ/kg and 5.96 ppm respectively as the cashew nut shells mix ratios was increased.

The optimum particles size was 11mm since it has higher calorific values and lower carbon monoxide emission.

As the particle sizes was increased from 3 mm to 11 mm, the density, moisture, ash content reduced from 729.08 Kg/m^3, 7.56 KN/m^2, 5.942 % to 492.41 kg/m^3, 6.88 %, 5.93 % respectively. There was no significant change on calorific value as the particle sizes increased. Durability index, compressive strength and carbon monoxide reduced significantly at all particle sizes.

The optimal compaction pressure was therefore 11 MPa that gave high CV and acceptable CO limits.

As the compaction pressures increased from 5 MPa to 11 MPa, density changed from 492.41 Kg/m^3 to 729.08 Kg/m^3. The ash content reduced insignificantly from 5.94 % to 5, 92 % as the pressure increased. Calorific value, durability index and CO increased from 21.60 MJ/kg, 97.41 % and 5.21 ppm to 25.74 MJ/kg, 98.87 % and 5.64 ppm respectively. This could be attributed to reduction in voids at higher pressure. A good fuel should have high calorific value and emit low levels of CO which is a toxic gas that can cause very severe risks to humans over long exposure time at high concentration levels. The emission level of CO should therefore be maintained at levels acceptable by set environmental standards. All the

CO levels fell below 9 ppm recommended by WHO, NAAQS and OSHA ACT, 2007 Standard for indoor air quality.

RECOMMENDATIONS

Having in mind that a good grade solid fuel a good grade solid fuel should have high calorific value, low emission of combustion gases (in this case carbon monoxide); high density, compressive strength and durability index for ease of handling and transportation. It may be necessary hence to select a sample with lower calorific value and low carbon monoxide emission and leave out one with the opposite of the attributes. From the results obtained, no single selection of sample was able to give the best results of all the cited variables. The sample with the best combination of all these attributes hence was 1:4 mix ratio, 5MPa compaction pressure and 3mm particle size due to a good balance of carbon monoxide and calorific value.

Further studies can be done to determine the following.

1. Physical characteristics such as water absorption, porosity index of mix ratio 2:3 and 5MPa compaction pressure with briquettes of varying particle sizes.
2. Effect of carbonization temperature on combustion and mechanical characteristics of briquettes
3. Mechanical and combustion characteristics of briquettes using different biomass at MSS:CNS ratios of 1:3,3:1

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APPENDIX A1

Effect of mixture ratios on mechanical and combustion characteristics

Replication	Mixture Composition ratio	Moisture content (%)	Ash content (%)	calorific value (MJ/kg)	Carbon monoxide (ppm)	Density Kg/m^3	Durability index (%)	Compressive strength (KN/m^2
1	**5:0**	**11.2**	**10.44**	**16.49**	**1.8**	**380.14**	**99.13**	**7.44**
2	5:0	11.34	10.32	16.495	1.81	379.05	99.11	7.43
3	5:0	11.27	10.35	16.493	1.8	378.57	99.13	7.44
4	5:0	11.28	10.37	16.398	1.8	387.45	99	7.45
1	**4:1**	**9.89**	**9.21**	**19.205**	**3.3**	**394.13**	**98.91**	**7.5**
2	4:1	9.96	9.23	19.201	3.31	392.54	98.8	7.5
3	4:1	9.9	9.27	18.998	3.3	391.56	98.7	7.47
4	4:1	9.91	9.28	18.885	3.32	393.45	98.63	7.45
5	4:1	9.93	9.25	18.887	3.3	392.56	98.61	7.5
1	**3:2**	**9.47**	**8.97**	**21.602**	**5.25**	**500.88**	**98.29**	**7.68**
2	3:2	9.53	8.85	21.599	5.25	495.85	98.4	7.65
3	3:2	9.6	8.9	21.604	5.23	480.05	98.3	6.69
4	3:2	9.51	8.95	21.597	5.26	498.5	98.4	7.63
5	3:2	9.56	8.97	21.598	5.2	486.76	98.23	7.68
1	**2.5:2.5**	**8.55**	**7.26**	**22.182**	**5.3**	**559.38**	**98.79**	**7.7**
2	2.5:2.5	8.58	7.38	22.089	5.2	555.78	98.99	7.67
3	2.5:2.5	8.54	7.27	22.005	5.1	554.54	99	7.66
4	2.5:2.5	8.56	7.29	22.155	5.22	557.87	98.97	7.68
5	2.5:2.5	8.59	7.28	22.101	5.23	560.85	98.6	7.7
1	**2:3**	**7.85**	**6.93**	**23.712**	**5.5**	**585.56**	**96.06**	**7.71**
2	2:3	7.86	6.94	23.699	5.4	584.34	98.72	7.71
3	2:3	7.87	6.91	23.753	5.5	581.89	98.5	7.73
4	2:3	7.84	6.93	23.775	5.6	582.56	98	7.7
5	2:3	7.85	6.94	23.723	5.3	583.56	98.21	7.71
1	**1:4**	**7.55**	**5.9**	**25.785**	**5.6**	**730**	**97.44**	**7.75**
2	1:4	7.56	5.95	25.656	5.7	729.05	97.43	7.74
3	1:4	7.54	5.97	25.76	5.6	731.25	97.41	7.76
4	1:4	7.57	5.98	25.775	5.7	728.55	97.36	7.75
5	1:4	7.58	5.91	25.725	5.6	726.55	97.4	7.4
1	**0:5**	**7.32**	**5.28**	**26.611**	**5.9**	**763.01**	**95.05**	**7.9**
2	0:5	7.29	5.29	26.615	6.1	764.24	96.14	7.89
3	0:5	7.3	5.27	26.598	6.2	765.56	95.85	7.9
4	0:5	7.31	5.28	26.61	5.8	762.56	95.86	7.86
5	0:5	7.29	5.29	26.605	5.8	761.89	95.01	7.88

