DENSIFICATION OF SAWDUST OF TROPICAL HARDWOODS AND MAIZE COBS AT ROOM TEMPERATURE USING LOW COMPACTING PRESSURE WITHOUT A BINDER

BY

STEPHEN JOBSON MITCHUAL

(BSc. Hons Agricultural Engineering, MSc Wood Science and Technology)

A THESIS SUBMITTED TO THE DEPARTMENT OF WOOD SCIENCE AND TECHNOLOGY, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY (PhD)

WOOD SCIENCE AND TECHNOLOGY

FACULTY OF RENEWABLE NATURAL RESOURCES

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DECLARATION

I, hereby declare that this submission is my own work towards the PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

This work is dedicated to God Almighty

ABSTRACT

This dissertation reports the findings of densifying maize cobs and sawdust of six selected tropical hardwood timber species at room temperature (25^{o}C) using low compacting pressure (CP) varied from 10 MPa to 50 MPa, without a binder. The maize cobs was crushed using a hammer mill. Particle size 1mm or less of the maize cobs was used for the study. Sawdust of the six timber species were sun dried and graded into particle sizes (P): P ≤ 1 mm, 1 mm < P ≤ 2 mm and 2 mm < P ≤ 3.35 mm. Briquettes were produced using a laboratory hydraulic press and a piston. Physical and mechanical characteristics of briquettes determined were briquettes' stability, relaxed density, compressive strength (CS) in cleft, impact resistance index (IRI) and water resistance (WR) quality. Additionally, some physico-chemical and thermal properties of the biomass materials used for the study were determined. The study revealed that at 5% level of significance the density of timber species used for the study had significant negative correlation with CS in cleft, IRI and WR quality of briquettes produced. Furthermore, species density significantly and positively correlated with relaxed density of briquettes produced. Generally, species, particle size and CP had significant effect on stability in length and diameter, relaxed density, CS in cleft, IRI and WR quality of briquettes produced (p-value < 5%). Linear regression models established between the research factors and dependent variables suggested that species density, particle size and CP were good predictors of stability in length and diameter, relaxed density, CS in cleft, IRI and WR quality of briquettes produced. The multiple correlation coefficient (R) and *adjusted* R^2 for the regression models ranged from 0.74 - 0.93 and 0.54 - 0.87 respectively with p-values less than 5%. The result further indicated that mixing sawdust of *C. pentandra* with *P. africana* or *T. superba* significantly improved upon the CS in cleft, IRI and WR quality of briquettes

produced. The mixing ratio of the sawdust also had significant effect on the mechanical and physical properties of the briquettes produced. The study further revealed that briquettes produced from maize cobs at low CP and room temperature had low CS in cleft, IRI and WR quality. However, these properties were significantly improved when maize cobs was combined with sawdust of *C. pentandra*, *T. superba* and *P. africana*. The gross calorific values of the six hardwood timber species were adequate and they ranged from 20.16 to 22.22 MJ/kg. The biomass materials used for the study were also found to be environmentally friendly since they contained low amount of nitrogen, sulphur and ash content. From this study it could be concluded that briquettes with adequate physical and mechanical properties could be produced from sawdust of tropical hardwood species and their mixture at room temperature using low CP. Additionally, briquettes with adequate physical and mechanical characteristics could be produced from maize cobs at room temperature using low CP when maize cobs particles are combined with sawdust of *Ceiba pentandra*. These findings could enhance the existing technology for densifying sawdust and maize cobs, especially in the rural communities.

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CHAPTER ONE

INTRODUCTION

1.1 Justification

Sustainable development and the role of energy in the development process worldwide are vital issues that have been gaining more attention and concern over the last few decades. Fossil fuels supplied about 80% of world primary energy demand in 2004 (IEA, 2006) and their use is expected to grow in absolute terms over the next 20 - 30 years in the absence of policies to promote low-carbon emission sources. The nearly total dependence on energy from fossil sources is clearly not ideal in that crude oil reserves are limited and unevenly distributed in the world, with the most important reserves in politically unstable regions. In the past and present, distortions in the supply of crude oil result in sharp increases in crude oil prices and therefore leading to worldwide economic uncertainty. Fossil energy use is also responsible for about 85% of the CO_2 emissions produced annually (IEA, 2004). This significantly adds to the greenhouse gas emissions. The above and others are the important reasons to find other means of getting energy for the ever-growing demand for energy worldwide.

Renewable source of energy is the fastest-growing source of world energy, with consumption increasing by 3.0 percent per year (EIA, 2009). This is due to its environmental friendliness as against the rising concern about the environmental impacts of fossil fuel use and also strong government incentives for increasing renewable penetration in most countries around the world (EIA, 2009). Biomass is one of the most common and easily accessible renewable energy resources. Globally, biomass currently provides around 46 exajoules (EJ) of bioenergy in the form of combustible biomass and wastes, liquid biofuels, solid biomass/charcoal, and gaseous fuels. This share is estimated to be over 10% of global primary energy, but with over two-thirds consumed in developing countries as traditional biomass for household use (IEA, 2009). Traditionally, energy in the form of firewood and charcoal has been the major source of renewable energy for many developing countries for which Ghana is no exception (Emerhi, 2011). In Ghana firewood and charcoal accounts for about 64% of primary source of energy and 95% of rural energy consumption (Duku, *et al*., 2011; Okrah, 1999). According to Okrah (1999), the Forestry Department of Ghana reported that 1.55 million cubic metres of firewood and charcoal were produced in Ghana in 1992 alone. Studies in developing countries where fuelwood is used for domestic purposes have found that apart from the serious negative impact that the use of fuelwood have on the forest, the inefficient use of fuelwood results in significant exposure to indoor pollution. Besides, women, children and the elderly face higher risks, owing to the long hours spent around solid fuel-based fires. Additionally, women and children spend a lot of time, travel long distances as well as exposing themselves to all manner of risk in fetching firewood. Additionally, World Health Organization's assessment of contribution of a range of risk factors to the burden of disease revealed that indoor air pollution is the 8th most important risk factor and is responsible for 2.7% of the global burden of diseases (World Health Organization's, 2005 as cited in Moturi, 2010).

Among the several kinds of biomass resources, agricultural residues and sawdust have become one of the most promising choices as cooking fuels due to their availability in substantial quantities as waste annually. In Ghana sawdust is an abundant waste material at the sawmills in areas such as Akim Oda in the Eastern Region, Takoradi in the Western Region, Kumasi in the Ashanti Region and Sunyani in the Brong Ahafo Region. Estimate from report of international tropical timber organisation's (ITTO) annual review and assessment of the world timber situation show that in 2008 alone, the total output of round log in Ghana and Africa were 1,291,600 m^3 and 18,136,200 m^3 with corresponding sawdust estimates of 142,080 m^3 and 1,994,980 m^3 respectively (ITTO, 2008). However, only a few mills in Ghana are able to use part of the raw sawdust produced as fuel to meet their own steam and power generation requirements. Most mills generate large quantities of sawdust, which accumulate at the mills annually. At best they are used for filling of land site or burnt.

Table: 1.1 Production of different agricultural crops in Ghana for 2010 and estimated potential residues

Crop	**Residue**	**Residue to product ratio (tonnes/tonnes of crop)**	**Total crop production ('000 tonnes)**	**Residue production ('000 tonnes)**
Maize	Cob	1.00	1,872	1,872
Millet	Stalk	3.00	219	657
Rice	Straw	1.50	429	643.5
Sugar cane	Bagasse	0.30	145	43.5
Coconut	Shell	0.60	298	178.8
Oil palm fruits	EFB	0.25	2,004	501
Cocoa	Pods, Husk	1.00	632	632
Coffee	Husk	2.10	1.2	2.52
Total			**5,600.20**	**4,530.32**

Source: FAOSTAT (2010); OECD/IEA, (2010) Ghana is an agricultural country and over 60% of her estimated workforce is employed by the agricultural sector (Amesimeku, 2012). This culminates into the cultivation of various crops such as millet, rice, maize, sugar cane and cocoa by farmers. This leads to the generation of large volumes of agricultural crop residues such as maize cobs, rice husk, millet stalks, baggasse and cocoa bean shells as presented in **Table 1.1**. These agricultural residues normally obtained from field and processing sites are often left to decay or burnt inefficiently in their loose form causing air pollution (Maninder *et al*, 2012). As shown in **Table 1.1**, by the end of the year 2010, about 1,872,000 tonnes of maize residue was generated in Ghana. This constitutes about 41% of the total agricultural crop residues generated. Maize cob, a residue of the maize crop, is a lignocellulosic biomass material which contains high amount of organic constituents and energy. Therefore, it is recognised as a potential source of renewable energy (OECD/IEA, 2010).

Sawdust and maize cobs in their natural form are bulky materials, they have low bulk density, low heat release and generate excessive amounts of smoke (Akowuah, *et al*., 2012). It is estimated that the highest bulk density of unprocessed wood residue is around 250 kgm^{-3} (Demirbaş, 2001). This makes its transportation and storage about five times more costly and also less efficient source of fuel than alternatively using it in the form of briquettes or pellets (Aruna, *et al*., 1997). Densification of agricultural residue and wood biomass waste into pellets and briquettes is now a major source of energy in Europe, North America and Asia. Previous studies conducted to examine the economic impacts of using biomass energy clearly show that the benefits of production of briquettes for many economies clearly exist. Briquettes are used for heating of homes, cooking, as well as for other industrial heating and generation of electrical energy. A good briquette which has sufficient toughness to withstand exposure to weather and shocks during transportation has a much higher net calorific value than firewood. It is also easier to kindle than a solid wood since most of its volatile substances as well as the moisture are removed during its manufacture. Briquettes are considered to be carbon neutral and therefore more environmentally friendly than fossil fuels. They are uniform in size and quality and also easy to transport and store. Additionally, utilisation of briquettes will help to reduce pressure on the forest by providing substitute to fuel wood and charcoal and thereby reduce the time spent by women and children on basic survival activities like gathering of firewood. Briquetting also provides solution to the desposal problems associated with sawdust. It can also lead to the creation of jobs and increased revenue for sawmills and farmers in localities where briquettes are produced.

The most advanced project in Ghana on briquetting is probably the sawdust briquetting plant that was established at Akim Oda in 1984 (Atakora, Unpublished). The production could not be sustained due to operational, marketing and standardisation challenges, though the briquettes had high prospect as an alternative to firewood and charcoal (Akowuah, *et al*., 2012). The main operational challenge that mitigate against production of briquette is high investment cost and high energy input to the process which result in high production cost. Besides, the briquetting process requires high pressure which leads to high wear rate of machine parts (Dutta, 2007). Additionally, the mode of processing of logs in sawmills in Ghana results in sawdust of different species being mixed up at the disposal ground. It could be deduced from literature that different biomass materials required different optimum conditions for briquetting process (Tumulura, *et al*., 2010). Thus, designing suitable equipment and adoption of optimum scientific conditions for pressing such residues require adequate knowledge of the factors that influence the compacting process. This calls for intensive research in this area in order to document the best scientific practices for producing briquettes from these locally available residues. This research will consist of a series of experiments investigating the optimum conditions for producing briquettes from sawdust and maize cobs generated in Ghana without a binder. It is expected that the success of this work, among other things, will lead to better understanding of scientific method of production of briquettes from sawdust and agricultural residue generated in Ghana.

1.2 Objectives of the study

The objective of this study is to determine the optimum conditions for producing briquettes from sawdust of selected timber species and maize cobs at low compacting pressure and room temperature without a binder. Specifically the study seeks to determine the:

i. Mathematical relationship between compacting pressure, particle size and species density and physico-mechanical properties of briquettes produced from six timber species at room temperature using low compacting pressure without a binder.

ii. Effect of combination of sawdust of three timber species on the physico-mechanical properties of briquettes produced at room temperature using low compacting pressure without a binder.

iii. Effect of mixing sawdust and maize cobs on the physico-mechanical properties of briquettes produced at room temperature using low compacting pressure.

iv. Fuel characteristics of sawdust of six selected tropical hardwood species and maize cobs.

1.3 Significance of the study

The significance of this study among others are:

(i) It would help to document the optimum scientific procedure for densifying selected biomass residue generated in Ghana.

(ii) The results of this study would extend the knowledge in producing briquettes from tropical hardwood species and maize cobs.

(iii) It would help provide technology for producing briquettes in rural areas where there is lack of electricity.

(iv) This study would provide better understanding of variables that influences briquetting of sawdust of tropical hardwood species.

(v) It would help to reduce pressure on the forest by minimizing the usage of firewood and charcoal as domestic and small scale industrial fuel would be substituted with briquettes.

(vi) Women and children would no longer have to travel long distances, spend a lot of time and also be exposed to numerous risks in acquiring fuel.

(vii) A shift from the use of petroleum products like kerosene, coal and liquefied petroleum product to the use of biomass briquettes as industrial and domestic fuel would help reduce the greenhouse effect since biomass is carbon neutral.

(viii) It would help to diversify the sources of energy in Ghana and therefore help to improve the energy security in Ghana.

1.4 Limitations to the study

The limitations to this study among others are:

i. Estimating the effect of cell wall thickness on the mechanical properties of briquettes produced would have enhanced the value of the study, however the unavailability of equipment hindered such estimation.

ii. The researcher had wanted to examine the ultra structure of the briquette produced and it relationship with the formation of bonds in the briquettes produced but the lack of equipment did not permit that examination.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter consists of the relevant literature on the research work. It comprises of a brief information on sustainable economic development of biomass energy, the current trends and setbacks concerning fossil and biomass fuels. It also looks at the use of wood and agricultural residue for production of biomass fuel and their quality characteristics.

2.2 Energy supply and demand situation in the world

Although energy use and economic growth are decoupled at higher levels of development, for the world's poorest people, small increases in energy consumption are often associated with dramatic improvements in quality of life. Energy consumption has been noted to correlate closely with both welfare and economic growth (IEA, 2004; Vivekanad, 2012). For every productive activity, power is a must. Power has quickened the speed of production in most countries around the world (Vivekanad, 2012). In rural areas, modern energy services could help to reduce drudgery of women's labor, improve health and education, and stimulate micro-enterprises. At the national level, energy services facilitate economic development by underpinning industrial growth and providing access to global markets and trade (UK-DFID, 2002).

Notwithstanding the above importance of energy, currently more than two billion people in the world do not have access to affordable energy services, 2.4 billion people worldwide rely on traditional biomass for cooking and 1.6 billion people do not have access to electricity at all. These people often go without refrigeration, radio, communication and even light (REN21). This energy divide entrenches poverty, constrains the delivery of social services, limits opportunities for women and children, and erodes environmental sustainability at the local, national, and global levels. Thus, greater access to energy services is essential to address this situation and to support the achievement of the United Nations Millennium Development Goals (UN-Energy, 2005).

Access to modern decentralized small-scale energy technologies, particularly renewable (including biofuels), are an important element for successful and effective poverty alleviation policies (IEA, 2004). Renewable energy and biomass fuels are not only important issues in themselves but are among several new and dynamic sectors that developing countries would stand to benefit from if they participated in developing these kinds of energy. Besides the environmental benefits from biomass energy due to the partial replacement of fossil fuels, biofuel production and trade could also give rise to significant social benefits due to the possible job creation mainly in rural areas (IEA, 2004).

2.3 Fossil fuels, their importance and current setbacks

Fossil fuels are of great importance because they are burnt to produce significant amounts of energy for industrial work. However, they are non-renewable resources as they take millions of years to form. Currently, fuels from crude oil supply about 96% of the worldwide energy demand for transportation (IEA, 2004). Other forms of energy (coal, natural gas, alcohols, electric energy) only have a significant role at a local level or for specific transport applications (IEA, 2004). The nearly total dependence on fuels from crude oil is not ideal. The world is currently in energy crisis, with global demand of energy significantly rising (Parry & Anderson, 2005). Crude oil reserves are limited and unevenly distributed in the world. Besides, its utilization contributes immensely to green house effect. These and others are the important reasons to find other means of getting energy for the ever-growing world population. Therefore, a diversification of primary energies for fuel production will be necessary, especially to energy forms that are locally available, environmentally friendly or at least more evenly distributed than crude oil.

2.4 Renewable energy

Renewable energy commonly refers to both traditional biomass (i.e. fuelwood, animal wastes, and crop residues burned in stoves) and modern technologies based on solar, wind, biomass, geothermal, and hydropower (Martinot, *et al*., 2002). It accounted for over 15% of world primary energy supply in 2004, including traditional biomass (7 - 8%), large hydro-electricity (5.3%, being 16% of electricity generated), and other 'new' renewables (2.5%) (Sims, *et al*., 2007). In general the benefit of increased utilization of renewable energy resources, among others, is for the long term energy sustainability and also acts as a means of pollution control. Specifically, utilization of renewable energy will help to address the environmental concerns that emerged due to the greenhouse gas emission such as carbon dioxide (CO_2), oxides of nitrogen (NOx), oxides of sulfur (SOx) and particulate matters as a result of power generation from oil, natural gas and coal (Mustapa, *et al*., 2010). It can also contribute to the security of energy supply, as well as playing a dominant role in the achievement of the UN Millennium Development Goal (REN21). Additionally, renewable energy sources like solar, wind, biogas, biomass and biofuels, and small hydropower are helpful and can be applied for agricultural support, new techniques, development of transport, employment generation, self employment, rural electrification, gender equality, forest conservation, harvesting, drying and irrigation (Vivekanad, 2012).

2.5 Current development and utilization of renewable energy technology

As indicated in **Table 2.1** renewable energy technologies meet a wide range of energy needs, though their suitability and economic feasibility vary widely within and between countries. The world at large is already using several renewable energy technologies, including small-scale biogas, hydro, wind, and solar, extensively to meet the needs of rural areas of the developing world, particularly in South Asia and sub-Saharan Africa (REN21). In other cases, developing countries are deploying advanced, large-scale renewables, including large-hydro, geothermal, wind power, and biofuels, in much the way these technologies are used in industrialized nations (Martinot, *et al*., 2002). Although these grid connected energy sources primarily meet the needs of the urban middle class, by reducing overall dependence on fossil fuels they may improve general economic conditions and thus help in achieving the Millennium Development Goals (REN21).

Over the past five years, annual installations of wind energy on farms have doubled, while annual installations of solar power systems have increased six-fold (Sawin, 2005). Total installed capacities of both technologies have grown at an average annual rate of 20 - 30 percent over the past decade, closer to the high growth rates seen in computers and mobile phones than to the single - digit growth rates common in today's fossil-fuel markets (REN21). While the costs of on-shore wind turbines have declined by 12 - 18 percent with each doubling of global capacity, the costs of solar PV have declined by 20 percent per doubling. Although costs of solar PV rose in 2004 due to market factors, further cost reductions in both technologies are expected due to efficiency and scale (REN21). The market for solar thermal collectors, which capture the sun's warmth to heat water and

Table 2.1: Major renewable energy technologies and application, 2005

Renewable Energy Technology/ Application	Energy Service	Locale of Application
Solar PV	Residential and industrial electricity (grid-connected)	Mostly urban
Solar Home Systems (SHS)	Lighting (homes, schools, streets) and other low-to-medium voltage electric needs (telecommunications, hand tools, etc)	Urban and rural
Solar PV Pumps	Pumping water (for agriculture and drinking)	Mostly rural
Solar Thermal	Residential and industrial electricity (grid-connected)	Mostly urban
Solar Water Heaters	Heating water	Urban and rural
Solar Cookers	Cooking (for homes, commercial stoves, and ovens)	Mostly rural
Solar Dryers	Drying crops	Mostly rural
Wind Turbines	Residential and industrial electricity (grid-connected), Mechanical power and low voltage electricity needs (small stand-alone)	Urban and rural
Wind Pumps	Pumping water (for agriculture and drinking)	Mostly rural
Biogas	Residential and industrial electricity (grid-connected), cooking and lighting (house-scale digesters), motive power for small industry and electric needs (with gas engine)	Urban and rural
Solid Biomass	Cooking and lighting (direct combustion), motive power for small industry and electric needs (with electric motor)	Mostly rural
Liquid Biofuel	Transport fuel and mechanical power, particularly for agricultural; heating and electricity generation; some rural cooking fuel	Urban and rural
Large Hydro	Grid electricity (residential and industrial)	Mostly urban
Small Hydro	Lighting and other low-to-medium voltage electric needs (telecommunications, hand tools, etc.), process motive power for small industry (with electric motor)	Mostly rural
Geothermal	Grid electricity and large-scale heating	Urban and rural

Source: REN21, Energy for Development: The Potential Role of Renewable Energy in Meeting the Millennium Development Goals advances, economies of scale in production, declining costs, and rapidly growing political support (REN21).

building space, grew some 50 percent between 2001 and 2004. About 18 million square meters of capacity were added in 2004, mostly in China, bringing the energy equivalent of global installations to a level far exceeding that of global wind and solar power combined (REN21). Meanwhile, costs have fallen from about 44 cents/kWh in the 1980s to 12 - 18 cents/kWh today, with future cost reductions expected due to efficiency and scale (REN21).

Production and use of biofuels also advanced quickly in 2004, spurred by agricultural, environmental, and consumer interests. Fuel ethanol production increased 13.6 percent, reaching almost 33 billion litres. Nearly twice as much ethanol was produced in 2004 as in 2000. Ethanol is the most widely used biofuel for transportation, and Brazil and United States dominate the market (Mustapa, *et al*., 2010). World production of biodiesel fuel, based on vegetable oil and fats, is smaller but has been growing faster to nearly 1.8 billion litres in 2003, up 18 percent over 2002 (US-DOE). Not with standing these gains, renewable energy technology development is hampered by several barriers which are financial, technical, regulatory/institutional and informational in nature that need to be addressed (Mustapa, *et al*., 2010).

2.6 Biomass energy

Behind coal and oil, biomass is the third largest energy resource in the world (Bapat, *et al*., 1997). Until the mid-19th century, biomass dominated global energy consumption. Even though increased fossil-fuel use has prompted a reduction in biomass consumption for energy purposes over the past 50 years, biomass still provides about 1.25 billion tons of oil equivalent (Btoe) or about 14% of the world's annual energy consumption (Purohit, *et al*., 2006; Zeng, *et al*., 2007). Biomass is becoming increasingly important globally as a clean and reliable source of energy alternative to fossil fuel (Duku, *et al*., 2011; Li & Hu, 2003).

The simplest and least expensive biomass resources are the waste products from wood or agro-processing operations, but their supply is limited. To overcome this limitation, countries around the world are considering biomass crops for energy purposes and have begun developing technologies to use biomass more efficiently. In the United States of America and most of Europe, biomass has already penetrated the energy market. The U.S. and Sweden obtain about 4% and 13% of their energy, respectively, from biomass (Hall, *et al*., 1992), and Sweden and Germany are implementing initiatives to phase out nuclear plants, reduce fossil fuel energy usage, and increase the use of biomass energy (Björheden, 2006).

Wood burning as a heat and light source has been popular for millennia. Biomass, if properly managed, as stated earlier offers many advantages. The most important advantage to be derived from the use of biomass is that it is a renewable and sustainable energy feedstock. It can significantly reduce net carbon emissions when compared to fossil fuels. For this reason, renewable and sustainable fuel is considered a clean development mechanism for reducing greenhouse gas emissions (Li & Hu, 2003).