APPENDIX A2

Effect of particle size on mechanical and combustion characteristics of briquettes

Replication	Particle size (mm)	Moisture content (%)	Ash content (%)	Calorific value (MJ/kg)	Carbon monoxide (ppm)	Density Kg/m^3	Durability index (%)	Compressive strength (KN/m^2
1	**3**	**7.55**	**5.9**	**25.64**	**5.6**	**730**	**98.44**	**7.75**
2	3	7.56	5.95	25.66	5.7	729.05	98.43	7.74
3	3	7.54	5.97	25.66	5.6	731.25	98.41	7.76
4	3	7.57	5.98	25.74	5.7	728.55	98.36	7.75
5	3	7.58	5.91	25.54	5.6	726.55	98.42	7.74
1	**5**	**7.35**	**5.9**	**25.68**	**5.6**	**628.09**	**98.44**	**7.45**
2	5	7.36	5.95	25.68	5.7	630.08	97.43	7.44
3	5	7.34	5.97	25.68	5.6	629.3	97.41	7.46
4	5	7.37	5.98	25.68	5.7	629.4	97.36	7.45
5	5	7.38	5.91	25.68	5.6	628.2	97.43	7.4
1	**7**	**7.25**	**5.93**	**25.72**	**5.5**	**585.56**	**96.96**	**6.92**
2	7	7.26	5.94	25.69	5.4	584.34	96.87	6.91
3	7	7.27	5.91	25.68	5.5	581.89	96.71	6.93
4	7	7.34	5.93	25.66	5.6	582.56	96.65	6.97
5	7	7.25	5.94	25.69	5.3	583.56	96.55	6.91
1	**9**	**7.15**	**5.95**	**25.72**	**5.25**	**559.38**	**96.19**	**6.7**
2	9	7.18	5.91	25.71	5.25	555.78	96.22	6.67
3	9	7.14	5.93	25.69	5.23	554.54	96.23	6.66
4	9	7.16	5.92	25.73	5.26	557.87	96.187	6.68
5	9	7.19	5.93	25.72	5.2	560.85	96.12	6.7
1	**11**	**6.87**	**5.96**	**25.785**	**5.3**	**500.88**	**95.29**	**6.38**
2	11	6.9	5.85	25.656	5.2	495.85	95.4	6.45
3	11	6.9	5.9	25.76	5.1	480.05	95.3	6.35
4	11	6.81	5.95	25.775	5.22	498.5	95.4	6.33
5	11	6.96	5.97	25.725	5.23	486.76	96.23	6.34

APPENDIX A3

Compaction pressure on mechanical and combustion characteristics of briquettes

Replication	Pressure (MPa)	Moisture content (%)	Ash content (%)	Calorific value (MJ/kg)	Carbon monoxide (ppm)	Density Kg/m^3	Durability index (%)	Compressive strength (KN/m^2)
1	**5**	**9.56**	**5.9**	**21.611**	**5.25**	**493.01**	**97.43**	**7.75**
2	5	9.51	5.95	21.61	5.17	492.05	97.37	7.74
3	5	9.6	5.97	21.59	5.22	491.25	97.41	7.76
4	5	9.53	5.98	21.591	5.21	492.52	97.4	7.75
5	5	9.47	5.91	21.598	5.19	493.21	97.43	7.72
1	**7**	**8.59**	**5.93**	**22.11**	**5.21**	**559.32**	**97.92**	**7.68**
2	7	8.56	5.94	22.106	5.29	558.62	97.88	7.65
3	7	8.54	5.91	22.101	5.21	555.82	97.87	7.69
4	7	8.58	5.93	22.109	5.23	557.71	97.91	7.71
5	7	8.55	5.94	22.103	5.252	556.95	97.86	7.67
1	**9**	**7.85**	**5.95**	**23.66**	**5.48**	**583.45**	**98.29**	**7.76**
2	9	7.84	5.92	23.764	5.4	584.28	98.33	7.61
3	9	7.87	5.91	23.766	5.48	584.58	98.32	7.74
4	9	7.86	5.92	23.745	5.42	583.43	98.34	7.73
5	9	7.85	5.93	23.725	5.51	582.23	98.32	7.57
1	**11**	**7.58**	**5.91**	**25.821**	**5.65**	**727.58**	**98.91**	**7.69**
2	11	7.57	5.91	25.694	5.65	729.61	98.93	7.68
3	11	7.54	5.93	25.811	5.63	727.2	98.91	7.73
4	11	7.56	5.94	25.645	5.66	731.4	98.78	7.71
5	11	7.55	5.91	25.725	5.6	729.6	98.81	7.75

The bolds show data beginning for every replication group.

APPENDIX B

B1Mix Ratios	Moisture content	Ash content	CV	Density	Durability index	Compressive strength	Flue gases (carbon monoxide)
1:0	m_1	a_1	h_1	ρ_1	i_1	c_1	o_1
4:1	m_2	a_2	h_2	ρ_2	i_2	c_2	o_2
3:2	m_3	a_3	h_3	ρ_3	i_3	c_3	o_3
1:1	m_4	a_4	h_4	ρ_4	i_4	c_4	o_4
2:3	m_5	a_5	h_5	ρ_5	i_5	c_5	o_5
1:4	m_6	a_6	h_6	ρ_6	i_6	c_6	o_6
0:1	m_7	a_7	h_7	ρ_7	i_7	c_7	o_7

B2:Particle size 3.2 Combustion and Mechanical characteristics (Mix ratio1:4, comp. press.5 bar)

	Moisture content	Ash content	CV	Density	Durability index	Compressive strength	Flue gases
3mm	m_1	a_1	h_1	ρ_1	i_1	c_1	o_1
5mm	m_2	a_2	h_2	ρ_2	i_2	c_2	o_2
7mm	m_3	a_3	h_3	ρ_3	i_3	c_3	o_3
10mm	m_4	a_4	h_4	ρ_4	i_4	c_4	o_4

m_i = moisture content a_i = ash content h_i = calorific value ρ_I = density i_i = durability index

o_i = carbon monoxide flue gas

B3: Compaction Pressure (MPa)	Mechanical characteristics			Combustion characteristics		
	Density (Kg/m^3)	Durability Index (%)	Compressive Strength (KN/m^2)	Calorific Value(MJ/kg)	Ash content (%)	Flue Gases (ppm)
3	ρ_1	i_1	c_1	h_1	a_1	o_1
5	ρ_2	i_2	c_2	h_2	a_2	o_2
7	ρ_3	i_3	c_3	h_3	a_3	o_3
9	ρ_4	i_4	c_4	h_4	a_4	o_4
11	ρ_5	i_5	c_5	h_5	a_5	o_5