2.7 Utilization of firewood and charcoal as a source of energy and associated problems

Wood fuel may be available as firewood (logs, bolts and blocks), charcoal, chips, sawdust, briquettes and pellets. The particular form used depends upon factors such as availability, quantity, quality and availability of technology. Wood fuel provides an average of 75 percent of developing countries' renewable energy demand (IEA, 2004). Energy from wood has traditionally been based on fuelwood and charcoal. Globally, the annual consumption of fuelwood (including wood for charcoal) was about 1.845 billion m^3 in 2009 and it contributed to an estimated 7 percent of the world's total energy supply of fuel (FAOFORESTSTAT, 2010). More than half of this roundwood is classified as non-industrial roundwood, and they are mostly used as fuelwood in the domestic sector of rural areas of

Table 2.2: Fuel wood production by region

Region	Production in 2009 (million m³)	Percentage (%)
Africa	602.4	33
Asia	770.7	42
Europe	141.4	8
Latin America & Caribbean	282.9	15
Northern America	42.6	2
Oceania	10.7	1
World	1850.7	100

Source: FAOFORESTSTAT (2010)

developing countries (FAOFORESTSTAT, 2010). Between 2004 and 2009 wood fuel production increased by 1.3% globally (FAOFORESTSTAT, 2010). In **Table 2.2** is shown the regional distribution of wood fuel production. Asia is the region with the highest production of wood fuels accounting for 771 million m³ or 42% of global production. This role is strongly driven by China and India. These two countries account for more than 25% of the global wood fuel production. Africa ranks second behind Asia. In 2009, wood fuel production in Africa totaled 602 million m³, or 33% of global production (FAOFORESTSTAT, 2010). In most developing countries, charcoal is still widely used in urban and rural areas as a smokeless domestic cooking fuel, with high heating value of about 29.6 MJ/kg. Production of charcoal in developing countries has increased, rising by an annual rate of 3.7 percent from 26 million tonnes in 1990 to reach 44 million tonnes in 2005 (FAO, 2009 as cited in Duku et al. (2011). In line with the annual increase in demand of energy globally, energy demand in Ghana has increased significantly as a result of population increase and urbanization.

Table 2.3: Consumption of wood fuel and wood charcoal in Ghana 2004 - 2008

Year	Wood fuel (m^3)	Wood charcoal (tonnes)
2004	20, 678, 000	752, 000
2005	20, 678, 000	752, 000
2006	33, 039, 530	1, 358, 977
2007	31, 477, 900	1, 418, 300
2008	35, 363, 400	1, 477, 700
Total	141, 236, 830	5, 758, 977

Source: FAO (2009) as cited in Duku et al. (2011)

The increased demand is, however, more pronounced in the consumption of wood fuel, particularly wood charcoal (Duku, *et al*., 2011). According to FAO (2009), as cited in Duku et al. (2011) and indicated in **Table 2.3** the consumption of wood fuel in Ghana increased from 20.7 million m^3 in 2004 to 35.4 million m^3 in 2008, whilst the consumption of wood charcoal also increased from 752,000 m^3 to 1.48 million m^3 during the same period.

2.8 Quantity of wood and agricultural waste generated in the world

In United Kingdom, Magin (2001) stated that wood residue or waste is generated at all stages of the life of a piece of timber, from harvesting and saw milling, through trading (e.g. furniture and joinery manufacture), to end of life disposal (e.g. demolition, disposal of old wood items). In general residues generated from forest products industry could be divided into two categories: logging residues and wood processing wastes (Duku, *et al*., 2011).

2.8.1 Logging residues

Logging residues are the branches, leaves, bark, stumps, off-cuts, sawdust and other wood and tree waste generated during and after logging at the logging site (Gustavsson, *et al*., 2011). A study conducted by Amoah and Becker (2009) on commercial logging efficiency in Ghana showed an average logging recovery of 75%. Using this percentage of recovery and figures in **Table 2.4**, it could be estimated that logging residue generated in ITTO member countries, Africa and Ghana in 2008 were 77,016,000 m^3, 6,045,400 m^3 and 430,530 m^3 respectively. In practice, not all of the logging residues can be used for bioenergy production due to technical constraints, ecosystem functions, and other uses such as animal fodder and fertilizer. There are also environmental concerns considering an extensive long term use of logging residues. For instance, leaving appropriate levels of logging residues protects soil quality and eliminates the need for the use of fertilisers (OECD/IEA, 2010; Domson & Vlosky, 2007).

2.8.2 Wood processing wastes

Wood processing wastes such as discarded logs, bark, sawdust, off-cuts, trimmings, split wood, sander dust, planer shavings are generated through sawmill and plywood mill processing activities . It is reported that, generally, sawmills in Ghana have recovery rates ranging from 20 to 40% of the log input, averaging 33.3% (Sekyere & Okyere, 2007). According to the Wood Explorer Glossary, generally the percentage of the log that winds up as lumber is between 54 - 55%, sawdust is 4 - 19%, and chips are 27 - 41%.

Table 2.4: Average annual logs and sawdust production (1000 m^3)

Region	Year					Average annual quantity of logs produced	Estimated quantity of sawdust generated per annum
	2004	2005	2006	2007	2008		
All ITTO member countries	226,248	236,232	232,899	234,770	225,091	231,048	25,415
Africa	18,005	17,633	18,805	18,175	18,063	18,136	1,995
Ghana	1,370	1,220	1,324	1,324	1,220	1,292	142

Source: ITTO Annual review and assessment of the world timber situation 2008

NB. Sawdust generated is estimated as 11% of log input

Report on Sector Reform and the Pattern of the Poor-energy use and supply indicated that sawmill residues are among the most promising feedstock for energy purposes in Ghana. Another report by UNDP/World Bank Energy Sector Management Assistance Project on Sawmill Residue Utilisation in 1988 indicated that solids and sawdust accounted for 79 and 21% respectively of the residues generated in Ghana (Atakora, *et al*., Unpublished). Estimates from reports of International Tropical Timber Organization's (ITTO) annual review and assessment of the world timber situation (2008) as shown in **Table 2.4** suggest that on the average sawdust generated annually between 2004 and 2008 in the whole of ITTO member countries, Africa and Ghana was about 25,415,280 m^3, 1,994,980 m^3 and 142,076 m^3 respectively (ITTO, 2008). In Ghana, agriculture is the backbone of the economy contributing about 42% of the gross domestic product. About 60% of the total workforce in Ghana is employed by the agricultural sector (Amesimeku, 2012). Most farmers in Ghana engage in the cultivation of crops like millet, rice, corn, sugar cane and cocoa. These activities result in the large volumes of agricultural residues as indicated in chapter one of this study.

2.9 Chemical composition of biomass

Chemical composition of wood cannot be defined precisely because it varies with tree part (root, stem, or branch), type of wood (i.e. normal, tension, or compression) geographic location, climate, and soil conditions. However, analytical data accumulated from many years of work and from many different laboratories have helped to define average expected values for the chemical composition of wood (Pettersen, 1984). Plant biomass has both low molecular weight and macromolecular compositions (Tumuluru, *et al*., 2010). Low-molecular-weight substances include extraneous materials mostly in the form of organic extractives and minerals (ash), while macromolecular substances are carbohydrate (which includes cellulose, hemi-cellulose) and lignin (Mohan, *et al*., 2006). Overall, wood has an elemental composition of about 50% carbon, 6% hydrogen, 44% oxygen, and trace amounts of several metal ions (Pettersen, 1984). Understanding some of the major chemical compositional changes that take place during processing of biomass can be useful in understanding their compaction behavior.

2.9.1 Lignin

Lignin is a phenolic substance consisting of an irregular array of variously bonded hydroxy- and methoxy-substituted phenylpropane units (Pettersen, 1984). Lignin varies in composition among tree species, and even among individual trees. Lignins are complex polymers that are amorphous and three dimensional in structure. The lignin molecule in a plant provides many structural purposes, such as acting as glue to the cellulose fibres. The lignin molecule in a plant provides many structural purposes, such as acting as glue to the cellulose fibres. Lignin content of wood can vary from 15 to 40% (Sarkanen & Ludwig, 1971). Pettersen (1984) also stated that the amount of lignin in wood is between 18 to 35%. Within a species, average lignin content of wood is much less variable, often ranging only a few percent (van Buijtenen *et al*., 1968). One important property of lignin that is important in biomass densification is its glass transition temperature. Irvine (1984) found that the glass transition temperature of lignin ranged from 60 to 90^{o}C. Back and Salmen (1982) also stated that dry lignin have glass transition temperatures between 130 and 205^{o}C. According to Lehtikangas (1999), moisture of between 8 - 15% in biomass will reduce the softening temperature of lignin to 100 - 135°C by plasticizing molecule chains. The adhesive properties of thermally softened lignin are thought to contribute considerably to the strength characteristics of briquettes made of lignocellulosic materials (Granada, *et al*., 2002).

2.9.2 Cellulose

Cellulose, the major chemical component of fibre wall contributes 40 - 45% of the wood's dry weight. The amount of cellulose in wood varies from species to species. It is composed of linear chains of D-glucose linked by ß-1,4-glycosidic bonds with the degree of polymerization from 10,000 in native wood to 1,000 in bleached kraft pulps (Shriver, *et al*., 1994). Cellulose has a strong tendency to form intra- and inter-molecular hydrogen bonds by the hydroxyl groups on these linear cellulose chains, which stiffen the straight chain and promote aggregation into a crystalline structure and give cellulose a multitude of partially crystalline fibre structures and morphologies (Klemn, *et al*., 2005).

Crystalline cellulose has a very limited accessibility to water and chemicals. Chemical attack can therefore be expected to occur primarily on amorphous cellulose and crystalline surface. Cellulose is insoluble in most solvents including strong alkali. It is difficult to isolate from wood in pure form because it is intimately associated with the lignin and hemicelluloses (Pettersen, 1984). A cellulose unit cell is the smallest component of the cellulose crystal that reproduces the whole crystal when repeated (Shriver, *et al*., 1994). The glass transition temperature for cellulose varies between 200 and 250^{o}C (Backman & Lindberg, 2001). Zandersons, *et al*. (2004) concluded that the binding strength of wood based products mainly depends on converting the cellulose to an amorphous state.

2.9.3 Hemicelluloses

Hemicelluloses are mixtures of polysaccharides synthesized in wood almost entirely from glucose, mannose, galactose, xylose, arabinose, 4-*O* methylglucuronic acid, and galacturonic acid residues (Pettersen, 1984). The main hemicelluloses of softwood are galactoglucomannans and arabinoglucuronoxylan while in hardwood is glucuronoxylan. Generally, hemicelluloses are of much lower molecular weight than cellulose and some are branched (Pettersen, 1984). Hemicellulose constitutes about 20% of wood substance by weight in softwoods and 15 to 35% in hardwoods. They are chemically related to cellulose in that both are carbohydrates chemical substances composed of carbon, hydrogen and oxygen (Pettersen, 1984). The degree of polymerization in hemicelluloses is much smaller than in cellulose, approximately 100 - 200, which makes them susceptible to chemical attack. They are soluble in alkali and easily hydrolyzed by acids (Tumuluru, *et al*., 2010). Some researchers believe that natural bonding may occur due to the adhesive degradation products of hemicelluloses (Tumuluru, *et al*., 2010). Back and Salmen (1982) stated that dry hemicellulose have glass transition temperatures of between 150 and 220^{o}C.

2.9.4 Extractives

Extractives are relatively low molecular weight compounds which often give wood colour and can also protect wood from decay. Extractives are soluble in organic solvents and water. The extractives content of trees is typically less than 10%, and the distribution of extractives varies by species, as well as location within an individual tree (Pettersen, 1984). The functions of extractives are diverse. For example, they may provide energy, or protect trees from microbiological or insect attack. Extractives include (1) terpenes, (2) resin acids (3) triglycerides and fatty acids, and (4) phenolic compounds (Pettersen, 1984).

2.10 Physical and chemical properties of maize cobs

The bulk density of crushed cobs was 227 kg/m^3 and it is more than double the density of uncrushed maize cobs unprocessed (Martinov, *et al*., 2011). Zhang *et al*. (2012) in their study titled physical properties of corn residues also indicated that the average bulk density of maize cobs was 282.38 kg/m^3. A group of researchers, Clark and Lathrop (1953) and Foley (1978) found that maize cobs contain 32.3 - 45.6% cellulose, 39.8% hemicelluloses - mostly composed of pentosan, and 6.7 - 13.9% lignin. Mullen, *et al*. (2010) also established that Cellulose, Hemicellulose and Lignin forms 30%, 38% and 3% respectively of maize cobs.

2.11 Biomass densification

Densification is a process in which materials like waste sawdust, chips, shavings, agricultural waste and other biomass materials are compressed under high pressure and temperature, which causes the content of lignin in the wood or lignocelluloses material to be softened, thereby binding the material to a firm briquette. Generally, it represents all technologies used for converting plant residues into compact biomass fuel. This technology, also known as pelleting, briquetting or agglomeration, aims at improving the handling characteristics of the biomass materials (Tumuluru, *et al*., 2010). Briquette has higher density and energy content, and is less moist compared to its raw materials. Briquetting of biomass can be done using various techniques, either with or without binder addition.

In most developed countries, wood processing industries have turned rapidly to energy self-sufficiency and to the sale of excess power to local electric grids through the use of densified wood residue and other residues. However, in developing countries the development of wood energy is rare because most sawmills lack the technical know-how or are simply not ready to invest into such area (Kristofferson & Bokalders, 1986). The idea of producing briquettes from fine timber waste and other residue dates back to the turn of 19th and 20th centuries and of late this technique has aroused the interest of most developing countries all over the world (Obernberger & Thek, 2002). Utilisation of lignocellulose waste by converting them into briquettes is economically and environmentally justified in that the net calorific value per unit volume of briquettes made is increased and is comparable to that of lower quality class of coal and higher than firewood and charcoal. Generally, two kilograms of wood briquettes holds the same energy as one litre of fuel oil (Bhattacharya, *et al*., 1989).

Brequetting of wood waste helps to resolve a key limitation to the use of biomass fuel which is its bulkiness compared to coal and other solid fuel. Briquettes made from wood are normally less than one tenth of the volume of the raw material and thus making its transportation a lot easier and far less expensive. Thus, compared to coal and other combustion fuels, biomass is expensive to handle and the cost of transportation looms large in assessments of financial viability. Additionally, the continuously increasing price of the fossil fuel, the greater greenhouse effect caused by utilization of the fossil fuel and the increasing damage to the environment due to the use of fire wood and charcoal justifies the need to use biomass residue.

2.12 Briquetting technology

Briquette pressing can be classified using several criteria. Based on the operating condition, briquetting can be classified into two categories:

- Hot and high pressure pressing
- Cold and low pressure pressing (Dutta, 2007)

Based on mode of operation, it falls into two categories:

- Batch pressing - with this the briquettes are pressed in an already dimensioned presser. As such they come out in their desired size.

- Continuous densification - with this briquettes are produced in a long cylinder and later cut to dimension (Dutta, 2007).

However, depending on the type of equipment used, it can be categorized into three main types:

- Hydraulic pressure press machine
- Mechanical piston press
- Screw compaction or extruder press

2.12.1 Hydraulic pressure press machine

Figures 2.1a and **b** are pictures of hydraulic press machine and briquettes produced from it. This machine was invented in Henan Agricultural University of China in 1990. It is different

Figure 2.1a: Hydraulic piston press machine

Figure 2.1b: Briquettes from hydraulic press

(**Source:** C. F. Nielsen A/S, Solbjergvej 19, DK-9574 Baelum, cited in Tumuluru, *et al*., 2010)

from the mechanical piston press in that the energy to the piston is transmitted from an electric motor via a high pressure hydraulic oil system (Grover & Mishra, 1996).

Additionally, this machine is compact and light. In pressing, the compressed material is heated by frictional forces as it is pushed through the die (FAO, 1990). Hydraulic press machine can tolerate higher moisture content than the usually accepted 15% moisture content for mechanical piston presses (Grover & Mishra, 1996). Briquettes produced from this machine have bulk density lower than 1000 kg/m³ (Grover & Mishra, 1996).

2.12.2 Mechanical piston press

Mechanical piston presses (**Figure 2.2**) are typically used for large-scale production, ranging from 200 to 2,500 kg/hr (Tumuluru, *et al*., 2010). The mechanical press is driven by electric motors instead of a hydraulic motor. Energy loss in the machine is limited, and the output in relation to power consumption is optimal. The operating life of a mechanical press is

Figure 2.2: Mechanical press

(**Source:** C. F. Nielsen A/S, Solbjergvej 19, DK-9574 Baelum, cited in Tumuluru, *et al.*, 2010)

considerably longer than hydraulic presses. Generally, a mechanical press gives a better return on investment than a hydraulic press (www.cfnielsen.com). For the piston press briquettes machines the wear of the contact parts e.g., the ram and die is less compared to the wear of the screw and die in a screw extruder press. The power consumption for piston press briquettes machines is also less than that of screw extruder press (Grover & Mishra, 1996).

2.12.3 Screw compaction or extruder press

Figure 2.3 and **2.4** are pictures of screw press extruder machine and briquettes produced from it respectively. The screw press extruder uses the screw press technology. In this technology, the biomass is extruded continuously by a screw through a taper die which is heated externally to reduce the friction. With this the sawdust from feed hopper is conveyed

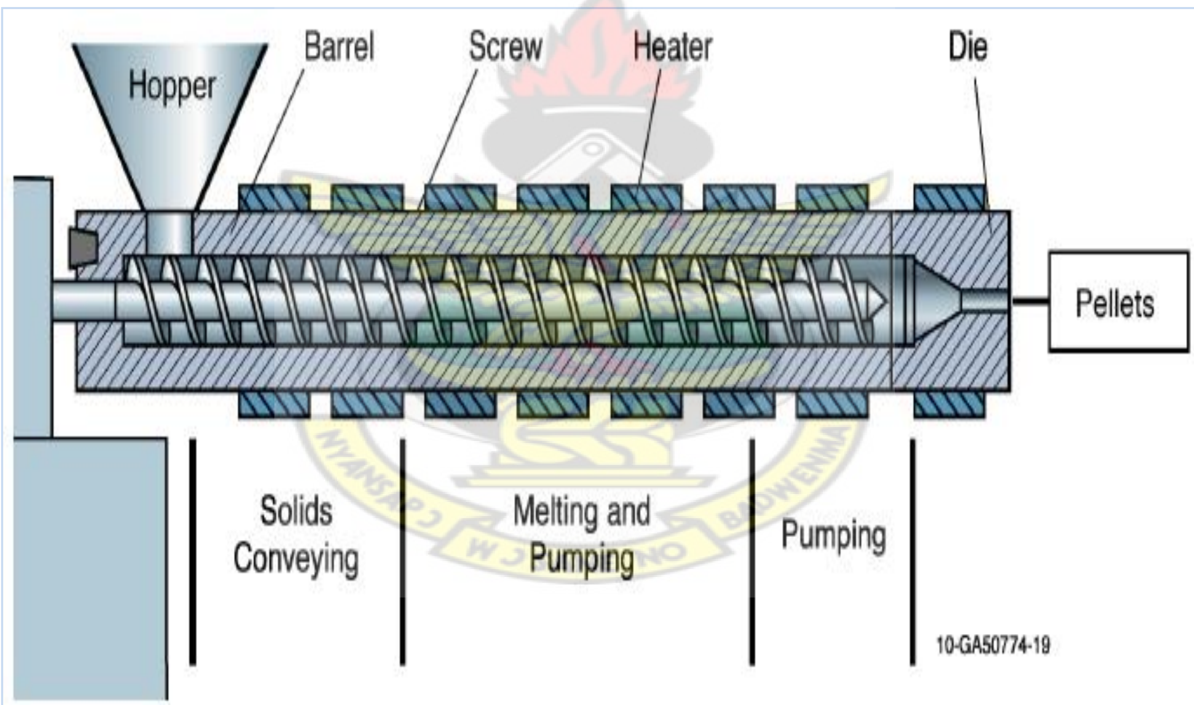


Figure 2.3: Screw press extruder for biomass processing
(Source: Scientific Principles [http://matse1.mse.uiuc.edu/polymers/prin.html])

and compressed by screw. During extrusion, the material moves from the feed port, with the help of a rotating screw, through the barrel and against a die, resulting in significant pressure gradient and friction due to biomass shearing (Grover & Mishra, 1996). The combined effects of wall friction at the barrel, internal friction in the material, and high rotational speed (~600 rpm) of the screw, increase the temperature in the closed system and heat the biomass. This heated biomass is forced through the extrusion die to form the briquettes or pellets with the required shape. If the die is tapered, the biomass is further compacted. If the heat generated within the system is not sufficient for the material to reach a pseudo-plastic state for smooth extrusion, heat is provided to the extruders from outside either using band or tape heaters (Grover & Mishra, 1996). In terms of briquette quality and production procedure,

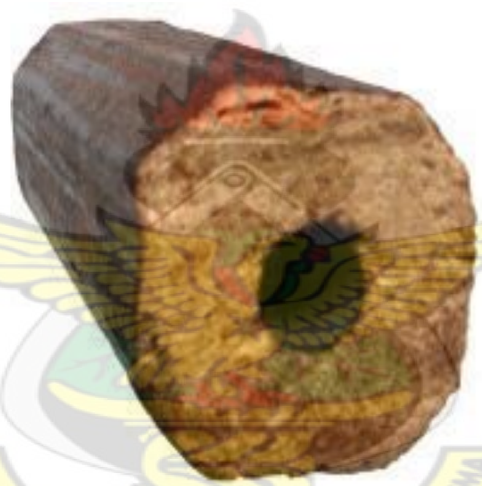


Figure 2.4: Briquettes produced from screw press

screw press is superior to the piston press technology, in that, it produces denser and stronger briquettes. Additionally, the central hole incorporated into the briquettes produced helps to achieve uniform and efficient combustion. Lastly, these briquettes can be carbonized (Grover & Mishra, 1996). There are basically two types of screw press: Conical screw press and screw press with heated die. The merit of screw press densification are:

- Output is continuous and uniform in size
- Easy ignition and combustion of briquettes produced

- A concentric hole in the briquette helps in combustion
- The machine runs very smoothly without any shock load
- The machine is light compared to the piston press
- The machine parts and the oil used in the machine are free from dust or raw material contamination.

The demerit of screw press densification are

- Wear of the screw and die is the main problem
- The power requirement of this machine is high compared to the piston press.

2.12.4 Roller pelleting machine

This consists of a matrix and roller. The pressure between them causes frictional heating and forces the material through the perforations in the matrix plate. The extruded pallets are cut off at a specified length by means of a knife. These are normally 5 - 15 mm in diameter with a length below 30 mm. Capacity of these presses ranges from slightly below 1ton/hr to about 30ton/hr (Faxalv & Nystrom, 2007).

2.13 Properties of biomass raw materials that affect densification

In order to produce good quality briquettes, the preparation of the raw material is very important. Different briquetting machines require varying optimum conditions of raw materials to ensure production of good quality briquette. Raw material characteristics that are of great importance include moisture content, particle size, shape, and particle size distribution. These variables are feedstock dependent and have a great effect on briquette quality and in selecting proper process conditions (Tumuluru, *et al*., 2010). Various researchers have also indicated that combination of different biomass materials may enhance the quality characteristics of briquettes produced (Grover & Mishra, 1996).

2.13.1 Moisture content

The most appropriate moisture content in biomass raw material for briquetting varies and it depends on the raw material as well as the process factors (Dutta, 2007). Moisture present in the biomass material facilitates starch gelatinization, protein denaturation, and fibre solubilization processes during densification of biomass (Tumuluru, *et al*., 2010). Steam-treated biomass is superior, as the additional heat modifies physiochemical properties (gelatinization of starch, denaturation of protein) to such an extent that binding between the particles is significantly enhanced, resulting in improved densification quality (Thomas, *et al*., 1997). Demirbas, *et al*. (2004) found that increasing the moisture content from 7 to 15% of spruce wood sawdust significantly increased the strength of the pellets. Mani *et al*. (2006) in their article on densification of corn stover, found that low moisture (5 - 10%) resulted in denser, more stable, and more durable briquettes. Dutta (2007) suggested that suitable moisture content of biomass raw material could be between 8 and 12%. He further stated that too high moisture can cause steam formation and could cause expansions that will destroy the briquette. Križan (2007) in his study of the factors that affect the quality of briquettes obtained an optimal density when the material humidity values were 10 to 20%. However, it is recommended that water content of minimum 6% up to maximum 16% is appropriate. If the water content is beyond 16% even for smaller part of the raw material, it will reduce the quality of the briquettes and eventually make the process impossible. At high moistures (>20% w.b.), coherent biomass briquettes/pellets may not be produced because the cell structure remains largely intact at high moisture levels due to the incompressibility of high moisture biomass particles (Pickard, *et al*., 1961).

2.13.2 Particle size, shape and distribution

Particle size and shape are of great importance for densification. In general, density and durability (mechanical strength) of pellets are inversely proportional to particle size since smaller particles have greater surface area during densification (FAO, 1990; Križan, 2007; Tumuluru, *et al*., 2010). MacBain (1966) and Payne (1996) in their studies on alfalfa, concluded that medium or fine-ground materials are desirable in pelleting because, at these sizes, they have greater surface area for moisture addition during steam conditioning, which results in increased starch gelatinization and better binding. Finely ground materials, for example sanding dust from woody plants, will make very dense briquettes but requires high pressure and temperature to agglomerate without a binder (FAO, 1990). Payne (1996) reports

Table 2.5: Best particle size distribution for producing quality pellets from lignocellulosic biomass

Sieve size (mm)	Material retained on sieve
3.0	≤ 1%
2.0	≤ 5%
1.0	≈ 20%
0.5	≈ 30%
0.25	≈ 24%
< 0.25	≤ 20%

Source: (Payne, 1996)

that a certain percentage of fine to medium particles are required to improve pelleting efficiency and reduce costs. Payne (1996) further reiterated that the best particle size distribution of biomass raw material for producing quality pellet is as indicated in **Table 2.5**.

The absence of coarse particles in the feed or biomass mix will significantly affect the production efficiency of commercial pellet mills. Very small particles can also jam the pellet mills and significantly affect production capacity. It is generally agreed that biomass material of 6 - 8 mm size with 10 - 20% powdery component (< 4 mesh) gives the best results (Grover & Mishra, 1996). Many researchers have worked on identifying the optimum particle sizes for different biomass materials to produce the best quality of pellets in terms of density and durability. The presence of different size particles improves the packing dynamics and also contributes to high static strength (Ludwig, 1994). Only fine and powdered particles of size less than 1 mm are not suitable for a screw extruder because they are less dense, more cohesive, non-free flowing entities (Grover & Mishra, 1996). Dobie (1959) indicated that fine grinding of the feed material produces pellets with higher density and increases the capacity of the machine as the material passes through the die more easily. Coarsely ground materials tend to yield less-durable pellets because they may create natural fissures in the pellets, which are then susceptible to breakage (MacBain, 1996).

2.13.3 Raw material mix or mixture of different raw materials

Studies on densified fuels derived from blends of two biomass materials indicates that the durability and mechanical strength of briquettes produced from only one type of biomass can be improved by blending that biomass with another biomass material. For example the durability of wheat straw briquette can be enhanced by blending the straw with wood waste (Yaman, *et al*., 2001; Yaman, *et al*., 2000; Wamukonya & Jenkins, 1995). Physical and mechanical properties of mixed biocoal briquettes produced that was examined indicated that mixing ratio had a significant effect on the physical and mechanical properties of briquettes produced (Jindaporn & Songchai, 2007).

2.13.4 Flowability and cohesiveness

Briquetting material should be granular and uniform so that it can flow easily in bunkers and storage silos. It should also be easy for the material to flow. Cohesiveness is also an important characteristic of the biomass material. Lubricants and binders can impart these characteristics for compaction (Grover & Mishra, 1996).

2.14 Process characteristics that affect briquettes quality

The process factors which affect briquettes' quality are: temperature, pressure, preheating of raw material, cooling lines and non-homogeneous distribution of wood dust.

2.14.1 Effect of temperature on quality of briquettes

By varying the temperature of biomass the briquette density, briquette crushing strength and moisture stability are significantly influenced (Grover & Mishra, 1996). Hill and Pulkinen (1988) found that high temperature conditioning of the raw materials result in increase of pellet durability. Hill and Pulkinen (1988) further reported that pellet durability of alfalfa increases by about 30 - 35% when pelleting temperature was increased from 60 to 104^{o}C. Mani, *et al*. (2003) and Sokhansanj, *et al*. (2005) observed a similar effect in terms of temperature, where higher temperatures resulted in reduced resistance of the material against an applied load for densification and resulted in better quality of pellets. Smith, *et al*. (1977) in their article on briquetting of wheat straw, found that for a given pressure, at temperatures between 60 and 140^{o}C, the degree of compaction and dimensional stability were higher. Additionally, the expansion of briquettes was less when the die temperature was between 90 and 140^{o}C. Tabil and Sokhansanj (1996) observed that pelleting temperatures greater than 90^{o}C significantly improved durability values of alfalfa pellets. Kaliyan and Morey (2009) concluded that the durability values of densified biomass outside the glass transition temperature were lower compared to ones within the range of the glass transition temperature. The glass transition temperature is the minimum temperature required for softening of natural binders to produce durable densified products. This is necessary to facilitate plastic deformation of particles, reduce the viscosity and increase the mobility of natural binding components. Temperature should not be increased beyond the decomposition temperature of biomass which is around 300^{o}C (Kaliyan & Morey, 2009). In screw press the temperature of the die should be kept at about 280 to 290^{o}C (Grover & Mishra, 1996). If the die temperature is more than the required one, the friction between the raw material and the die wall decreases such that compaction occurs at lower pressure which results in poor densification and inferior strength. Conversely, low temperature will result in higher pressure and power consumption and lower production rate (Grover & Mishra, 1996).

2.14.2 Effect of pressure on quality of briquettes produced

Compacting pressure plays an important role in the quality of briquettes/pellets made from biomass materials. Low pressure systems such as manual press which generate pressure of 0.2 - 5.0 MPa are only able to eliminate the voids between particles but incapable of raising the temperature or collapse the cells within the particles. Increasing the compressing force results in increased density and binding force between the particles (Lindley & Vossoughi, 1989; Clauß, 2002). Briquettes manufactured at lower pressures (30 - 60 MPa) fall to pieces easily. However, briquettes produced at higher pressures (150 - 250 MPa) are consistent and compact (Kers, *et al*., 2010). Butler and McColly (1959) observed that the density of chopped alfalfa-hay pellets was proportional to the natural logarithm of the applied pressure and that an increase in pressure significantly increases density. Yaman, *et al*. (2000) recommended that briquetting pressure should be selected at an optimum value that influences the mechanical strength by increasing plastic deformation. However, above an optimum briquetting pressure, fractures may occur in the briquette due to a sudden dilation. For a given die size and storage condition, there is a maximum die pressure beyond which no significant gain in cohesion (bonding) of the briquette can be achieved (Ndiema, *et al*., 2002). Demirbas, *et al*. (2004), in their article on compaction of biomass waste materials like waste paper, observed that increasing pressure from 300 to 800 MPa, with about 7% moisture (w.b.), increases the density sharply from 182 to 325 kg/m^3, and then the densities slightly rise to 405 kg/m^3.

2.14.3 Effect of preheating of raw material in briquetting

Preheating biomass raw material before densification is widely used, as it results in the formation of more stable and dense pellets or briquettes (Bhattacharya, *et al*., 1989; Bhattacharya, 1993). Aqa and Bhattacharya (1992) and Tumuluru, *et al*. (2010) indicated that preheating biomass could significantly increase the throughput of the pelletizing machine and reduce the energy requirement per kilogram of the biomass pellets formed. Additionally, Tumuluru, *et al*. (2010) indicated that preheating biomass to temperatures between 100 and 130^{o}C improves its binding characteristics. A regional research and dissemination programme, Renewable Energy Technologies in Asia, which was to develop improved heated-die screw-press biomass briquetting systems, by reducing the electrical energy consumption and incorporating a smoke removal system observed that the quality of briquettes produced, with and without pre-heating, was more or less similar, with the outer surface slightly charred (Dutta, 2007). However, on the average, electrical energy savings at the heater, motor and overall system were 23.5%, 10.8%, and 10.2% respectively when the raw material was preheated before briquetting (Dutta, 2007). Pre-heating is found to reduce the wear and energy consumption in the process of briquetting because: (1) It softens the raw material before it is compacted (2) Work and pressure of compression could be reduced by a factor of two by preheating to 200 - 225°C before densification (3) In case of sawdust a study shows that preheating increases the screw life from 17 to 44 hours (Dutta, 2007).

2.14.4 Cooling lines and quality of briquettes

When a mechanical press is used for producing briquettes the quality of briquettes produced depends highly on the cooling and transport lines mounted on the machine. A briquette being pushed out of a press is very hot because of the friction in the nozzle. A hot briquette does not need substantial strokes or twists. The longer time the briquette can remain under pressure in the cooling line the longer and harder it will be. Cooling lines of 35 to 50 m in length are very common (Glover & Mishra, 1996).

2.14.5 Non-homogeneous distribution of wood dust

Research work by Krauss and Szymański (2006) to investigate the possible reasons for breaking of the flow of the briquette ribbon from the moulding matrix, established that the important reason for the breaking of the flow of the briquette ribbon was the inhomogeneous distribution of wood dust and not the size of its fraction in the bulk of the lignocellulose mass introduced into the briquetting machine. They further observed that periodically, the dust from the dust filters was supplied to the wood waste storage such that there were sites with accumulation of prevalent amounts of dust and sometimes only dust was supplied to the briquetting machines. Excessive amount of dust supplied simultaneously disturbs the operation of the perpetual screw press, leading to a break in the ribbon of the briquettes formed and in high temperatures smoke is produced and the external surfaces of briquettes are carbonised. Such situations are potentially dangerous and result in dust explosions (Krauss & Szymański, 2006).

2.15 Mechanism of bonding of particles

Two important things to consider during densification are the ability of the particles to form pellets/briquettes with considerable mechanical strength and the ability of the process to increase density. The first is a fundamental issue that raises the question which type of bonding or interlocking mechanism could result in a better densified biomass (Tumuluru, *et al*., 2010). Tumuluru, *et al*. (2010) suggested that the strength of pellets/briquettes formed from densification depends only on the type of interaction and the material characteristics.

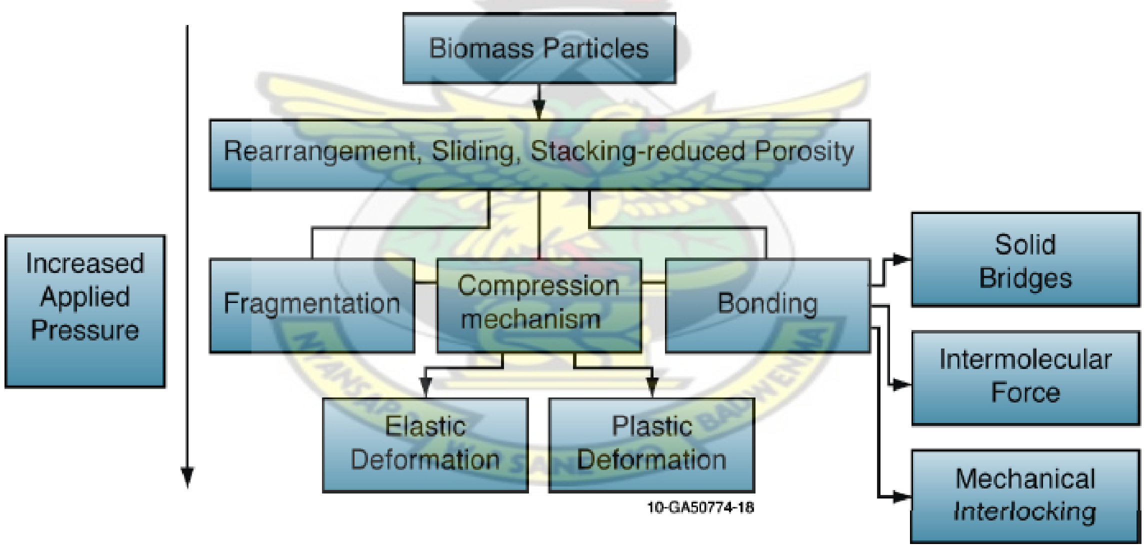


Figure 2.5: Deformation mechanisms of powder particles under compression (**Source:** Comoglu, 2007; Denny, 2002)

The type of interaction which is also the process variables that could affect the quality of the densified biomass are the die diameter, die temperature, compacting pressure, usage of binders, and preheating of the biomass mix. Alternatively, the physical properties of biomass raw material that could affect the quality of briquettes includes moisture content, particle size, density of the individual particles, bulk density, void volume and thermal properties. Furthermore, the chemical characteristics of the raw material that are of importance include the proximate and ultimate analysis, and the higher heating value. The physical properties of the biomass are very important in any description of the binding mechanisms of biomass densification (Tumuluru, *et al.*, 2010). The mechanism of bonding during densification of biomass continues to be a complex subject. However, it can be simplified as presented in **Figure 2.5.** Chung (1991) suggested that pressure, heat (above glass transition temperature), and solvent such as water are the industrial techniques to promote adhesion by increasing molecular contact between two sets of molecules. Macroscopically, the binding forces between particles can act through two binding mechanisms (Pietsch, 2002; Rumpf, 1962): (i) bonding without a solid bridge, and (ii) bonding with a solid bridge between particles. Without a solid bridge, attraction forces between solid particles help bond the particles. Short-range forces such as molecular force (valance forces (i.e., free chemical bonds), hydrogen bridges, and van der Waals' forces), electrostatic, and magnetic forces can cause solid particles to adhere to each other if the particles are brought close enough together (Pietsch, 2002; Rumpf, 1962). Valance forces are effective only if the inter-particle distance is about 10Å. The effectiveness of short-range forces diminishes dramatically as the size of the particles or inter-particle distance increases (Pietsch, 2002; Rumpf, 1962; Sherrington & Oliver 1981) Van der Waals' forces is believed to make the most contribution to all intermolecular attractive forces and are partly responsible for the adhesion between particles less than 0.1μm apart. Electrostatic forces help binding when there is an excess charge or electrical double layer, which may be created during grinding or by inter-particle friction.

According to Tabil (1996) and Tabil and Sokhansanj (1996), the compaction of biomass during densification could also be attributed to elastic and plastic deformation of the particles at higher pressures. Rumpf (1962), Sastry and Fuerstenau (1973) and Kaliyan and Morey (2010) suggested that the possible mechanism of bonding during densification of biomass could be due to the formation of solid bridges. During compaction, solid bridges are developed by chemical reactions and sintering, hardening of the binder, solidification of the melted substances, or crystallization of the dissolved materials (Tumuluru, *et al*., 2010). The pressure applied during densification reduces the melting point of the particles and causes them to move towards one another, thereby increasing the contact area and changing the melting point to a new equilibrium level (Pietsch, 1984; York & Pilpel, 1972).

Kaliyan and Morey (2010) in their study entitled "Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass" without a binder confirmed that the solid bridges developed during briquetting were made mainly by natural binders such as lignin and protein. The constituents of biomass such as lignin, protein, starch, fat, and water soluble carbohydrates are ''natural binders" in biomass materials (Kaliyan, 2008; Kaliyan & Morey, 2009). Application of high compression pressures during biomass densification can result in crushing the biomass particles, thus opening up the cell structure and exposing the protein and pectin that act as natural binders which assists in increasing the strength of the pelletized product (Bilanski & Graham, 1984; O'Dogherty & Wheeler, 1984; Briggs, *et al*., 1999). Other natural binders (amorphous materials) change their state from a hard glassy to a soft rubbery state (softened or melted locally) either by high moisture or elevated temperature (in the range of glass transition temperature) or steam (Kaliyan & Morey, 2009; Roos, 1995). These conditions are important to make durable particle to particle bonding. At glass transition condition diffusion of polymer chains and chain ends from one fibre into the proximity of an adjacent fibre is greatly facilitated, promoting bonding area, especially under applied pressure. On cooling, these bonds are consolidated (Back, 1987). Within the glass transition region, many characteristics of the materials such as viscosity and mechanical properties (e.g. modulus of elasticity) would change their values dramatically (Irvine, 1984). Lignin and hemicelluloses are example of amorphous thermoplastic materials that undergo plastic deformation at low compaction pressures and temperatures in the range of their glass transition temperatures (Back & Salmen, 1982). Water as moisture in the biomass is one of the most useful agents that is employed as a binder and lubricant (Kaliyan & Morey, 2010). Moore (1965) reported that water is particularly suitable as an aid in briquetting mixtures containing water soluble constituents such as starches, sugars, soda ash, sodium phosphate, potassium salts, and calcium chloride. With the help of heat, water induces a wide range of physical and chemical changes such as thermal softening of biomass, denaturation of proteins, gelatinization of starch, and solubilization and consecutive recrystallisation of sugars and salts (Thomas, *et al*., 1998). These physico-chemical changes affect binding properties of the biomass particles. Water also acts as a film type binder by strengthening and promoting bonding through van der Waals' forces as a result of increasing the contact area of the particles (Mani, *et al*., 2003; Pietsch, 2002).

Densification of biomass under high pressure brings about mechanical interlocking and increased adhesion between the particles, forming intermolecular bonds in the contact area (Tumuluru, *et al*., 2010). Closed bonds or interlocking occurs in fibres, platelets, and bulk particles, where particles interlock or fold about each other, thereby causing the bonding

(Pietsch, 1984). Interlocking of the particles can help provide sufficient mechanical strength to overcome the destructive forces caused by elastic recovery after compression (Rumpf, 1962). To obtain this type of bond, compression and shear forces must always act on the system (Mani, *et al*., 2002). Tumuluru, *et al*. (2010) in summary postulated that there are three stages during densification of biomass.

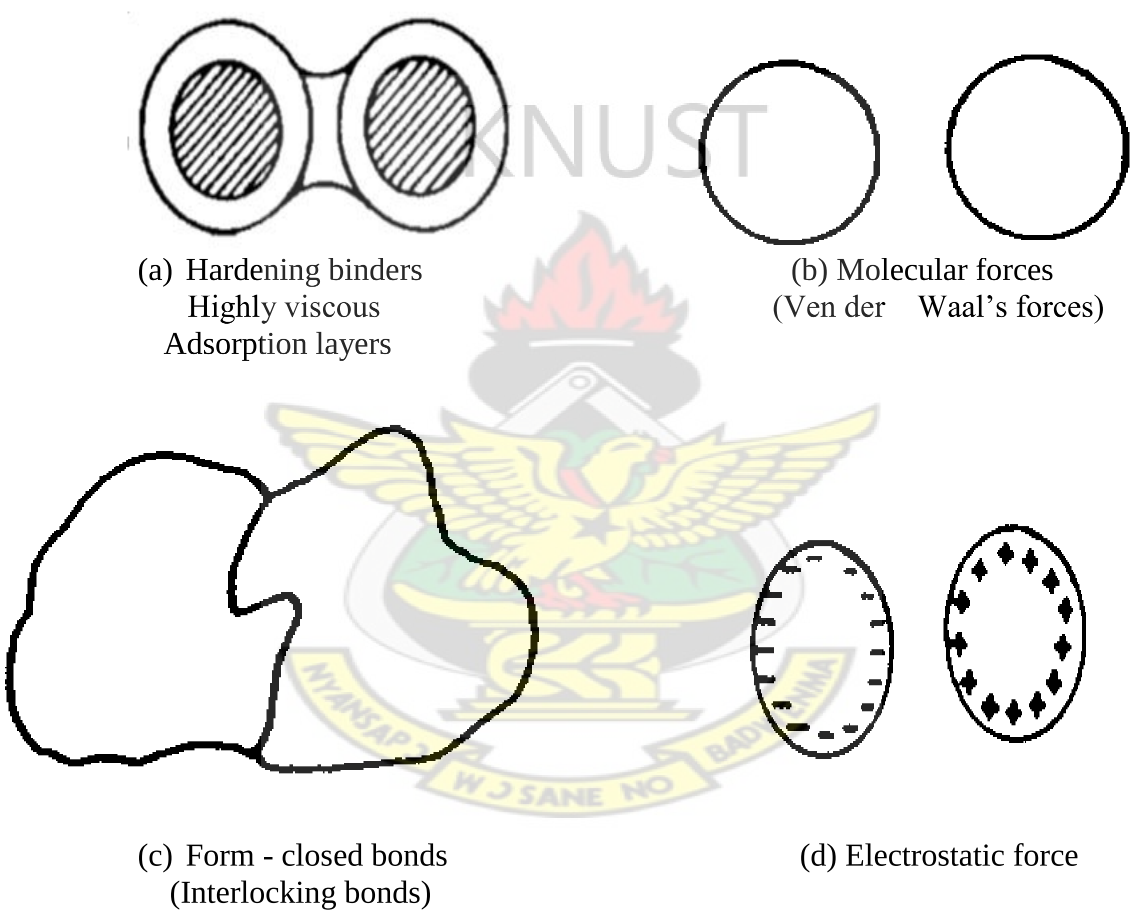


Figure 2.6: Types of bonds formed in densification of biomass
Source: (Grover & Mishra, 1996)

In the first stage, particles rearrange themselves to form a closely packed mass where most of the particles retain their properties and the energy is dissipated due to inter-particle and particle-to-wall friction. In the second stage, the particles are forced against each other and undergo elastic and plastic deformation, which increases the inter-particle contact significantly resulting in particles becoming bonded through van der Waal's electrostatic forces. In the third phase, a significant reduction in volume at higher pressures results in the density of the pellet/briquette reaching the true density of the component ingredients. By the end of the third stage, the deformed and broken particles can no longer change positions due to a decreased number of cavities and a 70% inter-particle conformity. **Figure 2.6** shows the types of bonds formed during densification.

2.16 Quality characteristics of a good briquette

Two main qualities of briquettes that need to be considered are that: (1) it shall remain solid until it has served its function and (2) it shall perform well as a fuel. The first aspect which implies that the product should be intact when handled or stored, is mainly a function of the quality of the densification process for a given raw material. The second aspect is mainly related to the properties of the raw material, the shape and density of the individual briquette (FAO, 1990). A briquette of good quality should be stable enough to withstand handling and long-term storage (Krauss & Szymański, 2006). The external surface should be smooth and the structure of their cross-section be compact (Krauss & Szymański, 2006).

2.16.1 Physical properties of briquettes

Moisture content

The final moisture content of briquette or pellet made from biomass is greatly dependent on process conditions like initial moisture content, temperature, and pressure. Higher moisture content in the final product occurs when the initial moisture content is greater than 15% (Dutta, 2007). According to the Austria, Sweden, Germany and Italy standards ÖNORM M7135, SS 18 71 20, DIN 51731 and CTI - R 04/5 respectively the moisture content of briquettes should be less or equal to 18%, 12%, 12% and 15% respectively. The British standard for briquettes, BioGen/UK Code of Good Practice also specifies that the moisture content of briquettes should be less than 10% (Hahn, 2004). Pellets with moisture content lower than 5% can result in revenue loss for the pellet manufacturer as they tend to break up during storage and transportation. Pellets with high moisture content can be subject to spoilage due to bacterial and fungal decomposition resulting in significant dry matter losses during storage and transportation (Tumuluru, *et al*., 2010).