APPENDIX C: Data analysis sheet

```
                         The SAS System
                         The ANOVA Procedure
                              Dependent Variable: mc
                                Sum of
Source              DF        Squares     Mean Square    F Value    Pr> F
Model                6     57.05154912     9.50859152    9653.39    <.0001
Error               27      0.02659500     0.00098500
Corrected Total     33     57.07814412
           R-Square     CoeffVar      Root MSE       mc Mean
           0.999534      0.357182      0.031385      8.786765
Source              DF       Anova SS     Mean Square    F Value    Pr> F
Comp                 6     57.05154912     9.50859152    9653.39    <.0001
                    The ANOVA Procedure
                              Dependent Variable: ac
                               Sum of
Source              DF        Squares     Mean Square    F Value    Pr> F
Model                6     96.36299824    16.06049971    11644.3    <.0001
Error               27      0.03724000     0.00137926
Corrected Total     33     96.40023824
           R-Square     CoeffVar      Root MSE       ac Mean
           0.999614      0.486385      0.037138      7.635588
Source              DF       Anova SS    Mean Square    F Value    Pr> F
Comp                 6     96.36299824    16.06049971    11644.3    <.0001
                               The ANOVA Procedure
                              Dependent Variable: cv
                                 Sum of
Source              DF        Squares     Mean Square    F Value    Pr> F
Model                6       354.0598597     59.0099766    11169.2    <.0001
Error               27         0.1426488      0.0052833
Corrected Total     33       354.2025085
           R-Square     CoeffVar Root MSE       cv Mean
```

```
               0.999597     0.325181     0.072686     22.35253

Source                DF        Anova SS     Mean Square    F Value    Pr> F

Comp                   6    354.0598597     59.0099766    11169.2    <.0001

                           The ANOVA Procedure

                           Dependent Variable: co

                                   Sum of

Source                DF         Squares     Mean Square    F Value    Pr> F

Model                  6    61.22550147     10.20425025    1255.34    <.0001

Error                 27      0.21947500     0.00812870

Corrected Total      33    61.44497647

               R-Square     CoeffVar      Root MSE       co Mean

               0.996428     1.900680     0.090159     4.743529

Source                DF        Anova SS     Mean Square    F Value    Pr> F

Comp                   6    61.22550147     10.20425025    1255.34    <.0001

                             The SAS System

                           The ANOVA Procedure

                                    Sum of

Source                DF         Squares     Mean Square    F Value    Pr> F

Model                  6      1.52941176      0.25490196     Infty<.0001

Error                  27      0.00000000      0.00000000

Corrected Total       33      1.52941176

Source                DF        Anova SS     Mean Square    F Value    Pr> F

Comp                   6      1.52941176      0.25490196     Infty<.0001

                             The SAS System

                           The ANOVA Procedure

                                      Dependent Variable: density

                                  Sum of

Source                DF         Squares     Mean Square    F Value   Pr> F

Model                  6    642794.2194     107132.3699    6945.73    <.0001

Error                 27        416.4537         15.4242

Corrected Total       33    643210.6731

              R-Square     CoeffVar      Root MSE    density Mean
```

```
              0.999353     0.698364     3.927367       562.3671

     Source                DF       Anova SS     Mean Square    F Value    Pr> F

     Comp                   6    642794.2194     107132.3699    6945.73    <.0001

                             The SAS System

                            The ANOVA Procedure

                               Dependent Variable: durability index

                                    Sum of

     Source                DF        Squares     Mean Square    F Value    Pr> F

     Model                  6    42.71356794      7.11892799      33.05    <.0001

     Error                 27     5.81563500      0.21539389

     Corrected Total       33    48.52920294

               R-Square     Coeff.of Var.      Root MSE       di Mean

               0.880162      0.473800      0.464105      97.95382

     Source                DF       Anova SS     Mean Square    F Value    Pr> F

     Comp                   6    42.71356794      7.11892799      33.05    <.0001

                            The ANOVA Procedure

                            Dependent Variable: compressive strength

Sum of

     Source                DF        Squares     Mean Square    F Value    Pr> F

     Model                  6     0.77242412      0.12873735       4.05    0.0051

     Error                 27     0.85792000      0.03177481

     Corrected Total       33     1.63034412

               R-Square     Coeff. Of Var.      Root MSE       cs Mean

               0.473780      2.337228           0.178255      7.626765

     Source                DF       Anova SS     Mean Square    F Value    Pr> F

     Comp                   6     0.77242412      0.12873735       4.05    0.0051

                            The ANOVA Procedure

                       Duncan's Multiple Range Test for mc

                            Alpha                                        0.05

                       Error Degrees of Freedom                         27

                       Error Mean Square                                0.000985

                       Harmonic Mean of Cell Sizes                      4.827586
```

```
                NOTE: Cell sizes are not equal.
Number of Means     2         3         4         5         6         7
Critical Range   .04145    .04355    .04490    .04587    .04659    .04715
          Means with the same letter are not significantly different.
          Duncan Grouping        Mean          N        Comp
                G              7.30200         5        5:0
                F              7.56000         5        4:1
                E              7.85400         5        3:2
                D              8.56400         5       2.5:2.5
                C              9.53400         5        2:3
                B              9.91800         5        1:4
                A             11.27250         4        0:5
                    The ANOVA Procedure
```