Density

Pellets or briquettes with higher density are preferred as fuel because of their high energy content per unit volume and slow burning property (Kumar, *et al*., 2009; Križan, 2007). Several researchers have found that the density of briquettes is greatly influenced by the material's moisture content, particle size, process pressure and temperature (Mani, *et al*., 2006). Tumuluru, *et al*. (2010) concluded that both unit and bulk density greatly depends on feed moisture and die temperature where a maximum density of 1200 kg/m^3 is achievable at temperatures of about 100°C and feed moisture content of about 5 - 7%. It is generally accepted that raw-material particle size influences the density of the pellets. Small particle size gives a higher density (Shankar & Bandyopadhyay, 2005). Generally, materials with higher moisture and larger particle size reduce the unit and bulk density of the product, while higher process temperatures, pressures and time increase the unit and bulk density (Kumar, *et al*., 2009). It has also been stated that the density of biomass briquettes depends on the density of the original biomass (Demirbas & Sahin, 1998; Demirbas as cited in Kers *et al*., 2010). Most processes are capable of producing briquettes with densities above 1000 kg/m^3, i.e. the individual briquettes will sink in water (FAO, 1990). High pressure processes such as mechanical piston presses, pellet presses and some screw extruders produces briquettes with density ranging from 1200 to 1400 kg/m³. Hydraulic piston presses make less dense briquettes, sometimes below 1000 kg/m^3 (FAO, 1990). The German DIN 51731 defines briquettes density to be within the interval values 1000 - 1400 kg/m^3.

Wilaipon (2009) in briquetting banana-peel and banana waste in Northern Thailand obtained an exponential relationship between die pressure and relaxed density over the studied range as following: $D = -1.15385P^2+30.15071P+839.65602$ where, P is pressure in MPa, D is the density in kg/m^3. The coefficient of multiple determination for prediction is 94%. Rhen, *et al*. (2005) also found a strong positive correlation between unit density and compression strength. Rhen, *et al*. (2005) stated that briquettes with higher density are likely to have high compressive strength.

Stability of the briquettes

Stability of briquette refers to the changes in its dimensions after the briquette has been removed from the die. It arises from the pressure loosed by the humidity escaped from the briquette as steam (Križan, 2007). The extent of these changes may be detrimental to the net benefits realized, in that, it results in decrease in density of the briquettes. Stability serves as an index of the extent of resistance of briquettes to changes in their initial physical dimensions and shape. It is desirable that briquettes maintain their initial state. Thus, the less the change, the more stable the product (Al-Widyan, *et al*., 2002). The relaxation behaviour of briquette following its removal from die depends on factors related to die geometry, magnitude and mode of compression, the type and properties of the feed material, and storage conditions such as relative humidity (Wamukonya & Jenkins, 1995). Some works on hay have indicated that the expansion in briquettes occurs mainly in the first 15 minutes and that after the first 30 minutes it is slight (Butler & McColly, 1959). O'Dogherty and Wheeler (1984) working on straw, found briquette relaxation almost complete 1hour after removal from the die and this resulted in a total density reduction of 64 - 75%.

Moshenin and Zaske (1976) reported no appreciable expansion in length after 5hours and found radial expansion to be negligible. Other workers have reported a continuous decrease in density over a period of 1000hours, but after 10hours the decrease was small (Bruhn, 1957). Shaw (2008) reported that particle size had maginal effect on the dimensional expansion of pellets. Shrivastava, *et al*. (1990) as cited in Tumuluru, *et al.* (2010) used statistical analysis of rice husks to establish a multiple correlation equation in the following form: $Y = \alpha_0 + \alpha_1 P + \alpha_2 T$, where Y = percent volume expansion, T (°C) and P (kg/m^2) = die temperature and pressure, respectively. $\alpha_{0,}$ α_1 and α_2 = constants. According to Chuen-Shii, *et al*. 2009 hot-pressing temperature during briquetting significantly facilitates the solidification of the briquette, and declines the expansion of the briquette.

2.16.2 Mechanical properties of briquettes

Mechanical properties of briquettes which is also known as its durability refers to the ability of the briquette to withstand mechanical handling (Ferrero & Molenda, 1999). Briquettes' durability is probably the most important criterion for evaluating the quality of densified biomass and this test is intended to assess the ability of densified units to withstand the rigors of handling such that they keep their mass, shape, and integrity (Al-Widyan, *et al*., 2002). Compressive strength, impact resistance index, tensile strength and hardness are some of the mechanical properties relevant to the durability of briquettes. Materials with higher density are more likely to possess higher ultimate stress than those with lower density (Jindaporn & Songchai, 2007).

Compressive strength of briquette

Plíštil, *et al*. (2005) concluded that the mechanical strength of briquettes depends on the properties of the raw material, its structure, water content and compaction pressure. The higher the compacting pressure the higher the compressive strength of briquettes produced (Plíštil, *et al*., 2005). A study by Rahman, *et al*. (1989) titled "Influence of size and shape on the strength of briquettes", they concluded that the method of testing cylindrical briquettes may be restricted either to axial (i.e. surface compression) or lateral (i.e. line compression). The surface compression strength is usually about 10 times that of the line compression (Rahman, *et al*., 1989). Rahman, *et al*. (1989) also stated that briquettes strength of 20 kg/cm^2 ($1.96N/mm^2$) is reasonably adequate for handling.

Hardness

Briquette quality can also be evaluated in terms of it hardness. Harder briquettes are of better quality. Mochida and Honda (1963) as cited in Rahman *et al*. 1989) stated that hardness of briquettes is related to it mechanical properties especially elastic and plastic properties. The harder the briquettes the higher will be its breaking strength. It is possible to check briquettes' hardness by inserting it into a glass of water (Križan, 2007). A quality briquette should fall to the bottom in a moment because it has a higher specific density than water. Next, when the briquette dipped into water falls into pieces sooner than in 5 minutes, we are usually dealing with a very low briquette quality. When the briquette falls into pieces before 15 minutes, it is a medium quality briquette and up to 20 minutes we are dealing with a good quality briquette (Križan, 2007).

Impact resistance index

Impact resistance index of briquette is its ability to withstand shock load. Briquettes with impact resistance index value equal to 100 or more are considered as good briquettes (Wilaipon, 2009). Additionally, according to the Italian standard for briquettes/pallets (CTI-R04/5), briquette's durability greater or equal to 97.7% is adequate. Generally, researchers have classified the impact resistance index into high (>0.8), medium (0.7 - 0.8), and low (<0.7) (Tabil & Sokhansanj, 1996; Adapa, *et al*., 2003).

2.16.3 Fuel properties of briquettes

The important chemical properties for combustion of fuels are the overall heating value, ultimate analysis, proximate analysis and analysis of pyrolysis products (Ragland & Aerts, 1991).

Calorific value

Calorific value or heat of combustion is commonly used as a basic criterion for comparison of fuels. Calorific value is expected to vary among various tree species and to some extent within species. Ravindranath and Oakley Hall (1995) suggested that there are no large differences of calorific value between species or between trees and shrubs. Ravindranath and Oakley Hall (1995) further stated that calorific value positively correlate with the density of timber species. Cellulose has a smaller heating value than lignin because of its higher degree of oxidation. Elemental hydrogen and carbon contents of fuel and lower degrees of oxidation tend to raise the heating value of the biomass. Softwood species generally have higher carbon content and higher heating values than hardwood species because of the presence of more lignin and resinous materials in softwood species. The presence of extractives in wood raises the heating values of wood fuels. Heating value of wood fuels decreases with increasing moisture content of the wood (Demirbas & Demirbas, 2009). The calorific values for most woody materials are between 17 - 19 MJ/kg; for most agricultural residues, the heating values are about 15 - 17 MJ/kg (Stahl, *et al*., 2004). A study of 22 commonly used tree species showed that three quarters had calorific values between 14 - 19 MJ/kg of oven-dry wood (Jain, 1991).

The calorific value of pellets and briquettes depends upon process conditions like temperature, particle size, and feed pretreatment. Generally, pellets with higher density have higher calorific value. The typical calorific values of wood pellets range from 17 to 18 MJ/kg (Tumuluru, *et al*., 2010). The typical calorific values of straw-based pellets range from 17 - 18 MJ/kg (Satyanarayana, *et al*., 2010). Pretreatment processes such as torrefaction and steam explosion can have a significant effect on the calorific value of the final product and increase them to 20 - 22 MJ/kg. Tumuluru, *et al*. (2010) in their studies on pretreatment of corn stover and miscanthus biomass using the torrefaction method, found that the calorific value increases by about 20% of its original value when torrefied at temperature ranges of 200 - 300^{o}C.

The lower heating value of maize cobs has been reported by a couple of authors. Kromer and Martinov (1981) found that the heating value of maize cobs was 14.6 MJ/kg when the moisture content was 15%. Schneider and Hartmann (2006) also measured lower heating values of maize cobs for different maturity stages and obtained values ranging from 17.2 - 18.1 MJ/kg based on dry matter. A value of 18.2 MJ/kg for dry matter was reported by Zabaniotou and Ioannidou (2008) in their paper "Evaluation of Utilization of Corn Stalks for Energy and Carbon Material Production by Using Rapid Pyrolysis at High Temperature". Based on a moisture content of 15%, the heating value is very close to that mentioned by

Kromer and Martinov (1981). Wilaipon (2008) also referred to an average lower heating value of maize cobs as being 14.2 MJ/kg. Mullen, *et al*. (2010) also stated that the high heating value of corn cobs was 17.8 MJ/kg. In summary the heating value of maize cobs is comparable with other crop residues and even above average.

Ash content of biomass fuel

Biomass residues normally have much lower ash content (except for rice husk with 20% ash) but their ashes have a higher percentage of alkaline minerals, especially potash (Grover & Mishra, 1996). The potassium released during combustion can condense as chloride (KCl) or sulphates (K_2SO_4). KCl when deposited on heat exchanges may cause accelerated corrosion (Kassman & Vattenfall, 2006 as cited in Broström, 2010). Flying ash may also be deposited on the surface of heat exchangers leading to reduced efficiency of the boiler. The ash content of different types of biomass is an indicator of slagging behaviour of the biomass. Generally, the greater the ash content, the greater the slagging behavior (Grover & Mishra, 1996). But this does not mean that biomass with lower ash content will not show any slagging behaviour. The temperature of operation, the mineral compositions of ash and their percentage determine the slagging behavior (Grover & Mishra, 1996). Usually slagging takes place with biomass fuels containing more than 4% ash and non-slagging fuels with ash content less than 4%. (Grover & Mishra, 1996).

Ultimate analysis

The ultimate analysis provides weight percentage of C, H, O, N, and S (Ragland & Aerts, 1991). All wood species contain about 6% H (Petura, 1979 as cited in Ragland & Aerts, 1991). Oxygen content ranges from 40 to 44%, S is less than 0·1% and N ranges from 0·1 - 0·2%.

Carbon content of softwood species is 50 - 53%, and that of hardwood species 47 - 50% due to the varying lignin and extractives content (Ragland & Aerts, 1991). Fixed carbon gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Akowuah, *et al*., 2012). The higher the carbon, nitrogen and sulphur content, the more likely is the formation of carbon monoxide and carbon dioxide (Extension, 2010).

Nitrogen is a component of all fuel systems. During combustion process, it is oxidized into nitrogen oxides (NOx). When emitted from combustion facilities at relatively low levels, NOx may have a useful fertilizing effect on forests. However, as emission levels increase, NOx produces adverse health effects and increases the acidification of water and soils (Extension, 2010). When NOx and volatile organic compounds (VOCs) react in the presence of sunlight, they form a photochemical smog, which is a significant form of air pollution (Sillman, 2003). Nitrogen oxides also play an important role in the atmospheric reactions creating ozone and acidic rain by the formation of nitric acid. Exposure to nitrogen oxides increases the risk of respiratory infections as it is highly toxic and irritating to the respiratory system (Sillman, 2003).

Sulphur emissions from combustion of fuels cause extensive damage to ecosystems and buildings, so fossil fuels are often graded by the amount of sulfur present. As with nitrogen, sulfur is oxidized during combustion to form sulfur oxides (SOx). This compound can have serious environmental effects and causes the acidification of soils and water (Extension, 2010).

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Chapter three of this study comprises of the methodology that was used in performing the research work. It considers the research design, selection and collection of research materials, material preparation, experimental procedures and the data analysis.

3.2 Materials and methods

In section 3.2 the research design and the materials and methods used for the study is described.

3.2.1 Research design

The research method employed for this study was experimental design. The reason being that this work involved the study of cause-effect relationship resulting from manipulation of research factors; compacting pressure (CP), particle size (P) and species on physical and mechanical characteristics of briquettes produced from sawdust and maize cobs. The study also investigated the effect of combining species on quality of briquettes produced. Factorial experiment in complete randomized design was employed for the study. Trochim (2006) reported that randomized experiment generally is the most appropriate research design when the interest of the researcher is in establishing a cause-effect relationship.

3.2.2 Materials and material collection

Sawdust from *Triplochiton scleroxylon* (Wawa), *Ceiba pentandra* (Ceiba), *Aningeria robusta* (Asanfina)**,** *Terminalia superba* (Ofram), *Celtis mildbreadii* (Celtis), *Piptadenia africana* (Dahoma) were selected for the research work. The selection of the above species was based on the fact that they are among the most frequently processed timber species in the wood industry in Ghana. Additionally, the resource base of these selected timber species is not threatened. The other material used was maize cobs. Sawdust of the six timber species were collected from Fabi Timbers Limited in the Ashanti Region of Ghana. Fabi Timbers was selected because the Company processes a wide range of timber species and also they readily accepted to make their facility available for the study. Logs from which sawdust was collected were physically pre-inspected to ensure that they were without visual defects like pin-holes and rot. The sawdust was randomly collected in batches of species from various points of the processing lines depending on the production schedule. Agricultural residue used for the study was maize cobs (Baatanpa variety). This was due to its relatively abundance in Ghana.

3.2.3 Material preparation

Material drying

The sawdust was dried at an average relative humidity and temperature of 759.28% and 28.23^{o}C respectively as obtained from Meteorological Service Department. Drying was done on a rubber mat for a minimum of five days and a maximum of seven days. The number of days required for the materials to completely dry depended on the species, environmental conditions (temperature and relative humidity) as well as initial moisture content of the sawdust.

Determination of particle size distribution of sawdust

After drying, the particle size distributions of the sawdust of the six selected tropical hardwood species were determined in accordance with BS 1377: 1975. To do that 50g sample of each of the species was weighed using an electronic pan balance with serial number N64083 capable of measuring up to 0.01 g. The sawdust was then transferred into a set of sieves with sieve hole dimensions 3.35 mm, 2 mm, 1 mm, 0.6 mm, 0.425 mm, 0.3 mm, 0.2mm, 0.1 mm and 0.075 mm. The set of sieves containing the test sample was then mounted on an automatic sieve shaker with serial number A060-01/ZG/0038 and Model A060-01. Shaking was done for 10 minutes. Thereafter, the weight of materials retained on each sieve was determined using the same electronic balance and the weight recorded on a grading analysis sheet. The percentage of materials retained on each sieve was then computed and graph plotted. The same procedure was used in determining the particle size distribution for all the species. For each species the experiment was repeated five times.

Grading of sawdust

After determining the particle size distribution of the sawdust of each of the species, they were graded into particle sizes (P): $P \leq 1$ mm, 1 mm $< P \leq$ 2 mm and 2 mm $< P \leq$ 3.35 mm. This was done by using three sieves with sieve diameters 1 mm, 2 mm and 3.35 mm. The graded sawdust were then bagged and labeled.

Preparation of mixture of sawdust and maize cobs

As part of this project work the researcher investigated into the effect of CP and species mix on quality characteristics of briquettes produced. Species used were *C. pentandra* (low density species), *T. superba* (medium density species), *P. africana* (high density species) and maize cobs. Mixtures were made from the following combination of sawdust: *P. africana* and *C. pentandra*, *P. africana* and *T. superba*, *T. superba* and *C. pentandra*, and *P. africana*, *T. superba* and *C. pentandra*. Each of the first three combinations were prepared in the following mixing ratios: 80 : 20, 60 : 40, 40 : 60 and 20 : 80 and the latter one (*P. africana*, *T. superba* and *C. pentandra*) was prepared using the following mixing ratio: 40 : 30 : 30, 30

: 40 : 30, 30 : 30 : 40 and 1 : 1 : 1. Maize cobs was also combined with *C. pentandra*, *T. superba* and *P. africana*. The mixtures of: *C. pentandra* and maize cobs, *T. superba* and maize cobs and *P. africana* and maize cobs were made in the following mixing ratio: 90 : 10, 70 : 30 and 50 : 50. The selection of the above ratios was informed from literature.

3.2.4 Determination of moisture content of biomass materials

The moisture content of the graded biomass materials was determined just before briquetting was done. This was done in accordance with European Standard BS EN 13183-1 2002. A sample of 2 g of biomass material of each species was weighed into a glass disc and placed in a laboratory oven at a temperature of (103 ± 2) ^{o}C and dried until the difference in mass between two successive weighing separated by an interval of two hours was less than 0.01 g. The oven-dry moisture content of the specimen was computed as follows:

$$Moisture\ content\ (\%)\ db = \frac{M_1 - M_o}{M_o} \times 100$$

Where:

M_1 = Mass of the test sample before drying (g)

M_o = Oven-dry mass of the test sample (g)

3.2.5 Determination of density of wood samples

Density of the six timber species from which sawdust was collected was determined in accordance with ASTM D 2395 - 07a. Five clear specimens of dimension 20 mm x 20 mm x 30 mm were prepared for each species. The oven-dried masses of the specimens were determined. Thereafter, they were dipped one-by-one in a paraffin wax and then kept in a desiccator. The volume displacement method which employs the use of Eureka can and a measuring cylinder was used to determine the volumes of the specimen. Density of each specimen was then computed as;

$$Density = \frac{Mass\ of\ specimen}{Volume\ of\ specimen}$$

The density of each species was replicated five times.

3.2.6 Determination of fibre length of sawdust particles

This part of the methodology describes the method used for the determination of fibre length of the sawdust of each species graded into particle sizes: P ≤ 1 mm, 1 mm < P ≤ 2 mm, and 2 mm < P ≤ 3.35 mm. The fibre length determination was carried out in accordance with Franklin's method of maceration followed by measurement of fibre length.

Figure 3.1: Macerated wood fibres in test tubes

Sawdust of each particle size and for each species was placed in a test tube. A 1:1 glacial acetic acid and 30% hydrogen peroxide mixture was added to cover the specimens in the test tubes. The sample-solution mixture was then placed in an incubator at a temperature of 65^{o}C for a minimum of two days and a maximum of 4 days. After maceration, the sample was flooded with distilled water (**Figure 3.1**). To measure the fibre length, the microscope was calibrated. The micrometer value obtained was 9.836065574µ. Ten random samples of the macerated materials of each particle size and species were mounted on ten slides of a microscope using a dropper.

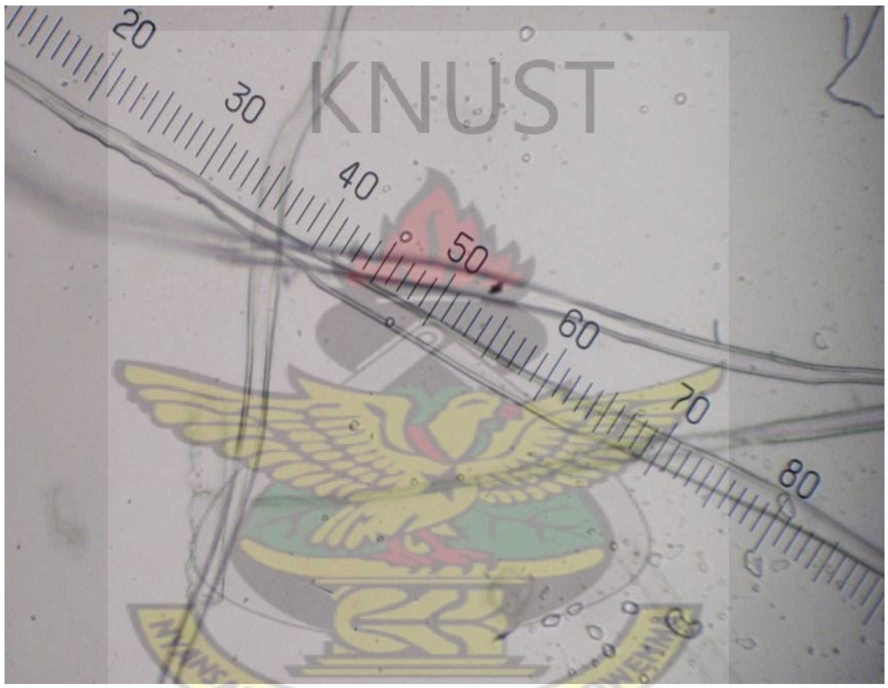


Figure 3.2: Measuring of wood fibre

This was covered with a cover slip. Each of them was placed in turns on the stage of the microscope and observed under the microscope with 10 x 10 eye and object lens (**Figure 3.2**). All the fibres observed on each slide were measured and recorded under that sample. The value obtained for each fibre length was multiplied by the micrometer value (9.836065574µ) to obtain the fibre length in micro millimeter. The means were then computed. The above procedure was repeated for each of the species and particle size.

3.2.7 Preparation of extractive free material

ASTM D1105 - 96 (2007) method was used for the preparation of extractive free material of the timber species and maize cobs which was then used for determination of lignin, cellulose and hemi-cellulose. Suitable quantity of each sample was placed in a Soxhlet extraction thimble making sure that the samples did not extend above the level of the top of the siphon tube. The specimen in the thimble was extracted for 4 hours with alcohol-acetone mixture in Soxhlet extraction apparatus. The specimen was then removed from the thimble in order to remove excess solvent with suction, followed by washing the thimble and specimen with alcohol to remove the acetone. The specimen was returned into the extractor and the extraction continued with 95% alcohol for 4 hours until the alcohol siphons became colourless. The specimen was then removed from the thimble and spreaded out in a thin layer to dry in the air until free of alcohol. The dry material was further returned into the extractor and extracted with distilled water until the water siphons became colourless. The specimen was then allowed to become thoroughly dry in the air. The air dried extractive free material was used for lignin, holocellulose and alpha-cellulose determination.

3.2.8 Determination of percentage acid-insoluble lignin content of biomass materials

ASTM D1106 - 96 (2007) was used for determination of acid-insoluble lignin content of the timber species and maize cobs. Samples of the materials were grounded and sieved with sieve of dimension 425µm (number 40). Thereafter, the grounded materials were thoroughly air-dried and used for the determination of lignin. Determination of lignin content of the samples started with preparation of extractives free samples from 1 g of test sample using ASTM D1105 - 96 (2007) standard method of preparation of extractive free wood.

Additionally, oven-dry weight of 1g of the test sample was determined using BS EN 13183-1 2002.

The air dried extractive free test sample was transferred into a 50ml beaker with a glass cover and 15ml of cold (12 - 15^{o}C) H_2SO_4 (72%) was slowly added while swirling. The specimen was well mixed with the acid by stirring constantly for one minute and then allowed to stand for 2 hours with frequent stirring at a temperature of 18 - 20^{o}C in a water bath. Thereafter, the material was washed into a one litre Erlenmeyer flask with 560ml of distilled water to dilute it to a 3% concentration of H_2SO_4. The mixture was boiled for 4 hours in a nearly constant volume condition maintained by occasional addition of hot distilled water. After boiling for 4 hours, the sample was left to cool overnight to allow the insoluble material to settle. The content of the flask was filtered into a glass filtering crucible that has been dried at 105^{o}C. The residue was washed free of acid with 500ml of hot water. After this the crucible and its content was dried in an oven for 2 hours at 105^{o}C. It was then cooled in a desiccator and the content weighed as lignin. Drying and weighing were repeated until the weight became constant. The weight of lignin was expressed as a percentage of the moisture free wood using the formula;

$$\%\, lignin = \frac{A}{W} \times 100$$

A = Oven dried weight of lignin

W = Oven dried weight of test specimen (moisture free wood)

3.2.9 Determination of holocellulose constituent of timber species

The holocellulose content of the samples was determined using a modified ASTM D1104 - 96 (2007) method. For every 2 g of extractive free sample, 180ml distilled water, 8.6 g sodium acetate, 6 g (5.7 ml) ethanoic acid and 6.6 g sodium chlorite was mixed for the holocellulose extraction process. In addition the oven-dry weight of 2 g of the test sample was determined using BS EN 13183-1 2002.

The extractive free sample was digested with the solution prepared in a 250 ml conical flask and the flask covered. The sample solution mixture was placed in a water bath in a fuming chamber at a temperature of 60^{o}C. After 4 hours, the sample was filtered, washed with distilled water and dried in an oven at 105^{o}C. The amount of holocellulose was expressed as a percentage of the moisture free wood using the formula:

$$\%\,Weight\ of\ holocellulose = \frac{X}{Y} \times 100$$

X = Oven dry weight of holocellulose

Y = Weight of moisture free sample

The above process was replicated five times for each of the six species.

3.2.10 Determination of alpha-cellulose constituent of timber species

Samples of the six selected timber species and maize cobs used for the research work were grounded to pass through No. 60 (250 µm) sieve and retained on No. 80 (180 µm) sieve. Thereafter, the grounded samples were thoroughly air dried and used for the alpha-cellulose determination as follows. 2 g of the grounded samples was weighed and the extractives removed from it in accordance with ASTM D1105 - 96 (2007) method and then air dried. Thereafter, the lignin was removed from the extractive free wood in accordance with modified ASTM D1106 - 96 (2007) method for preparing holocellulose sample of wood and then air dried. Beside this, 2 g of the test specimen was used to prepare moisture free wood in accordance with BS EN 13183 - 1 2002.

The sample of air-dry holocellulose (i.e. extractive free and lignin free wood sample) was quantitatively transferred into a 250 ml chemically resistant glass beaker with a cover glass. Twenty five milliliters (25 ml) of NaOH solution (17.5%) was carefully measured and adjusted and maintained at 20^oC in a water bath. Ten milliliters (10 ml) of the NaOH solution was added to the holocelullose in the 250ml beaker, maintained at 20^oC in a water bath and covered with a watch glass. The holocellulose was manipulated lightly with a flattened end glass rod until the entire specimen was soaked with the NaOH solution. After 2 minutes, the specimen was manipulated again with the glass rod by stirring until the particles were separated from each other. Five minutes after addition of the first portion of NaOH (17.5%) solution to the specimen, additional 5ml of NaOH solution was added and the mixture thoroughly stirred. After additional 5 minutes, 5ml of the NaOH solution was added and thoroughly stirred. Fifteen minutes after the addition of the first portion of NaOH the remaining 5ml portion of the NaOH solution was added and stirred again with the glass rod. The mixture was allowed to stand at 20^oC for 30 minutes, making the time for total NaOH treatment of 45minutes. At the end of the 45 minutes of the NaOH treatment, 33ml of distilled water at a temperature of 20^oC was added to the mixture. The content of the beaker was thoroughly mixed and allow to stand at 20^oC for 1 hour.

After the 1 hour, the left over (alpha-cellulose) was filtered with the aid of suction. The residue (alpha-cellulose) was transferred into a crucible and washed with 100ml of NaOH solution (8.3%) at 20^oC. Washing was continued at 20^oC with distilled water until all the particles were transferred from the 250 ml beaker to the crucible. The washing step was repeated twice. After washing, 15 ml of acetic acid (10%) at room temperature was poured into the crucible and the acid drawn into the cellulose by suction but while the cellulose was still covered with acid, the suction was released. The cellulose was subjected to acid treatment for 3 minutes from the time the suction was released. The suction was then applied after the 3 minutes to draw off the acetic acid. Without releasing the suction, the crucible was filled almost to the top with distilled water at 20^{o}C and allowed to drain completely. The washing was repeated until the cellulose residue was free of acid. The cellulose was given a final washing by drawing by suction additional 250 ml distilled water through the cellulose in the crucible. The crucible was dried in an oven at 105^{o}C, until contant weight was obtained. The percentage of alpha-cellulose was estimated on the basis of the oven-dry wood sample as follows:

$$\%\, Alpha\ cellulose = \frac{W_1}{W_2} \times 100$$

W_1= Weight of the oven-dry alpha-cellulose residue (g)
W_2= Weight of the original oven-dry wood sample (g)

3.2.11 Determination of hemicellulose constituent of timber species

The hemicelluloses of the species were determined by difference after determination of holocellulose and alpha-cellulose according to modified ASTM D1104 - 96 (2007) and ASTM D 1103 - 60 methods respectively**.** The percentage of hemi-cellulose was estimated with the formula:

% hemicelluloses = % holocellulose - % alpha cellulose [ASTM D 1102 - 84 (2007)]

3.2.12 Briquetting of biomass materials

A 55.3-mm internal diameter × 52.5-cm height cylindrical mould (**Figure 3.3**), a piston of diameter 55.2mm and mass 3.45 kg (**Figure 3.4**) and a manual hydraulic press capable of generating a load of twenty-two tonnes were utilized to produce the briquettes.

Ninety grammes (90g) of graded biomass raw material was weighed with an electronic balance capable of weighing up to an accuracy of 0.01g and filled into the mould.

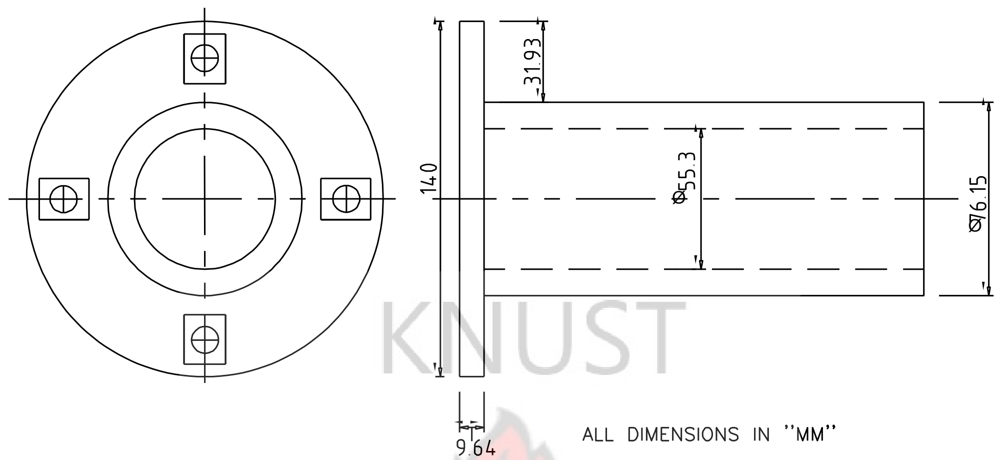


Figure 3.3: Schematic diagram of cylinder used for briquetting showing the inner and outer dimensions

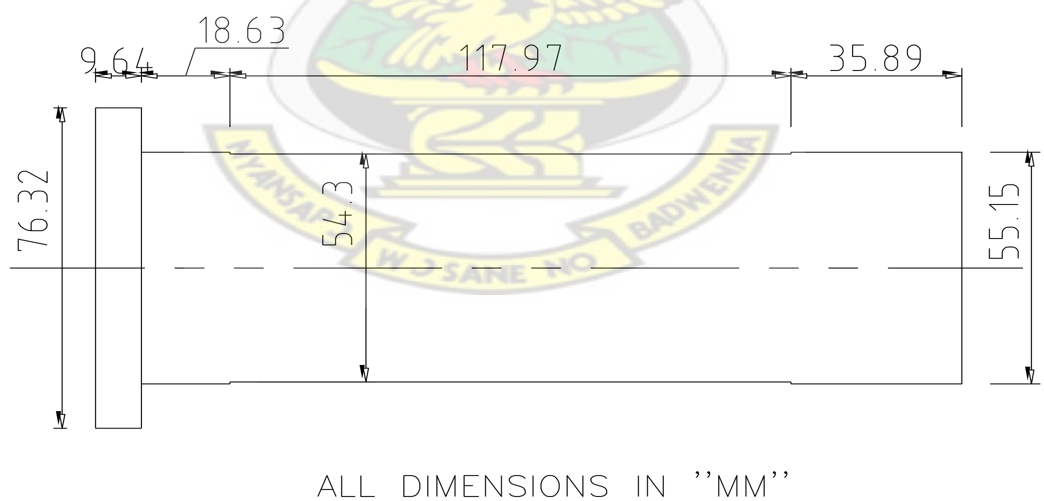


Figure 3.4: Schematic diagram of piston used for briquetting showing its dimensions

The manual hydraulic press and a piston were used to compress the raw material against the other end of the mould to form the briquettes. A clearance of about 0.1 mm was provided between the piston and the inner wall of the mould to allow for air escape. The samples were pressed using the following predetermined compacting pressure (CP) levels: 10 MPa, 20 MPa, 30 MPa, 40 MPa and 50 MPa. The temperature in the laboratory in which the pressing was done was about 25^{o}C. The dwelling time after each pressing was maintained at 10 sec for all the pressings made. This process was repeated for each particle size for all the six species. For each CP level particle size and biomass material, thirty briquettes were made. The calibration of the hydraulic press was in tonnes. This was converted into the mega pascal using the formula below:

$$Guage\ reading\ (tonnes) = \frac{MPa \times A \times 10^{3}}{g} - 0.00345$$

Where:

MPa = Required pressure in mega pascal
A = Cross-sectional area of the piston
g = Acceleration due to gravity
0.00345 = Mass of the piston in tonnes

$$Cross - sectional\ area\ of\ the\ piston\ (M^{2}) = \frac{\pi D^{2}}{4} \times 10^{-6}$$

Where:

D = Diameter of the piston (55.2 mm)
Π = 3.1429

3.2.13 Determination of physical and mechanical properties of briquettes

Stability in length and diameter, water resistance quality (WR), relaxed density, compressive strength (CS) in cleft and impact resistance index (IRI) of the briquettes produced were investigated using standard laboratory testing methods. These properties were determined thirty days after removal of briquettes from the press. This time lapse was allowed to ensure that the briquettes produced had attained dimensional stability.

Physical properties

The physical properties of briquettes determined were briquettes' stability in diameter and length, and relaxed density.

Stability of briquette

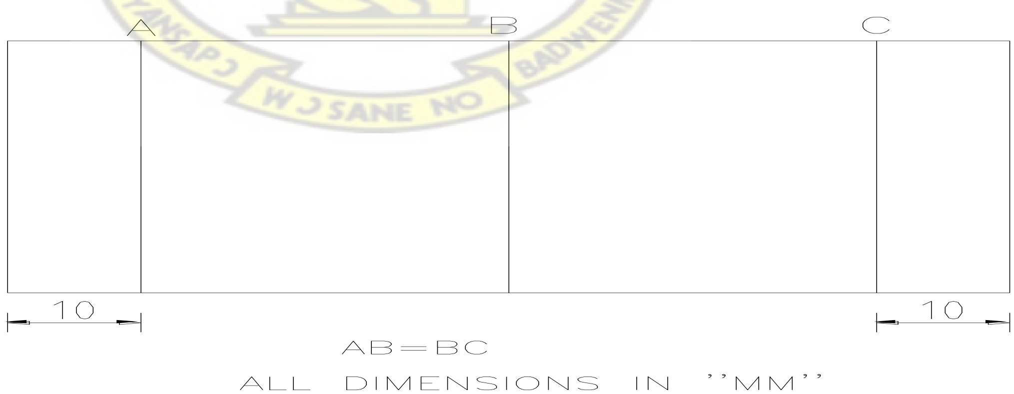
Sampling

Simple random sampling technique was used to pre-sample the briquette used for the stability test before briquetting was done. A table of random numbers was used for this purpose. To use this table, all the elements in the sampling frame (thirty briquettes in all for a particular species compacting pressure and particle size) were numbered i.e. 01 to 30. The table of random numbers was then used to pre-select briquettes used for determination of briquettes stability after pressing was done. For example, for the first sample, briquettes with numbers 22, 24, 15, 06 and 14 were pre-selected for this purpose. Thus, the 6th, 14th, 15th, 22nd and 24th briquettes produced were used for determination of briquettes stability.

Procedure

Briquettes' stability was determined as percentage expansion in length (lateral) and diameter (axial) of briquettes produced. This was done by measuring the extension in length and diameter immediately after removal of the pre-sampled briquettes from the press and 96

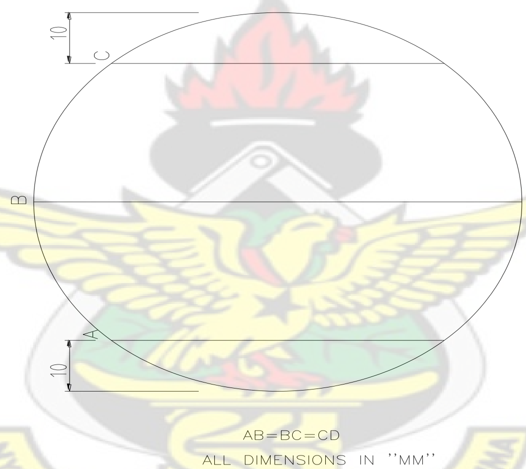
(a)



(b)

Figure 3.5a & b: (a) Photo of briquette showing measurement of briquette diameter, and (b) schematic diagram showing points of measurement along the briquette denoted by A-C.

(a)



(b)

Figure 3.6a & b: (a) Photo of briquette showing measurement of briquette length, and (b) schematic diagram showing points of measurement along the briquette denoted by A-C.

hours after removal from the pressing mould using Digital Vernier Calliper. Measurments were taken at three points on each briquette (**Figure 3.5a & b; Figure 3.6a & b**). The average of the three measurements was taken as the mean length and diameter of the briquette produced. These measurements were replicated five times for each level of CP, biomass material and particle size. Lateral and axial stability of the briquette were then calculated as follows:

$$\%\, Increase\ in\ length = \frac{L_f - L_o}{L_o} \times 100$$

Where:

L_0 = Length of briquette immediately after removal from the mould

L_f = Length of briquette 96 hours after removal from the mould

$$\%\, Increase\ in\ diameter = \frac{D_f - D_o}{D_o} \times 100$$

Where:

$D_o =$ Diameter of briquette immediately after removal from the mould

$D_f =$ Diameter of briquette 96 hours after removal from the mould

Relaxed density

Sampling

Simple random sampling technique was used to sample the briquette used for the determination of relaxed density. A table of random numbers was used for this purpose. Sampling was done for every thirty briquettes produced from every particular species, CP level and particle size (P). The sampling procedure is just as the one described under stability test except that in this case the sampling was done after the briquette was produced. This sampling proceedure was used for the test of mechanical properties.

Procedure

Relaxed density (ρf) of the briquettes was determined in accordance with ASTM D 2395-2008, 30 days after removal of briquettes from the press. In line with this method the mass of briquettes was determined with electronic balance (accuracy of 0.01 g). The diameter and length of briquette were determined using the same Digital Vernier Calliper with an accuracy of 0.01 mm as described earlier. Both the length and diameter were measured at three points on each briquette (**Figures 3.5a&b and 3.6a&b**). Relaxed density was then computed as follows:

$$Relaxed\ density\ \left(\frac{g}{cm}\right) = \frac{108000\ x\ M(g)}{\pi[d_1(mm) + d_2(mm) + d_3(mm)]^2\ x\ [l_1(mm) + l_2(mm) + l_3(mm)]}$$

Where:

M = Mass of briquette (g)

d_1 = Diameter of briquette at point one (mm)

d_2 = Diameter of briquette at point two (mm)

d_3 = Diameter of briquette at point three (mm)

l_1 = Length of briquette at point one (mm)

l_2 = Length of briquettes at point two (mm)

l_3 = Length of briquette at point three (mm)

Mechanical properties

Mechanical properties of briquettes determined were compressive strength in cleft, impact resistance index and water resistance quality.

Compression strength (CS)

The compressive strength in cleft of briquette was determined using Instron Universal Strength testing machine with serial number UK131 and load cell capacity of 100 kN in accordance with ASTM D 143 - 2008. The crosshead speed was 0.305mm/min. Only compact and intact briquettes were used for this test. A sample of briquette to be tested was placed horizontally in the compression test fixture as shown in **Figure 3.7**. Load was applied at a constant rate of 0.305 mm/min until the briquette failed by cracking or breaking. The maximum load that caused fracture of the briquette was recorded.

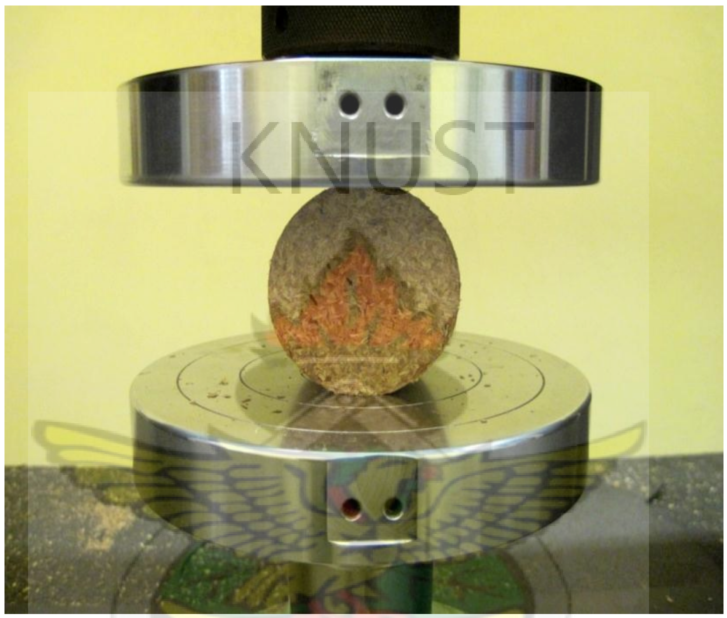


Figure 3.7: Determination of compressive strength in cleft of briquette

The compressive strength in cleft was then computed as follows:

$$\text{Compressive strength in cleft} \left(\frac{N}{mm}\right) = \frac{3\ x\ The\ load\ at\ the\ fracture\ point\ (N)}{l_1(mm) + l_2(mm) + l_3(mm)]}$$

Where:

$l_1 =$ Length of briquette at point one (mm)

$l_2 =$ Length of briquettes at point two (mm)

$l_3 =$ Length of briquette at point three (mm)

This test was replicated five times for every particular species, CP level and particle size.

Impact resistance index (IRI)

The impact resistance index of briquettes produced was determined in accordance with ASTM D440 : 2007 of drop shatter test for coal. Five drops was set as the standard for this experiment. Briquette was released from a vertical height of two metres (2 m) and allowed to fall freely and impact on a concrete floor. After five drops the broken pieces of briquettes were collected and each weighed using an electronic balance with accuracy of 0.01 g. Only the number of pieces that weighed 5% or more of the initial weight of the briquettes was recorded for the purpose of calculating the IRI. The targeted value of IRI was 100 (Wilaipon, 2009). That is, briquettes with IRI value equal to 100 or more would be considered as good. The IRI was then computed as follows:

$$IRI = \frac{N}{n} \times 100$$

Where:

N = Number of drops

n = Number of pieces that weighed 5% or more of the initial weight of briquette after N drops

Water resistance quality

Five briquettes were sampled from a set of 30 briquettes produced from a particular biomass material, particle size and CP level. Simple random sampling technique as described earlier was used. Briquette's water resistance quality was determined using the German Standard DIN 5173. This was done by immersing a briquette into a container filled water at room-temperature. The time taken for the briquette to completely disperse in the water was determined using a stop watch. Each experiment was replicated five times.

3.2.14 Determination of fuel properties of biomass materials used for the study

Fuel characteristics of biomass material determined were calorific value, ash content, sulphur, nitrogen and carbon content.

Gross calorific value (GCV) of wood species

The gross calorific value of the biomass materials used for the study was determined in accordance with ASTM E7111-87 - 2012. Equipments used were: Bomb calorimeter (Serial No. 04402.00), calorimeter, magnetic stirrer (Serial No. 090818336), oxygen (Maximum filling pressure 10bar), measuring cylinder, pellet press, iron wire of diameter 0.2 mm, analytical balance and a thermometer connected to a computer and power source. The calorimeter was initially calibrated using benzoic acid. This enabled the calculation of the heat capacity of the calorimeter as follows:

$$Heat\ absorbed\ by\ calorimeter(Q_c) + Heat\ absorbed\ by\ Water(Q_w) = \frac{m_b \times \Delta_c H_B}{M_B}$$

Where:

$\Delta_c H_B$ = Molar combustion enthalpy of benzoic acid (-3231.5 kJ/mol)
m_b = Mass of the benzoic acid pellet–mass of the igniter wire
M_B = Molar mass of benzoic acid
Q_c = Heat absorbed by calorimeter
Q_w = Heat absorbed by water

$$Heat\ capacity\ of\ calorimeter\ (C_{cal}) = \frac{Q_c}{\Delta T_{cal}}$$

Where:

ΔT_{cal} = Change in temperature of the calorimeter

Q_c = Heat absorbed by calorimeter

Samples of biomass materials were grounded into powder in a mortar and sieved with a 425µm sieve. Particle size that passed through 425µm sieve was used for the test. 400 mg of the materials was measured using a weighing dish and analytical balance. Approximately 10 cm length of iron wire was measured and weighed to an accuracy of 0.1 mg. The wire was then fitted in the guides of a pressing tool to give a good hold for the pallet. A funnel was used to fill the weighed sample into the pressing tool. Thereafter, a moderate pressure was exerted on the sample and wire in the pressing device using a vice to form a pellet. The weight of the pellet and wire formed was then determined to an accuracy of 0.1 mg. The weight of the sample was obtained by subtracting the weight of the iron wire from the weight of pellet and wire.

The two wire ends of the pellet were fixed to the tungsten electrode of the bomb calorimeter so that the pellet is above the middle of the sample holder. The calorimeter vessel was filled with 850 cm^3 of distilled water. The bomb calorimeter was set in place in the calorimeter vessel which was earlier filled with water. The oxygen, electrical leads, magnetic stirrer and the thermometer were connected. The magnetic stirrer was set at 750 rpm. Oxygen was allowed to fill the bomb calorimeter at a pressure of 7 bars after which the wire was ignited. After ignition, the changes in temperature were observed till the temperature readings became stable i.e. when the maximum temperature was reached. The difference between the maximum and minimum temperatures was obtained from the graph of temperature against time plotted. This process was repeated five times for each biomass material. The gross calorific values of the biomass materials were calculated as follows:

$$Q = \frac{(C_{water} + C_{cal})(T_2 - T_1)°C}{W_f}$$

Where:

Q = Calorific value of species (kJ/kg)

W_f = Weight of the biomass material sample (kg)

C_{cal} = Heat capacity of the bomb calorimeter

$T_2 - T_1$ = Rise in temperature which is obtained from a plot of temperature readings against time

C_{water} = Heat capacity of water (Specific heat of water x mass of water used)

Percentage (%) ash content (PAC)

Percentage ash content of the biomass materials were determined in accordance with ASTM D 1102 - 84 (2007). Sample of biomass material was grounded. Particles that passed through 425µm sieve was used for this test. Empty porcelain crucibles used for this experiment was preheated in a scientific electric furnace at temperature of 600°C for two hours, cooled in a desiccator and then weighed with an analytical balance with an accuracy of 0.1 mg. Approximately 2 grammes of the test specimen was placed in the porcelain crucible. The weight of the crucible plus specimen was determined to an accuracy of 0.1 mg. The content of the crucible was then dried at a temperature of 103°C until its weight became constant. After cooling in a desiccator and thereafter, its weight was determined. The crucible and its content was then placed in a furnace and heated at a temperature of 600°C for four hours until all the carbon was eliminated. It was then cooled in a desiccator and then weighed. Heating was repeated at 30 minutes intervals until the weight after cooling became constant to about 0.2 mg. Subsequently, the percentage ash content, based on the oven-dried wood was calculated as follows:

$$Ash\ content(\%) = \frac{M_{ash}}{M_{oven-dry}} \times 100$$

Where:

M_{ash} = Mass of ash

$M_{oven\text{-}dry}$ = Mass of oven-dry wood sample

Percentage (%) organic carbon (POC)

Percentage organic carbon content of samples of biomass materials used for this study was determined using the ASTM D 1102 - 84(2007) and FAO guide to laboratory establishment (2008). In line with the above standards, first the ash content of the biomass materials were determined as described under section 3.2.14 of this theses. Thereafter, the mass (g) of ash was subtracted from the oven-dry mass of the sample to obtain the mass (g) of organic matter component. The mass (g) of organic carbon was then estimated as 58% of that of the organic matter. Percentage organic carbon is then estimated as follows:

$$Organic\ carbon\ content(\%) = \frac{M_{organic\ matter} * 0.58}{M_{oven-dry}} \times 100$$

Where:

$M_{organic\ matter}$ = Mass of organic matter

$M_{oven\text{-}dry}$ = Mass of oven-dry wood sample

The above process was replicated five times for each of the six species.