Duncan's Multiple Range Test for ac

```
               Alpha                                      0.05
               Error Degrees of Freedom                   27
               Error Mean Square                     0.001379
               Harmonic Mean of Cell Sizes                4.827586
                NOTE: Cell sizes are not equal.
Number of Means         2         3         4         5         6         7
Critical Range   .04905    .05153    .05313    .05427    .05513    .05580
          Means with the same letter are not significantly different.
          Duncan Grouping      Mean          N            Comp
                G            5.28200         5            5:0
                F            5.94200         5            4:1
                E            6.93000         5            3:2
                D            7.29600         5            2.5:2.5
                 C           8.92800         5           2:3
                B            9.24800         5           1:4
                A           10.37000         4            0:5
                    The ANOVA Procedure
```

t Tests (LSD) for cv

```
          Alpha                                        0.05
          Error Degrees of Freedom                     27
          Error Mean Square                            0.005283
          Critical Value of t                          2.05183
          Least Significant Difference                 0.096
          Harmonic Mean of Cell Sizes                  4.827586
            NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.
   t Grouping              Mean        N      Comp
           G            16.46900       4      5:0
           F            19.03520       5       4:1
           E            21.60000       5      3:2
           D            22.10640       5      2.5:2.5
           C             23.73240       5      2:3
           B             25.74020      5      1:4
          A             26.60780       5      0:5
                 The ANOVA Procedure
                t Tests (LSD) for co
          Alpha                               0.05
          Error Degrees of Freedom            27
          Error Mean Square          0.008129
          Critical Value of t        2.05183
          Least Significant Difference   0.1191
          Harmonic Mean of Cell Sizes  4.827586
            NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.
        t Grouping              Mean      N        Comp
           F                  1.80250     4        5:0
           E                  3.30600     5        4:1
           D                  5.21000     5         3:2
           D                  5.23800     5         2.5:2.5
           C                  5.46000     5          2:3
```

```
     B                      5.64000     5          1:4
     A                      5.96000     5          0:5
           The ANOVA Procedure
         t Tests (LSD) for density
   Alpha                                       0.05
   Error Degrees of Freedom                 27
   Error Mean Square                         15.42421
   Critical Value of t                       2.05183
   Least Significant Difference              5.1867
   Harmonic Mean of Cell Sizes               4.827586
     NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.
    t Grouping                   Mean          N      Comp
     G                           381.303       4       5:0
     F                           392.848       5       4:1
     E                           492.408       5        3:2
     D                           557.684       5        2.5:2.5
     C                           583.582        5        2:3
     B                            729.080       5        1:4
     A                           763.452        5        0:5

           The ANOVA Procedure
                              t Tests (LSD) for di
   Alpha                                   0.05
   Error Degrees of Freedom               27
   Error Mean Square                       0.215394
   Critical Value of t                     2.05183
   Least Significant Difference           0.6129
   Harmonic Mean of Cell Sizes            4.827586
     NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.
     t Grouping          Mean            N        Comp
```

```
     E              95.5820      5          5:0
  D                 97.4080      5          4:1
  D   C             97.8980      5          3:2
  B   A             98.8700      5          2.5:2.5
  B   C             98.3240       5         2:3
  B   A             98.7300       5         1:4
     A              99.0925      4          0:5
          The ANOVA Procedure
          t Tests (LSD) for cs
  Alpha                              0.05
  Error Degrees of Freedom          27
  Error Mean Square                    0.031775
  Critical Value of t                 2.05183
  Least Significant Difference        0.2354
  Harmonic Mean of Cell Sizes         4.827586
     NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.
  t Grouping            Mean        N      Comp
     D                 7.4400       4      5:0
  B   D   C             7.4840      5      4:1
     D   C             7.4660       5      3:2
  B   A   C             7.6800      5      2.5:2.5
  B   A   C            7.6820       5      2:3
  B   A                 7.7120      5      1:4
      A                7.8860       5      0:5
```

APENDIX D

Experiment plates

PLATE D1 MSS AND CNS RAW MATERIALS

PLATE D2: Matrials sieve for particle briquette segregation

PLATE D3: Mould and die for production

PLATE D4: Briquette samples

PLATE D5: Compressive strength ester

At KEBS civil engineering materials testing labs

PLATE D6: Bomb calorimeter arrangement At KEBS chemical lab

PLATE D7: Muffle Furnace at KEBS chemical lab

PLATE D8: Digital weighing scale at KEBS sample testing labs

PLATE D9: Flue gas analyzers at KEBS petroleum labs