Determination of nitrogen

Kjedahl method was used to determine the nitrogen content of the sawdust samples. The procedure consists of three steps: Digestion of the samples, distillation and titration.

Digestion of samples

Two (2) grammes of wood sample was weighed into a 500 ml long-necked Kjeldahl flask. Ten (10) ml of distilled water was then added to moisten the sample. Thereafter, one spatula full of Kjedahl catalyst (mixture of 1 part of Selenium + 10 parts $CuSO_4$ + 100 parts Na_2SO_4) was added to the sample. 20ml of concentrated H_2SO_4 was added to the mixture and digested until it was clear and colourless. The mixture was allowed to cool and then decanted into a 100 ml volumetric flask. Distilled water was added to make up the mark of 100 ml.

Distillation of digested sample

Ten (10) ml of the digested sample was transferred into a Kjeldahl distillation apparatus. Thereafter, 90ml of distilled water was added to the sample to make it up to 100 ml. 20ml of 40% NaOH added. The distillate was collected over 10ml of 4% Boric acid and three (3) drops of mixed indicator in a 200ml conical flask.

Titration of the distillate

The collected distillate was titrated with 0.1 normality HCl till blue colour changes to grey and then sunddenly flashed to pink. The percentage nitrogen was calculated as follows:

$$\text{Weight of sample used for distillation} = \frac{2g \times 10\, ml}{100\, ml}$$

$$\text{Percentage of Nitrogen} = \frac{14 \times (A - B) \times N \times 100}{1000 \times 0.2}$$

Where:

A = Volume of standard HCl used in the sample titration

B = Volume of standard HCl used in the blank titration

N = normality of standard HCl

The above process was repeated five times for each of the six species.

Determination of sulphur

The sulphur content of the biomass materials were determined by wet digestion of the samples in accordance with FAO guide to laboratory establishment 2008 followed by estimation of sulphur in the resulting solution by spectrophotometric method. 1 g of the grounded biomass materials was placed in a 250-ml conical flask, and 10 ml of the di-acid mixture (HNO_3 and $HClO_4$, 9:4 v/v) was added and the contents mixed by swirling. The flask and its content was placed on a hotplate in the fumehood and heated; starting at 80 - 90°C and then temperature raised to about 150 - 200^{o}C. Heating was continued until the production of red NO_2 fumes ceased. The content was further heated until the volume was reduced to 3 - 4 ml and became colourless. After cooling, the content was filtered through No.1 filter paper into 100ml volumetric flask and the volume was made up with distilled water. This solution was used for sulphur estimation using spectrophotometer.

To estimate the sulphur, six serial standards of 5, 10, 20, 30, 40 and 50 mg/l were prepared from pure sodium sulphate compound. Five percent of $BaCl_2$ was also prepared from pure compound. 0.5 g of gum acacia-acetic acid (GAAA) was dissolved in 100ml of distilled water and poured into labeled test tubes, 2 ml of each serial standard was pipetted. 2ml of the sample solution was also pipetted into labeled test tubes. To each tube 0.5 ml of GAAA and 1 ml of $BaCl_2$ were respectively added and incubated at room temperature for 30 minutes. The turbidity intensity was read on a spectrophotometer at 420 nm. A calibration curve was plotted from the serial standards and their corresponding absorbances. The graph was used to calculate the concentration of sulphur in the samples. The above process was repeated five times for each of the six species.

3.3 Data analysis

Three-way ANOVA was used to investigate the effect of the experimental factors on the quality characteristics of briquettes produced. Factors considered were species, CP and particle size. Linear regression was used to establish relationship(s) between variables. Statistical Analysis System (SAS) and Statistical Package for the Social Sciences (SPSS) were the statistical softwares used for the data analysis. Two-way ANOVA was also used to determine the effect of combining species and also combining sawdust and maize cobs on the quality characteristics of briquettes produced.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Densification increases the bulk density of biomass raw material, thereby increasing the efficiency of its transportation and burning characteristics. This therefore improves its competitiveness with low-cost fossil energy. In this chapter the results and discussion of a research work conducted to determine optimum conditions for densifying sawdust of six selected tropical hardwood species is presented. This chapter also presents the results of physical, mechanical and burning characteristics of briquettes produced from combination of sawdust of different species and that of a mixture of sawdust and maize cobs.

4.2 Particle size distribution and grading of sawdust of timber species used for the study

This part of the study investigated the particle size distribution of samples of sawdust of the six selected timber species used for the study. **Figure 4.1** shows the cumulative particle size distribution of sawdust of the six tropical hardwood species (*Ceiba pentandra*, *Triplochiton scleroxylon*, *Aningeria robusta*, *Terminalia superba*, *Celtis mildbraedii* and *Piptadenia africana*) used for the study. It could be observed that for all the species 50% of the particles passed through the 1mm sieve. **Figure 4.2** shows details of percentages of the particle size distribution of the sawdust of the six species. **Figure 4.2** shows that the composition of particle size (P): 0.075 mm $\leq$ P < 1 mm ranges from 45.68% (*C. pentandra*) to 85.55% (*T. scleroxylon*) whilst that of particle size, 1 mm $\leq$ P < 2 mm, ranges from 8.36% (*T. scleroxylon*) to 31.24% (*C. pentandra*).

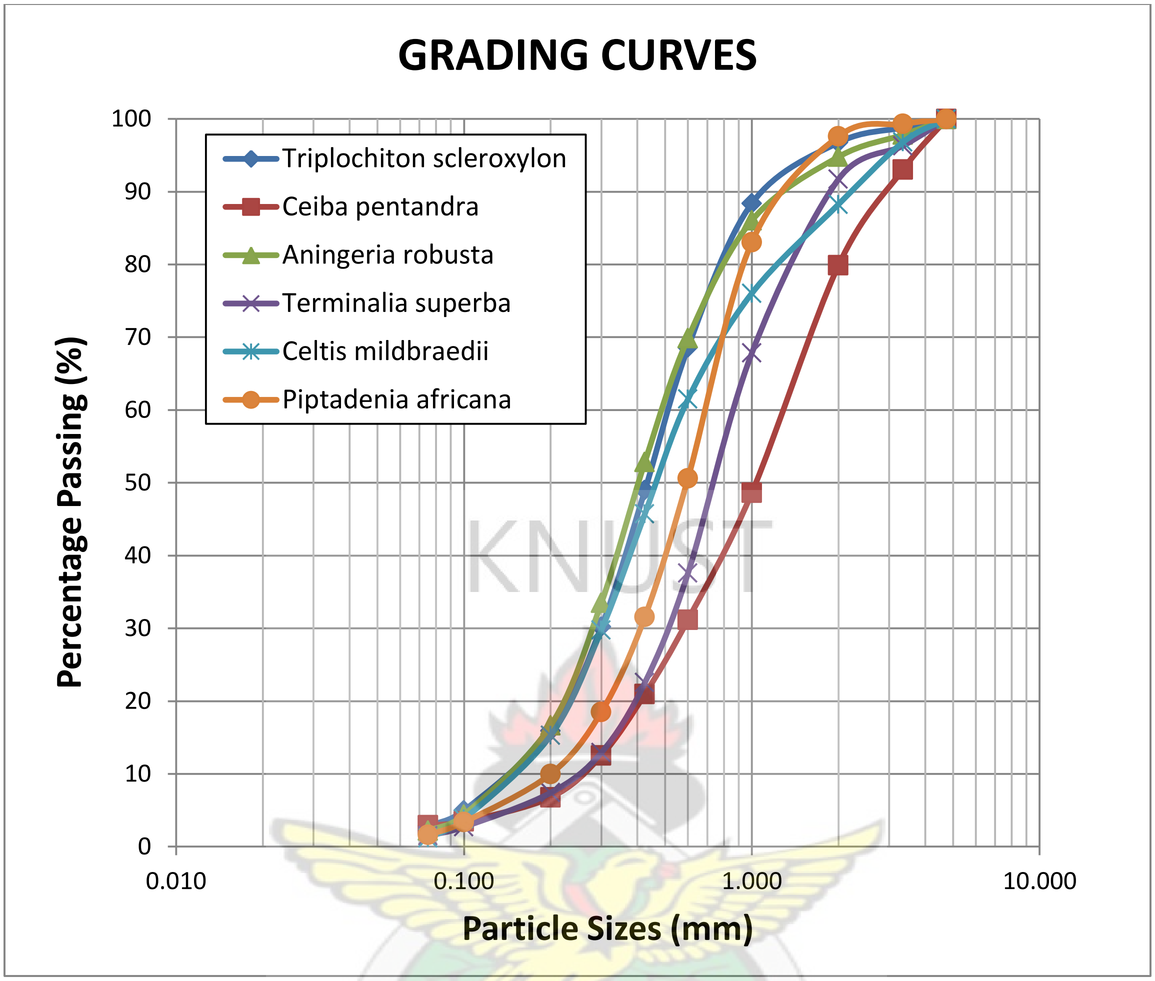


Figure 4.1: Particle size distribution cumulative curves for six timber species.

The composition of particle size 2 mm ≤ P < 3.35 mm also ranges from 1.7% (*P. africana*) to 13.16% (*C. pentandra*) whilst that of particle size, P ≥ 3.35 mm ranges from 0.69% (*P. africana*) to 6.96% (*C. pentandra*). The results shown in **Table 4.1** also indicate that the mean composition of particle sizes 0.075 mm ≤ P < 1 mm, 1 mm ≤ P < 2 mm, 2 mm ≤ P < 3.35 mm and P ≥ 3.35 mm of the sawdust of the six tropical hardwood species were 72.95%, 16.50%, 5.51% and 2.99% respectively. It could also be deduced from **Table 4.1** that, cumulatively,

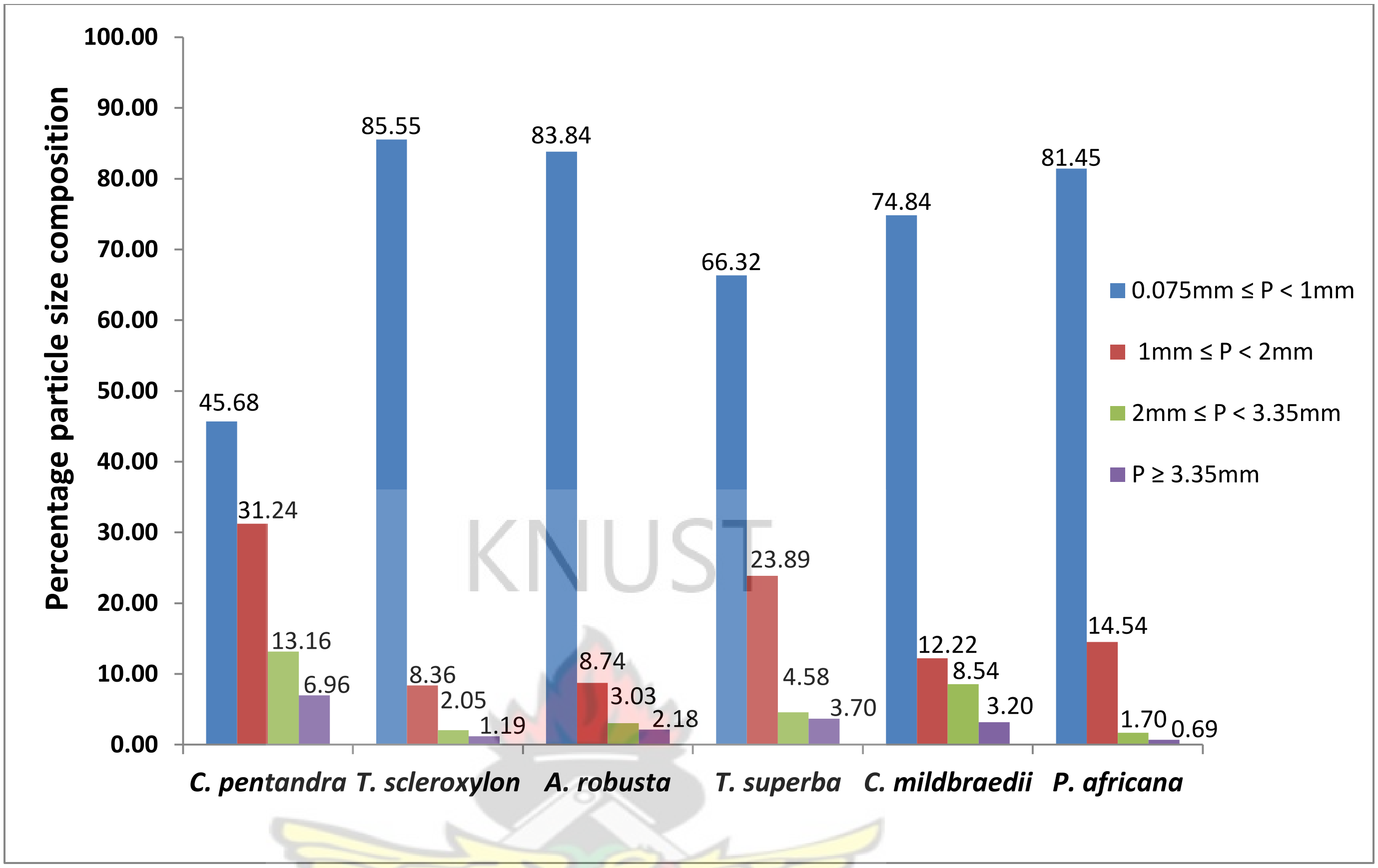


Figure 4.2: Percentage particle size distribution of sawdust of six timber species

Legend: P = Particle size

particle sizes 0.075 mm ≤ P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm forms 90.08% for *C. pentandra*, 95.96% for *T. scleroxylon*, 95.61% for *A. robusta*, 94.79% *T. superba*, 95.60% *C. mildbraedii* and 97.69% for *P. africana* of the sawdust used for the study. The above percentages deviate from the assertion by Seppanen, (1988) that approximately 80% of particles of sawdust are smaller than 2.5 mm. The reason for the deviation is that in this study the largest sieve hole was 3.35 mm. Additionally, the sawdust produced was significantly influenced by the timber species and the type of saws used for the wood processing.

Table 4.1: Summary of percentage particle size distribution of sawdust of six timber species and their mean

Species	Particle size distribution (%)			
	0.075mm ≤ P < 1mm	1mm ≤ P < 2mm	2mm ≤ P < 3.35mm	P ≥ 3.35mm
C. pentandra	45.68	31.24	13.16	6.96
T. scleroxylon	85.55	8.36	2.05	1.19
A. robusta	83.84	8.74	3.03	2.18
T. superba	66.32	23.89	4.58	3.70
C. mildbraedii	74.84	12.22	8.54	3.20
P. africana	81.45	14.54	1.70	0.69
Mean	**72.95**	**16.50**	**5.51**	**2.99**

Legend: P = Particle size

On the basis of the result in **Table 4.1** the sawdust of each species was graded into particle sizes (P): P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm and used for the experiment.

4.3 Density of timber species used for the study

In **Table 4.2** is indicated the densities of the six hardwood species used for the study. The density of the species ranged from a low value of 409.22 kg/m^3 (*C. pentandra*) to a high value of 764.11 kg/m^3 for *C. mildbreadii*. *Ceiba pentandra* and *T. scleroxylon* could be classified as low density species. *A. robusta* and *T. superba* could also be classified as medium density species and finally *C. mildbreadii* and *P. africana* could be classified as high density species.

Table 4.2: Density of six timber species used for the study (kg/m^3)

Species	Replicate	Density	Standard deviation
C. pentandra	5	409.22	18.61
T. scleroxylon	5	450.62	21.16
A. robusta	5	572.64	29.01
T. superba	5	570.08	15.29
C. mildbraedii	5	764.11	33.63
P. africana	5	744.89	26.06

4.4 Percentage acid-insoluble lignin content of six timber species used for the study

It is largely believed that during pressing of lignocellulosic materials to form briquettes, at high temperature and pressure, lignin together with other natural binders such as water soluble carbohydrates, protein, starch and fat in the biomass materials serve as a binding agent (Kaliyan & Morey, 2009). Thus, the type and percentage of Lignin in wood affect the quality of briquettes produced (Kaliyan & Morey, 2009). The result in **Table 4.3** indicates the percentage acid-insoluble lignin content of the six hardwood species used for the study. The result indicates that the acid-insoluble lignin content of the timber species ranges from 18.36% for *C. mildbraedii* to 25.11% for *P. africana*. The lignin content is within the range suggested by Biermann (1996). Biermann (1996) suggested that in North America the lignin content of hardwoods is approximately between 18% and 25%. Pettersen (1984) in his write-up on the chemical composition of wood also indicated that generally the lignin content of wood ranges from 18% to 35%.

Table 4.3: Percentage acid-insoluble lignin content of six timber species used for the study

Species	Number of replicate	Acid-insoluble Lignin (%)	Standard deviation	Range
C. pentandra	5	23.34	0.6495	22.47 - 24.14
T. scleroxylon	5	23.58	0.4018	22.99 - 23.86
A. robusta	5	23.72	0.5637	23.08 - 24.44
T. superba	5	22.87	1.0085	21.11 - 23.60
C. mildbraedii	5	18.36	1.8794	16.13 - 21.21
P. africana	5	25.11	0.3162	24.73 - 25.56

4.5 Percentage alpha-cellulose content of six timber species used for the study

Cellulose is composed of molecules of glucose formed through photosynthesis. It is noted to play a role in the bonding process when briquette is manufactured. In **Table 4.4** is presented the percentage alpha-cellulose content of the timber species used for the study.

Table 4.4: Percentage alpha-cellulose content of six timber species used for the study

Species	Number of replicate	α-Cellulose (%)	Standard deviation	Range
C. pentandra	5	41.24	1.99	38.54 - 43.43
T. scleroxylon	5	34.36	1.12	33.14 - 35.71
A. robusta	5	45.36	1.07	44.31 - 46.75
T. superba	5	39.40	2.72	38.10 - 42.60
C. mildbraedii	5	35.05	1.47	33.14 - 37.13
P. africana	5	41.44	1.96	38.64 - 43.71

On the average of all the six species, *A. robusta* was the species with the highest alpha-cellulose content of 45.36% and *T. scleroxylon* the lowest (34.36%). The cellulose content obtained for the six timber species is consistent with that suggested by Pettersen (1984) and Ritter and Fleck (1922). Pettersen (1984) in his write-up on the chemical composition of wood, indicated that cellulose content of wood ranges from 40 to 50% of the dry wood weight. Additionally, a study conducted by Ritter and Fleck (1922) on 10 American wood species revealed that the alpha-cellulose content of the 10 species ranged from 19.52 to 40.96%.

4.6 Percentage hemicelluloses content of six timber species used for the study

It is believed that hemicelluloses play a significant role in the binding mechanism of briquette (Petterson, 1984). Dutta (2007) stated that some researchers suggested that self bonding in the production of briquettes may be partly attributed to adhesive degradation products of

Table 4.5: Percentage hemicellulose content of six timber species used for the study

Species	**Number of replicate**	**Hemi-cellulose** (%)	**Standard deviation**	**Range**
C. pentandra	5	34.42	3.1381	30.05 - 37.72
T. scleroxylon	5	38.06	3.1095	33.77 - 40.76
A. robusta	5	27.00	1.3990	24.91 - 28.65
T. superba	5	33.73	2.7349	29.51 - 36.39
C. mildbraedii	5	35.59	1.4690	33.60 - 37.08
P. africana	5	33.45	1.7671	31.72 - 36.08

hemicelluloses. In **Table 4.5** is presented the hemicellulose content of the species used for the study. The hemicellulose content of all the species ranges from 27.00% (*A. robusta*) to 38.06% (*T. scleroxylon*). The hemicelluloses content of the species do not significantly deviate from that suggested by Pettersen (1984) that the percentage hemicellulose of wood is between 25 and 35%.

4.7 Fibre length of sawdust particles of six timber species

In **Table 4.6** is presented the average fibre lengths of the particle size classification of the sawdust used for the study. The result (**Table 4.6**) shows that for all the species, on the average the fibre length of sawdust containing particle sizes; 2 mm $\leq$ P $<$ 3.35 mm was highest followed by 1 mm $\leq$ P $<$ 2 mm and lastly P $<$ 1 mm. For particle size P $<$ 1 mm, the fibre length varied from 0.3843 mm (*P. africana*) to 0.5940 mm (*C. pentandra*). The fibre length of particle size 1 mm $\leq$ P $<$ 2 mm also varied from 0.5406 mm (*P. africana*) to 0.7286 mm (*C. pentandra*) and lastly that of particle size 2 mm $\leq$ P $<$ 3.35 mm varied from 0.5347 mm (*P. africana*) to 0.8072 mm (*C. pentandra*). For the same particle size classification, fibre length was also found to vary from species to species. The variability in fibre length for each of the particle size classification is due to the fact that sawdust with higher proportions of larger particle size components has less broken fibres or longer broken fibres. This results in the overall average fibre length being relatively longer. On the contrary sawdust with higher proportions of smaller particle size components has lower proportion of unbroken fibres as well as larger proportions of shorter length fibres resulting in the overall average fibre length being shorter. Additionally, for the same particle size classification as mentioned earlier, fibre length varied from species to species.

Table 4.6: Fibre length of sawdust particles of six timber species graded into particle sizes; P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm

Species	Number of samples	P < 1 mm			1 mm ≤ P < 2 mm			2 mm ≤ P < 3.35 mm		
		Length (mm)	SD (mm)	Range (mm)	Length (mm)	SD (mm)	Range (mm)	Length (mm)	SD (mm)	Range (mm)
C. Pentandra	10	0.5940	0.1523	0.3934 - 0.8527	0.7286	0.1831	0.5803 - 1.0560	0.8072	0.1143	0.6867 - 0.9629
T. scleroxylon	10	0.4273	0.0487	0.3486 - 0.5070	0.6350	0.1162	0.4596 - 0.7842	0.7060	0.1055	0.5267 - 0.8776
A. robusta	10	0.4812	0.0799	0.3713 - 0.6125	0.6738	0.1259	0.5070 - 0.8189	0.7798	0.1090	0.5972 - 0.9880
T. superba	10	0.5067	0.0721	0.3968 - 0.6142	0.6341	0.0760	0.5480 - 0.7800	0.6750	0.1415	0.4313 - 0.8018
C. mildbraedii	10	0.5789	0.0251	0.5403 - 0.6175	0.5834	0.1030	0.4523 - 0.7315	0.6109	0.1029	0.4353 - 0.7801
P. africana	10	0.3843	0.0450	0.3295 - 0.4721	0.5406	0.0754	0.4525 - 0.6674	0.5347	0.1523	0.2447 - 0.7940

Legend: P = Particle size

This is likely due to the different particle size distribution of the sawdust samples as well as the variations in the fibre lengths of the species used for study.

4.8 Effect of species, particle size and compacting pressure on mechanical and physical characteristics of fuel briquettes produced from sawdust of six timber species

One of the factors that limit the use of biomass briquettes as fuel is its high cost compared to fossil fuels. Thus in the 21st century most research work on biomass briquettes are geared towards ways of reducing cost of its production. Some variables that have been noted to have significant influence on the quality of briquettes produced are particle size/particle size distribution, moisture content, compacting pressure (CP), temperature, the nature of biomass raw material, hardness of raw biomass material, material mix or mixture of different raw materials, flowability and cohesiveness of the raw material. Thus, the understanding of how these variables unilaterally or interactively influence the cost and quality of briquettes

Figure 4.3: Samples of briquettes produced from sawdust of *C. pentandra*

produced from biomass residues is worth investigating. In this part of the study the result of effect of species, particle size and CP on the stability, relaxed density, compressive strength (CS) in cleft, impact resistance index (IRI) and water resistance (WR) quality of briquettes produced is presented and discussed. **Figure 4.3** shows samples of briquettes produced from sawdust of *C. pentandra*.

4.8.1 Stability of briquettes produced from sawdust of six timber species

The stability of briquette refers to the changes in it dimensions after it has been removed from the pressing mould. It results from pressure loss due to humidity escaped from the briquette in the form of steam (Križan, 2007). The changes in dimension of briquettes following its removal from the die depend on many factors related to die geometry, the magnitude and mode of compression, the type and properties of the biomass raw material, and storage conditions. The extent of changes in dimension may be detrimental to the net benefits realized from the compaction of the biomass raw material (Al-Widyan, *et. al*., 2002). Many studies on high-pressure compaction of biomass materials have indicated that, on removal of densified material from the die, the density of the compacted material decreases with time to a final relaxed density. This decrease in density is as a result of expansion of the briquette laterally and axially after removal from the die. An increased in volume of briquette with the mass being constant will result in decreased density. In this part of the study the stability in length and diameter of briquettes produced is examined.

Stability in length

Stability of briquette, which refers to the changes in it dimensions after removal from die could result in a total density reduction of between 64 - 75% (O'Dogherty & Wheeler, 1984). **Tables 4.7a, 4.7b and 4.7c** shows the results of percentage elongation of briquettes made

Table 4.7a: Stability (%) in length of briquettes made from sawdust of six timber species, at compacting pressure levels 20 to 50 MPa and particle size (P) P < 1 mm

Species	Compacting pressure			
	20MPa	30MPa	40MPa	50MPa
C. pentandra	12.04	13.55	13.71	14.78
T. scleroxylon	10.63	11.13	11.39	12.71
A. robusta	7.61	8.46	8.74	8.91
T. superba	9.51	10.42	10.72	11.54
P. africana	7.35	7.86	7.95	8.42
C. mildbreadii	7.23	7.47	7.67	8.04

Table 4.7b: Stability (%) in length of briquettes made from sawdust of six timber species, at compacting pressure levels 20 to 50 MPa and particle size (P) 1 mm ≤ P < 2 mm

Species	Compacting pressure			
	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	12.58	14.59	15.15	16.33
T. scleroxylon	11.28	12.63	13.79	14.34
A. robusta	8.06	8.65	8.84	9.38
T. superba	10.12	10.44	10.94	11.76
P. africana	7.91	8.47	8.52	8.83
C. mildbreadii	7.49	7.82	8.19	8.30

Table 4.7c: Stability (%) in length of briquettes made from sawdust of six timber species, at compacting pressure levels 20 to 50 MPa and particle size (P) 2 mm ≤ P < 3.35 mm

Species	Compacting pressure			
	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	12.64	14.68	15.22	16.39
T. scleroxylon	11.51	12.76	13.87	14.37
A. robusta	8.19	8.76	9.06	9.52
T. superba	10.29	10.67	11.07	11.85
P. africana	8.06	8.63	9.13	9.32
C. mildbreadii	7.61	7.97	8.42	8.55

at CP levels; 20 MPa, 30 MPa, 40 MPa and 50 MPa, and particle sizes (P); P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm. Species used for the study as indicated earlier were *C. pentandra*, *T. scleroxylon*, *A. robusta*, *T. superba*, *C. mildbraedii* and *P. africana*. The result indicates that for all CP levels and particle sizes, briquettes' percentage change in length for *C. pentandra* was higher than that of the other species. This was followed by that of *T. scleroxylon*. In the case of particle size less than one millimeter (P < 1 mm) the percentage elongation of *C. pentandra* briquettes ranged from 12.04 to 14.78%, corresponding to CP levels 20 to 50 MPa. That of particle size; 1 mm ≤ P < 2 mm also ranged from 12.58 to 16.33%, corresponding to CP levels 20 to 50 MPa. Lastly, the percentage change in length for *C. pentandra* corresponding to particle size 2 mm ≤ P < 3.35 mm ranged from 12.64 to 16.39% (CP level 20 to 50 MPa). The result further indicates that considering all the three particle sizes, *C. mildbraedii* exhibited the least percentage elongation. This means that briquettes made from *C. mildbraedii* could be more stable and therefore could have less changes in relaxed density than those made from the other species. The result also suggests that considering all the species, within CP level range of 20 and 50 MPa, increased in CP level resulted in increased percentage change in length of the briquettes produced. Additionally, increase in particle size of sawdust used resulted in an increased in percentage change in length of the briquettes for all the species used. In view of the above trend further analysis was conducted to determine the correlation between experimental factors; CP and particle size of the sawdust on one hand and percentage change in length on the other hand. The result indicated that at 5% level of significance, there was a weak positive significant correlation between CP and percentage change in length of briquettes produced (Pearson's r = 0.260, p-value = 0.000; N = 360; 1-tailed). Particle size of sawdust was also found to be significantly and positively correlated with percentage change in length of briquettes produced (Pearson's r = 0.138, p-value = 0.004; N = 360; 1-tailed, α = 0.05). This result is consistent with that of Moshenin and Zaske (1976). Moshenin and Zaske (1976), in their study on densification, reported that materials having lower moisture content and fewer long fibres (more fines) gave more stable wafers due to limited expansion. In general, the finer the grind, the higher the dimensional stability and durability of the biomass compacts. The reason is that fine particles usually absorb more moisture than large particles; hence, they undergo a higher degree of conditioning. Furthermore, large/coarse ground materials tend to produce less quality compacts because they may create natural fissure points that cause cracks and fractures (Tabil, 1996; Kaliyan & Morey, 2009). Three-way ANOVA at 5% level

Table 4.8: ANOVA of effect of biomass material, particle size and compacting pressure on stability in length of briquettes produced from sawdust of six timber species

Source	**DF**	**ANOVA SS**	**Mean Square**	**F-Ratio**	**p-value**
Species	5	1996.0937	399.2187	1640.02	< 0.0001*
Particle size	2	50.0630	25.0315	102.83	< 0.0001*
CP	3	161.8521	53.9507	221.63	< 0.0001*
Species*CP	15	41.2578	2.7505	11.30	< 0.0001*
Species*Particle size	10	17.8792	1.7879	7.34	< 0.0001*
Particle size *CP	6	1.9146	0.3191	1.31	0.2521†
Species* Particle size* CP	30	6.5311	0.2177	0.89	0.6296†
Error	288	70.1056	0.243422		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

of significance as indicated in **Table 4.8** revealed that species, particle size and CP as experimental factors have significant effect on the percentage elongation of briquettes produced ($p < 0.05$). Additionally, the interactions between species and CP, and species and particle size, at 5% level of significance, have significant effect on the percentage elongation of briquettes produced ($p < 0.05$). However, the interaction between particle size and CP, as well as the interaction between species, particle size and CP were found not to have any significant effect on the percentage elongation of briquettes produced ($p > 0.05$, $\alpha = 0.05$). The multiple coefficient of determination and RMSE of the ANOVA model were 0.9701 and 0.4937 respectively. The multiple coefficient of determination value of 0.9701 means that about 97.01% of the variability of the percentage change in length of the briquettes produced could be explained by the independent variables used (ie species, particle size and compacting pressure).

In view of the result obtained from the ANOVA, a multiple regression analysis was performed using SPSS to establish the relative contribution of species density, particle size and CP to the prediction of percentage change in length of the briquettes produced. A mathematical relationship between the dependent variable, percentage change in length and the independent variables; species density, particle size and CP was also established. The summarized results, as indicated in **Table 4.9** shows the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), *adjusted* R^2, the value of t and its associated p-values for each of the independent variables. The result indicates that the species density, particle size and CP collectively explained 80.1% (*adjusted* $R^2 = 0.801$) of the variance in percentage change in length of the briquettes produced. This suggests that the regression model is a good predictor of percentage change in length of the briquettes

Table 4.9: Regression of percentage change in length of briquettes on species density, particle size and compacting pressure

Variables	β	Beta	R	*adjusted* R^2	t	p-value
Constant	16.950				47.017	0.000
Species density	-0.016	-0.846			- 35.951	0.000
Particle size	0.432	0.138			5.865	0.000
Compacting pressure	0.059	0.260			11.067	0.000
			0.896	0.801		

produced (R^2 = 0.801, p-value = 0.000). The standardized regression coefficients values (Beta) for the three predictive variables suggest that species density explained the bulk of the variance in the percentage change in length of the briquette produced (Beta = -0.846, t = -35.951, p-value = 0.000) and was the best predictor of percentage change in length of briquette produced. That not withstanding, particle size of sawdust and CP significantly contributed to the regression model (Particle size: Beta = 0.138, t = 5.865, p-value = 0.000; Compacting pressure: Beta = 0.260, t = 11.067, p-value = 0.000). From **Table 4.9** column two, (i.e. unstandardized (β) regression coefficients values) it could be established that the relationship between the dependent variable, percentage change in length and the independent variables; species density(S), particle size (P) and compacting pressure (CP) is:

$$\text{Percentage change in length} = 16.950 - 0.016S + 0.432P + 0.059CP$$

Where;

S = Species density
P = Particle size
CP = Compacting pressure

Stability in diameter

Stability in diameter of briquette is the measure of its percentage change in diameter just after removal from pressing mould. As mentioned earlier positive changes in dimensions of briquettes negatively affect its fuel value in that it reduces it density. **Tables 4.10a, b** and **c** indicates the result of percentage change in diameter of briquette made from sawdust of the six species for particle sizes P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm. Compacting pressure levels 20 to 50 MPa for this part of the study. The result in **Table 4.10a** (i.e. P < 1 mm) indicates that with the exception of briquettes pressed at 20 MPa, briquettes made from *T. superba* exhibited the least or best percentage change in diameter. The percentage change in diameter of briquette made from *T. superba* ranged from 0.75 to 1.06% corresponding to CP level 20 to 50 MPa. *P.africana* exhibited the highest percentage change in diameter for all corresponding CP levels. Percentage change in diameter of *P. africana* also ranged from 1.13 to 1.36% i.e. for CP 20 to 50 MPa. The result in **Tables 4.10b** and **c** showed similar trend as that in **Table 4.10a**. The result in **Table 4.10b** (i.e. 1 mm ≤ P < 2 mm) indicated that at all CP level *T. superba* exhibited the least percentage change in diameter. The percentage change in diameter of *T. superba* ranged from 0.82 to 1.17% i.e. for CP 20 MPa and 50 MPa whilst that of *P. africana*, the species which exhibited the highest percentage change in diameter ranged from 1.21 to 1.51%. For all the three particle sizes, the result indicated that within CP level 20 and 50 MPa, increased in CP resulted in increased percentage change in diameter of the briquettes made. This is confirmed by a moderate positive significant correlation between CP levels and percentage change in diameter (Pearson's r = 0.515, p-value = 0.000; N = 360, α = 0.05, 1-tailed). Additionally, increased particle size of sawdust used for the study resulted in an increased percentage change in diameter of briquettes produced for all the species used.

Table 4.10a: Stability (%) in diameter of briquettes made from sawdust of six timber species, at compacting pressure levels 20 to 50 MPa and particle size (P) P < 1 mm

	Compacting pressure			
Species	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	0.72	0.89	0.95	1.08
T. scleroxylon	0.86	0.94	1.03	1.12
A. robusta	0.80	0.92	0.99	1.11
T. superb	0.75	0.81	0.86	1.06
P. Africana	1.13	1.16	1.23	1.36
C. mildbreadii	0.93	1.05	1.11	1.29

Table 4.10b: Stability (%) in diameter of briquettes made from sawdust of six timber species, at compacting pressure levels 20 to 50 MPa and particle size (P) 1 mm ≤ P < 2 mm

	Compacting pressure			
Species	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	0.83	1.00	1.12	1.25
T. scleroxylon	1.10	1.18	1.34	1.36
A. robusta	0.96	1.09	1.24	1.32
T. superba	0.82	0.95	1.02	1.17
P. africana	1.21	1.37	1.43	1.54
C. mildbreadii	1.16	1.28	1.40	1.51

Table 4.10c: Stability (%) in diameter of briquettes made from sawdust of six timber species,at compacting pressure levels 20 to 50 MPa and particle size (P) 2 mm ≤ P < 3.35 mm

	Compacting pressure			
Species	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	0.88	1.06	1.23	1.26
T. scleroxylon	1.11	1.19	1.40	1.42
A. robusta	0.97	1.14	1.25	1.29
T. superba	0.87	0.98	1.14	1.19
P. africana	1.21	1.43	1.55	1.61
C. mildbreadii	1.18	1.31	1.51	1..52

This is also confirmed by a correlation analysis which suggest that there was a weak positive significant correlation between particle size and percentage change in diameter of briquettes produced (Pearson's r = 0.393, p-value = 0.000; N = 360, $\alpha = 0.05$, 1-tailed).

In **Table 4.11** is the result of a three-way ANOVA to determine the effect of species, particle size and CP on percentage change in diameter of briquettes produced. The result shows that at 5% level of significance, species, particle size and CP have significant effect on the percentage change in diameter of briquettes produced ($p < 0.05$).

Table 4.11: ANOVA of effect of the species, particle size and compacting pressure on stability in diameter of briquettes produced from sawdust of six timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
Species	5	6.53356250	1.30671250	82.63	< 0.0001*
Particle size	2	3.64185500	1.82092750	115.14	< 0.0001*
CP	3	5.54341639	1.84780546	116.84	< 0.0001*
Species x CP	15	0.09736528	0.00649102	0.41	0.9757†
Species x Particle size	10	0.17798500	0.01779850	1.13	0.3427†
Particle size x CP	6	0.17526944	0.02921157	1.85	0.0899†
Species x Particle size x CP	30	0.07686389	0.00256213	0.16	1.000†
Error	288	4.55468000	0.01581486		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

However, the interactions between species and CP, species and particle size, particle size and CP and species, particle size and CP at 5% level of significance did not have any significant effect on percentage change in diameter of briquettes produced ($p < 0.05$). The multiple coefficient of determination (R^2) and RMSE of the ANOVA model were 0.7810 and 0.125757 respectively. Thus, the R^2 value of 0.7810 means that about 78.10% of the variance in percentage change in diameter of briquettes produced could be explained by the experimental factors considered.

A multiple regression analysis performed using SPSS to establish a mathematical relationship and the relative contribution of species density, particle size and CP in the prediction of percentage change in diameter of the briquette produced is indicated in **Table 4.12**. The summarized results as indicated in **Table 4.12** consist of the unstandardized (β) and standardized (Beta)

Table 4.12: Regression of percentage change in diameter of briquettes on species density, particle size and compacting pressure of briquettes produced from sawdust of six timber species

Variables	β	Beta	R	*adjusted* R^2	t	p-value
Constant	0.105				2.113	0.035
Species density	0.001	0.401			11.666	0.000
Particle size	0.116	0.393			11.450	0.000
Compacting pressure	0.011	0.515			14.998	0.000
			0.762	0.577		

regression coefficients, the multiple correlation coefficient (R), *adjusted* R^2, the value of t and its associated p-value for each of the variables. The result indicates that species, particle size and CP collectively explained 57.7% (*adjusted* R^2 = 0.577) of the variance in percentage change in diameter of briquettes produced. This suggests that the regression model is a good predictor of percentage change in diameter of briquettes produced (R^2 = 0.580, p-value = 0.000). The standardized regression coefficient values (Beta) for the three predictive variables suggest that CP explained the bulk of the variance in the percentage change in diameter of the briquettes produced (Beta = 0.515, t = 14.822, p-value = 0.000) and was the best predictor the of percentage change in diameter. Besides this, species density and particle size of sawdust also significantly contributed to the regression model (Species density: Beta = 0.401, t = 11.666, p-value = 0.000; Particle size: Beta = 0.393, t = 11.450, p-value = 0.000). Based on the unstandardized (β) regression coefficient values it could be established that the mathematical relationship between the dependent variable, percentage change in diameter, and the independent variables; species density (S), particle size (P) and compacting pressure (CP) is:

$$\text{Percentage change in diameter} = 0.105 - 0.001S + 0.116P + 0.011CP$$

Where;

S = Species density
P = Particle size
CP = Compacting pressure

4.8.2 Relaxed density of briquettes produced from sawdust of six timber species

Density is an important parameter in briquetting. The higher the density of a briquette the higher its energy/volume ratio. The results presented in **Tables 4.13a, b** and **c** indicate the relaxed density of briquettes produced from six tropical hardwood species at CP levels ranging from 10 to 50 MPa for three different particle sizes (P): P < 1 mm, 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm. Considering the result in **Table 4.13a** (P < 1 mm) it could be deduced that the relaxed density of briquettes produced from *C. pentandra*, the species with lowest density (409 kg/m^3) ranged from 398 to 716 kg/m^3 whilst that of *C. mildbreadii* the

Table 4.13a: Relaxed density (kg/m^3) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and particle size (P) P < 1 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	398	523	622	666	716
T. scleroxylon	366	458	545	594	632
A. robusta	440	543	607	636	695
T. superba	447	557	631	675	727
P. africana	465	567	637	679	741
C. mildbreadii	453	533	611	662	706

Table 4.13b: Relaxed density (kg/m^3) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and particle size (P) 1 mm ≤ P < 2 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	386	503	606	646	692
T. scleroxylon	354	452	535	591	627
A. robusta	362	466	538	586	658
T. superba	437	548	615	651	680
P. africana	441	534	610	664	723
C. mildbreadii	435	491	562	621	658

Table 4.13c: Relaxed density (kg/m^3) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and particle size (P) 2 mm ≤ P < 3.35 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	373	489	598	618	651
T. scleroxylon	324	435	508	552	597
A. robusta	345	463	519	571	573
T. superba	396	514	591	649	673
P. africana	417	530	604	658	720
C. mildbreadii	430	487	543	612	655

species with highest density (764 kg/m^3) ranged from 453 to 706 kg/m^3. For all the briquettes produced from P < 1 mm, the lowest relaxed density was 366 kg/m^3 for *T. scleroxylon* when the CP was 10MPa and the highest was 741 kg/m^3 for *P. africana* when the CP level was 50 MPa. Considering particle size, 1 mm ≤ P < 2 mm, the result as indicated in **Table 4.13b** shows that the relaxed density of briquettes made from *C. pentandra*, the species with lowest density (409 kg/m^3) ranged from 386 to 692 kg/m^3 whilst *C. mildbreadii*, the species with the highest density (764 kg/m^3) ranged from 435 to 658 kg/m^3. Considering the briquettes produced for all the species for 1 mm ≤ P < 2 mm, the lowest relaxed density was 354 kg/m^3 for *T. scleroxylon* when the CP level was 10 MPa and the highest was 723 kg/m^3 for *P. africana* when the CP level was 50 MPa.

Table 4.13c which also indicates the result of relaxed density for 2 mm ≤ P < 3.35 mm shows that briquettes made from *C. pentandra*, species with the lowest density (409 kg/m^3) had relaxed density ranging from 373 to 651 kg/m^3 whilst that of *C. mildbreadii* the species with highest density (764 kg/m^3) ranged from 430 to 655 kg/m^3. The lowest relaxed density, considering all the species for this particle size was 324 kg/m^3 for *T. scleroxylon* when the CP was 10MPa and the highest was 720 kg/m^3 for *P. africana* when the CP was 50MPa. Briquettes' densities obtained from this study was consistent with suggestion by some researchers that briquettes made from hydraulic piston press are usually less than 1000 kg/m^3 (Tumuluru, *et al*., 2010) and are usually between 300 - 600 kg/m^3 (Saeidy, 2004). Nevertheless, the density of briquettes obtained was less than the optimum value suggested by the Austria ÖNORM M7135 (ρ ≥1000 kg/m^3) and the Germany DIN 51731 / DIN plus (ρ = 1000 to 1400 kg/m^3) (Austria ÖNORM M7135 as cited in Hahn, 2004; Germany DIN 51731 / DIN plus as cited in Hahn, 2004). Research has established that the density of briquette is greatly influenced by the material's moisture content, particle size, process pressure and temperature (Mani, *et al*., 2006). In a comparison of different densification equipment, in terms of feedstock material properties, specific energy consumption, and suitability of the densified material for different end-use applications and some physical characteristics of briquettes produced, FAO (1996), Kaliyan, *et al*. (2009) and Grover and Mishra (1996) concluded that briquettes produced from piston press have optimum density values ranging from 1000 to 1200 kg/m^3. The deviation of the relaxed density of briquettes produced from the optimum range suggested above may be due to the fact that the briquettes were compacted at room temperature and at a lower pressure (CP level 10MPa to 50MPa). Kers, *et al*. (2010) iterated that pressing biomass materials at high temperature result in the production of briquettes with higher densities even at lower CP. Tumuluru, *et al*. (2010) concluded that both unit and bulk density greatly depends on feed moisture and die temperature where a maximum density of 1200 kg/m^3 is achievable at temperatures of about 100°C.

Correlation analysis was performed to establish the relationship between relaxed density on one hand, and CP level and particle size on the other hand. The result indicates that there was a weak significant negative correlation between relaxed density and particle size of briquettes produced (Pearson's $r = -0.188$, p-value = 0.000; N = 450; 1-tailed, $\alpha = 0.05$). CP level was also found to have a very strong positive significant correlation with the relaxed density of the briquettes produced (Pearson's $r = 0.901$, p-value = 0.000; N = 450; 1-tailed, $\alpha = 0.05$). This result generally suggest that the relaxed density of the briquettes produced increases with increasing CP level and decreases with increasing particle sizes. In order wards briquette produced from sawdust of tropical hardwoods with smaller particle sizes are likely to have higher relaxed density than those with larger particle size. This result confirms that of other researchers. Križan (2007) and Shankar and Bandyopadhyay (2005) reported that in reality in briquetting when the fraction of the raw material is smaller, the briquette produced will have a higher density. FAO (1990) also reported that finely ground materials, for example sanding dust from wood plants produces very dense briquettes but requires high pressure and temperature to agglomerate without a binder. The reason for this is that when the raw material is finer it gives a larger surface area for bonding which result in the production of briquette with higher density. Additionally, the reason for high significant positive correlation between CP level and relaxed density of briquettes produced is that increasing the CP level will lead to the particles of the biomass material being closely packed due to reduction of the void ratio and plastic deformation of the particles. Therefore, leading to increased density of the briquettes produced (Lindley & Vossoughi, 1989).

The result in **Tables 4.14** is Analysis of Variance (ANOVA) to determine the effect of species, CP and particle size on the relaxed density of briquettes produced. It indicates that at 5% level of significance species, particle size, CP and their interactions all have significant effects on the relaxed density of the briquettes produced ($p\text{-value} < 0.05$). The coefficient of determination value (R^2) and the root mean square error (RMSE) for the ANOVA Model were 0.9907 and 11.24 respectively. Thus, it could be deduced that species, particle size and CP and their interactions explain about 99.07% of the variability in the relaxed density of the briquettes produced. This result is consistent with result of research conducted by other researchers. According to Karunanithy, *et al*. (2012) the density and durability of briquettes depends on the feedstocks, machines, and process variables.

Table 4.14: ANOVA of effect of biomass material, particle size and compacting pressure on relaxed density of briquettes produced from sawdust of six timber species

Source	**DF**	**ANOVA SS**	**Mean Square**	**F-Ratio**	**p-value**
Species	5	452443.680	90488.736	715.19	< 0.0001*
Particle size	2	174914.253	87457.127	691.23	< 0.0001*
CP	4	4106254.742	1026563.686	8113.63	< 0.0001*
Species x CP	20	45562.164	2278.108	18.01	< 0.0001*
Species x Particle size	10	38280.947	3828.095	30.26	< 0.0001*
Particle size x CP	8	3449.324	431.166	3.41	0.0009*
Species x Particle size x CP	40	22406.809	560.170	4.43	< 0.0001*
Error	360	45548.400	126.523		

*Statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

Some of the variables mentioned in earlier research that influence the density of briquettes are particle size, moisture content, density and the chemical composition of the original biomass, compacting pressure, process temperature and the type of pressing equipment (Mani, *et al*., 2006; Tumuluru, *et al*., 2010). Additionally, species density was found to significantly and positively correlate with the relaxed density of briquettes produced (**Table 4.25**).

As a result of the above findings, multiple regression analysis was performed using SPSS to establish the relative contribution of species density, particle size and CP in the prediction of the relaxed density of the briquette produced as well as to determine the mathematical relationship between them. The summarized results indicated in **Table 4.15** shows the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), *adjusted R^2*, the value of t and its associated p-value for each of the variables.

Table 4.15: Regression of relaxed density of briquettes on species density, particle size and compacting pressure of briquettes produced from sawdust of six timber species

Variables	β	Beta	R	*Adjusted R^2*	t	p-value
Constant	334.628				34.255	0.000
Species density	0.125	0.160			9.454	0.000
Particle size	-23.986	-0.188			-11.110	0.000
Compacting pressure	6.639	0.901			53.261	0.000
			0.934	0.872		

As shown in **Table 4.15** species density, particle size and CP collectively explained 87.2% (*adjusted R^2* = 0.872) of the variance in relaxed density of briquette produced. This suggests that the regression model is a good predictor of relaxed density (R^2 = 0.872, p-value = 0.000). Based upon the standardized regression coefficient values (Beta), it could be deduced that CP explained the bulk of the variance in the relaxed density of the briquettes produced (Beta = 0.901, t = 53.261, p-value = 0.000) and was the best predictor of the relaxed density. However, species density and particle size of sawdust used significantly contributed to the model (Species density: Beta = 0.106, t = 9.454, p-value = 0.000; Particle size: Beta = -0.188, t = -11.110, p-value = 0.000). From **Table 4.15,** (i.e. unstandardized (β) regression coefficients values) it could be established that the relationship between the dependent variable, relaxed density and the independent variables; species density (S), particle size (P) and compacting pressure (CP) is:

$$\text{Relaxed density} = 334.628 + 0.125S - 23.986P + 6.639CP$$

Where; S = Species density, P = Particle size, CP = Compacting pressure

4.8.3 Compressive strength in cleft of briquettes produced from sawdust of six timber species

Briquettes' compressive strength is one of the indices used to assess its ability to be handled, packed and transported without breaking. In this part of the study the compressive strength (CS) in cleft of briquette produced from sawdust of six timber species is presented in **Tables 4.16a, b** and **c.** The result in **Table 4.16a**, (that is for P < 1 mm) indicates that for all the CP levels the CS in cleft of *C. pentandra* was exceptionally high compared to that of the other species. Compressive strength in cleft of *C. pentandra* ranged from 15.81 to 44.58 N/mm for CP levels 10 to 50 MPa. *C. mildbreadii* comparatively had the lowest CS in cleft ranging from 1.30 to 12.45 N/mm for the same CP levels (i.e. CP level 10 to 50 MPa). The result for particle sizes; 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm reflected the trend for particle size P < 1 mm. In both cases the CS in cleft of *C. pentandra* was exceptionally higher than that of the other species. For particle size, 1 mm ≤ P < 2 mm the CS in cleft of *C. pentandra* (lowest density species) ranged from 7.28 to 52.60 N/mm and that of *C. mildbraedii* (highest density species) ranged from 2.59 to 16.40 N/mm. In the case of 2 mm ≤ P < 3.35 mm the CS in cleft of *C. pentandra* (lowest density species) ranged from 13.80 to 51.45 N/mm and that of *C. mildbraedii* (highest density species) ranged from 3.62 to 19.18 N/mm. According to Rahman, *et al*. (1989), briquettes surface compressive strength (i.e. CS in cleft) of 19.6 N/mm is reasonably adequate for handling or use for domestic fuel purpose.

Table 4.16a: Compressive strength in cleft (N/mm) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and for particle size (P) P < 1 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	15.81	29.23	39.26	40.40	44.58
T. scleroxylon	3.33	9.35	14.27	20.66	30.56
A. robusta	3.97	8.23	16.28	19.48	26.63
T. superb	2.13	6.16	10.44	13.64	18.92
P. Africana	1.76	5.95	10.13	17.06	21.14
C. mildbreadii	1.30	3.55	6.69	10.51	12.45

Table 4.16b: Compressive strength in cleft (N/mm) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and for particle size (P) 1 mm ≤ P < 2 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	7.28	24.34	34.74	42.62	52.60
T. scleroxylon	6.97	14.66	27.53	36.57	38.31
A. robusta	3.47	9.51	14.42	21.62	27.50
T. superb	3.26	6.61	12.50	14.89	18.03
P. Africana	2.60	6.99	12.65	17.80	24.05
C. mildbreadii	2.59	5.64	9.63	12.49	16.40

Table 4.16c: Compressive strength in cleft (N/mm) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa and for particle size (P) 2 mm ≤ P < 3.35 mm

	Compacting pressure				
Species	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	13.80	26.71	36.73	45.40	51.45
T. scleroxylon	6.98	15.24	27.64	36.86	40.89
A. robusta	2.69	11.90	17.29	21.35	26.88
T. superb	4.22	9.58	13.05	15.80	24.67
P. Africana	3.97	15.28	24.24	41.83	55.45
C. mildbreadii	3.62	5.78	10.18	12.66	19.18

Therefore, it could be deduced from **Tables 4.16a, b** and **c** that all the briquettes produced using sawdust of *C. pentandra* at CP levels ranging from 20 to 50 MPa had adequate CS in cleft. Additionally, briquettes produced using sawdust of *T. scleroxylon* at the following pressing conditions (P < 1 mm, CP level 40 and 50 MPa; 1 mm ≤ P < 2 mm, CP level 30, 40 and 50 MPa; 2 mm ≤ P < 3.35 mm, CP level 30, 40 and 50 MPa) had adequate CS in cleft. With respect to *A. robusta* briquettes produced under the following pressing conditions; P < 1 mm, CP level 50 MPa; 1 mm ≤ P < 2 mm, CP level 40 and 50 MPa; 2 mm ≤ P < 3.35 mm, CP level 40 and 50 MPa had adequate CS in cleft. With the exception of briquettes produced at CP level 50 MPa using sawdust of particle size 2 mm ≤ P < 3.35 mm all the other briquettes produced using *T. superba* did not have adequate CS in cleft (CS in cleft < 19.6 N/mm). At CP level 50 MPa all the briquettes produced using sawdust of *P. africana* for the three particle sizes adequate CS in cleft with that of particle size 2 mm ≤ P < 3.35 mm having more than twice the minimum required CS in cleft. Lastly, all the briquettes produced using sawdust produced from *C. mildbreadii* did not have adequate CS in cleft (i.e. CS in cleft < 19.6 N/mm).

Correlation analysis between particle size of sawdust and CS in cleft indicated that there was a weak significant positive correlation between particle size and CS in cleft of briquettes produced (Pearson's r = 0.179, p-value = 0.000; N = 450; 1-tailed, α = 0.05). That is, as particle size increased the CS in cleft of briquettes produced also increased. This result contradict the assertion by FAO (1990), Križan (2007), MacBain (1966), Payne (1978) and Tumuluru, *et al*. (2010) that, in general the durability (Mechanical strength) of pellets are inversely proportional to particle size since smaller particles have greater surface area for moisture addition during steam conditioning therefore resulting in increased starch gelatinization and better binding. The reason for the deviation is that in this study the briquettes were formed at low temperature (i.e. room temperature) thus the formation of solid bridge resulting from the natural bonding chemicals may be minimal. Therefore the major contributing factor to the bonds formed during this densification may be the mechanical interlock or folding about each other of the particles of the biomass and adhesive force between the particles. Longer particle size of the biomass raw material could lead to mechanical interlocking of relatively longer or larger particles (Pietsch, 1984, Rumpf, 1962 and Tabil, *et al.* 2011) therefore resulting in the formation of strong bond which resulted in increased CS in cleft.

Correlation analysis between CS in cleft and CP level also indicated a strong significant positive correlation between CP and CS in cleft of the briquettes produced (Pearson's r = 0.670, p-value = 0.000; N = 450; 1-tailed, $\alpha = 0.05$). This result means that the CS in cleft of briquettes produced increased with increasing particle size and CP. Increasing the CP result in increased binding force between the particles (Lindley & Vossoughi, 1989; Clauß, 2002). The increase in binding force results from increased mechanical interlocking of sawdust particle as well as increased adhesion between the particles (Tumuluru, *et al*., 2010). **Tables 4.17** shows the Analysis of Variance (ANOVA) of the effect of species, CP and particle size on the CS in cleft of briquettes produced. The result indicates that at 5% level of significance, CP, species, particle size and their interactions had significant effects on the CS in cleft of the briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE for the ANOVA Model were 0.9802 and 2.1162 respectively. It could therefore be deduced that species of the biomass raw material, particle size and CP could explain about 98.02% of the variability in the CS in cleft of the briquettes produced.

Table 4.17: ANOVA of effect of species, particle size and compacting pressure on compressive strength in cleft of briquettes produced from sawdust of six timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
Species	5	29475.439	5895.088	1316.33	< 0.0001*
Particle size	2	2688.496	1344.248	300.16	< 0.0001*
CP	4	36597.173	9149.293	2042.97	< 0.0001*
Species*CP	20	4451.833	222.592	49.70	< 0.0001*
Species*Particle size	10	3592.241	359.224	80.21	< 0.0001*
Particle size *CP	8	902.633	112.829	25.19	< 0.0001*
Species* Particle size* CP	40	2186.188	54.655	12.20	< 0.0001*
Error	360	1612.234	4.47843		

*Statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

Multiple regression analysis was performed using SPSS to establish the relative contribution of species density, particle size and CP towards the prediction of CS in cleft of the briquette produced as well as to determine the mathematical relationship between them. The summarized results in **Table 4.18** shows the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), *adjusted* R^2, the value of t and its associated p-values for each of the variables. The result indicates that species density, particle size and CP collectively explained 68.5% (*adjusted* R^2 = 0.685) of the variance in the CS of briquette produced. This suggests that the regression model is a good predictor of CS of briquettes produced (R^2 = 0.687, p-value = 0.000).

Table 4.18: Regression of compressive strength in cleft of briquettes on species density, particle size and compacting pressure of briquettes produced from sawdust of six timber species

Variables	β	Beta	R	*adjusted* R^2	t	p-value
Constant	19.923				10.081	0.000
Species density	-0.046	-0.454			-17.147	0.000
Particle size	2.957	0.179			6.770	0.000
Compacting pressure	0.637	0.670			25.267	0.000
			0.829	0.685		

The standardized regression coefficients values (Beta) for the three predictive variables suggest that CP explained the bulk of the variance in the CS in cleft of the briquette produced (Beta = 0.670, t = 25.267, p-value = 0.000) and was the best predictor of CS in cleft of the briquette produced. That notwithstanding species density and particle size of sawdust used significantly contributed to the regression model (Species density: Beta = -0.454, t = -17.147, p = 0.000; Particle size: Beta = 0.179, t = 6.770, p = 0.000). Considering the values of the unstandardized (β) regression coefficients values it could therefore be established that the mathematical relationship between CS in cleft of the briquettes produced and, species density (S), particle size (P) and CP is:

$$\text{Compressive strength} = 19.923 - 0.046S + 2.957P + 0.637CP$$

Where;

S = Species density
P = Particle size
CP = Compacting pressure

4.8.4 Impact resistance index of briquettes produced from sawdust of six timber species

Impact resistance index (IRI) is a measure of the ability of a briquette to withstand shock load. Pietsch (2002) suggested that drop tests can be used to determine the safe height of pellet/briquette production. The minimum value of IRI set for this study was 100%. **Tables 4.19a, b** and **c** indicate the IRI of briquettes produced using CP levels ranging from 10 to 50 MPa. The result shows that for all the particle sizes and CP levels the IRI for *C. pentandra* was exceptionally higher than those of the other species. The IRI of *C. pentandra* for particle sizes (P): P < 1 mm ranged from 115 to 350% for CP levels 10 to 50 MPa. These values were greater than the targeted value of 100%. As such all the briquettes produced from this species and particle size had adequate IRI. Additionally, with the exception of *C. pentandra*, briquette produced from all the other five species for P < 1 mm had IRI less than the targeted value of 100% at CP level 10 MPa. At CP level 10 MPa briquettes produced from all the species for particle sizes; 1 mm ≤ P < 2 mm and 2 mm ≤ P < 3.35 mm had IRI less than the targeted value of 100%. For all the particle sizes and CP level briquettes produced from *C. mildbreadii* were found to have the weakest IRI. At CP levels 40 MPa and 50 MPa none of the species and particle sizes had IRI that was less than 100%. Thus, it could be concluded that, for all the species studied the application of CP levels greater or equal to 40 MPa would be adequate to obtain briquettes with good IRI. The relatively high IRI of *C. pentandra* compared to those of the other species may be attributed to the longer particle size of the *C. pentandra* sawdust particles (**Table 4.6**) as well as its lower density. Increased in fibre length resulting from larger particle size of biomass material could lead to mechanical interlocking or folding of relatively longer particles (Pietsch, 1984, Rumpf, 1962 and Tabil, *et al*., 2011) therefore leading to the formation of stronger bonds.

Table 4.19a: Impact resistance index (%) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) P < 1 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	115	200	283	316	350
T. scleroxylon	87	123	167	192	233
A. robusta	70	104	120	142	217
T. superb	91	133	192	233	283
P. Africana	0	72	137	184	217
C. mildbreadii	0	64	84	133	183

Table 4.19b: Impact resistance index (%) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) 1 mm ≤ P < 2 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	90	123	217	233	400
T. scleroxylon	72	105	133	184	200
A. robusta	68	107	128	133	159
T. superb	72	120	159	158	175
P. Africana	0	86	142	150	175
C. mildbreadii	0	59	82	128	137

Table 4.19c: Impact resistance index (%) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) 2 mm ≤ P < 3.35 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	75	150	233	400	450
T. scleroxylon	68	105	128	142	167
A. robusta	0	102	115	128	158
T. superb	96	115	128	150	158
P. Africana	0	125	167	217	225
C. mildbreadii	0	87	110	142	158

This would result in the formation of briquettes with higher IRI. Additionally, the lower density of *C. pentandra* might have contributed to the relatively high IRI of briquettes produced from *C. pentandra*. This assertion is supported by the result in **Table 4.25** which indicated that species density negatively and significantly correlates with IRI of briquettes produced. This trend may be due to the fact that in this study briquettes were pressed or produced at low CP (CP < 60MPa) therefore it was easier to press particle of a low density species to reach plastic deformation to facilitate bonding than that of higher density species.

Correlation analysis between particle size and IRI, and CP and IRI indicated that at 5% level of significance there was no significant correlation between particle size and IRI (Pearson's r = -0.061, p-value = 0.098, N = 450; 1-tailed). However, CP positively and significantly correlated with the IRI of the briquettes produced (Pearson's r = 0.634, p-value = 0.000, N = 450; 1-tailed, α = 0.05). This result confirms that of Srivastava, *et al.* (1981) and Singh and Kashyap (1985). Srivastava *et al*., (1981) found that increasing pressure from 5 to 44 MPa increased the wafer (150-mm diameter) durability rating (based on an impact resistance test) of grass hay (mixed with 20% alfalfa) from 5 to 91%. Singh and Kashyap (1985) also found that increasing pressure from 7.8 to 31.2 MPa increased the durability property of rice husk briquettes from 80 to 95% when the briquettes were made from rice husk with an average particle size of 4.05 mm and 25% of molasses added. Increased CP level would increase the libration of natural binding chemicals in the biomass material therefore enhancing the formation of solid bridge bond between particles of biomass material, and resulting in an increase in IRI of briquettes produced. Additionally, when CP is increased particles of the biomass material are brought more closer to each other therefore enhancing the formation of inter-particle bond.

Analysis of Variance (ANOVA) of effect of species, CP and particle size on IRI of briquettes produced is as indicated in **Table 4.20**. The result shows that with the exception of the effect of the interaction between CP level and particle size on IRI of briquettes produced which was not significant at 5% level of significance (p-value > 0.05), CP, species, particle size and the other interactions had significant effects on the IRI of the briquettes produced (p-value < 0.05).

Table 4.20: ANOVA of effect of species, particle size and compacting pressure on impact resistance index of briquettes produced from sawdust of six timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
Species	5	1019818.011	203963.602	91.00	< 0.0001*
Particle size	2	45057.351	22528.676	10.05	< 0.0001*
CP	4	1655335.178	413833.794	184.64	< 0.0001*
Species*CP	20	293392.022	14669.601	6.55	< 0.0001*
Species*Particle size	10	88770.196	8877.020	3.96	< 0.0001*
Particle size *CP	8	20872.116	2609.014	1.16	0.3200†
Species* Particle size* CP	40	142517.004	3562.925	1.59	0.0158*
Error	360	806858.400	2241.273		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

The multiple coefficient of determination (R^2) and RMSE values for the ANOVA Model were 0.8019 and 47.34 respectively. The multiple coefficient of determination value of 0.8019 means that species type of the biomass raw material, it particle size and CP could explain about 80.19% of the variability in IRI of the briquettes produced.

Further analysis to establish the mathematical relationship between IRI and the predictive variables; species density, particle size and CP indicated that particle size at 5% level of significance, does not significantly predict the IRI of the briquettes produced. Thus, particle size was dropped in the determination of the mathematical model that relates IRI and the predictive variables. The final summarized result of the SPSS output of the regression analysis indicates the unstandardized (*β*) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), *adjusted* R^2, the value of t and its associated p-values for each of the variables in **Table 4.21**. The result indicates that species density, particle size and CP collectively explained 54.3% (*adjusted* R^2 = 0.543) of the variance in IRI of the briquettes produced. This suggests that the regression model moderately predict the

Table 4.21: Regression of impact resistance index of briquettes on species density and compacting pressure of briquettes produced from sawdust of six timber species

Variables	β	Beta	R	*adjusted* R^2	t	p-value
Constant	174.770				11.584	0.000
Species density	-0.270	-0.379			-11.872	0.000
Compacting pressure	4.263	0.634			19.862	0.000
			0.738	0.543		

IRI of the briquettes produced (R^2 = 0.545, p-value = 0.000). The standardized regression coefficients values (Beta) for the two predictive variables suggest that the predictive strength of CP is about twice that of species density (CP: Beta = 0.634, t = 19.862, p-value = 0.000; Species density: Beta = -0.379, t = -11.872, p-value = 0.000). From the summarized information of the regression analysis in **Table 4.21** (i.e. unstandardized regression coefficients (β)) it could be established that the mathematical relationship between IRI of the briquettes produced and, species density(S) and CP is:

$$IRI = 174.770 - 0.270S + 4.263CP$$

Where;

S = Species density
CP = Compacting pressure

4.8.5 Water resistance quality of briquettes produced from sawdust of six timber species

Briquette quality can also be evaluated in terms of it hardness or water resistance. Harder briquettes are of better quality. It is possible to check briquettes' hardness by inserting it into a glass of water (Križan, 2007). **Tables 4.22a, b** and **c** indicates the result of water resistance (WR) quality of briquettes produced from sawdust of six tropical hardwood species which was graded into three particle sizes and pressed using CP levels 10 to 50 MPa. Briquettes for which when dipped into water falls into pieces sooner than 5 minutes are considered as having a very low WR quality. When the briquette falls into pieces before 15 minutes, it is of a medium quality, and up to 20 minutes it is of a good quality (Križan, 2007). The results in **Table 4.22a** ($P < 1$ mm) indicate that briquettes made from all the species at all CP levels had low WR quality i.e. WR quality less than 5 minutes. The WR quality of briquettes produced from *P. africana* sawdust was exceptionally low ranging from 0.59 to 0.70 minutes for CP levels 10 to 50 MPa. **Table 4.22b** and **c** also indicates the WR quality of briquettes made from the six species for particle sizes; 1 mm $\leq P <$ 2 mm and 2 mm $\leq P <$ 3.35 mm compressed at CP levels ranging from 10 to 50 MPa. The trend of this result is similar to that of particle size $P < 1$ mm.

Table 4.22a: Water resistance quality (minutes) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) P < 1 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	2.54	2.76	3.19	3.82	4.81
T. scleroxylon	1.79	2.39	3.04	3.61	3.69
A. robusta	2.07	2.36	2.56	3.12	3.42
T. superba	2.56	2.92	3.26	3.81	3.94
P. africana	0.59	0.62	0.69	0.69	0.70
C. mildbreadii	1.23	1.26	1.92	2.39	3.42

Table 4.22b: Water resistance quality (minutes) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) 1 mm ≤ P < 2 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	1.79	2.14	2.50	3.25	4.26
T. scleroxylon	1.70	1.95	2.04	2.29	3.13
A. robusta	1.38	1.49	1.66	2.21	3.07
T. superba	1.75	2.11	2.27	2.53	3.58
P. africana	0.55	0.58	0.59	0.60	0.62
C. mildbreadii	0.74	0.98	1.90	2.34	2.81

Table 4.22c: Water resistance quality (minutes) of briquettes made from sawdust of six timber species at compacting pressure levels 10 to 50 MPa using particle size (P) 2 mm ≤ P < 3.35 mm

Species	Compacting pressure				
	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	1.74	2.01	2.41	2.69	3.73
T. scleroxylon	1.46	1.54	1.66	2.06	3.09
A. robusta	1.31	1.42	1.91	2.30	3.07
T. superba	1.55	1.61	1.94	2.48	3.22
P. africana	0.50	0.53	0.54	0.54	0.58
C. mildbreadii	0.67	0.87	1.75	2.27	2.58

None of the briquettes produced for these particle sizes had WR quality that could be classified as moderate or good i.e. WR ≥ 5 minutes. The above result is consistent with studies conducted by other researchers. Li and Liu (2000) observed that biomass briquettes made from oak sawdust, pine saw dust, and cottonwood sawdust could not stand for more than 5 minutes after being immersed in water at room temperature. The biomass logs swelled rapidly when immersed in water and disintegrated within a few minutes. This means that short-term exposure to rain of briquettes produce in this part of the study would be detrimental to the physical quality of the densified products.

The result (**Tables 4.22a b & c**) also indicates that generally, the WR quality of the briquettes produced increased with increasing CP levels and decreased with increasing particle size. Correlation analysis confirmed the above relationship. The correlation analysis indicated that briquette's WR quality positively and significantly correlated with the CP levels (Pearson's r = 0.518, p-value = 0.000, N = 450; 1-tailed, α = 0.05). Additionally, the WR quality of the briquettes produced was found to have significant, negative correlation with particle size of sawdust used (Pearson's r = -0.274, p-value = 0.000, N = 450; 1-tailed, α = 0.05). This means that briquettes made with higher CP levels are likely to have better WR quality. However, briquettes made from sawdust with smaller particle sizes are likely to have better WR quality. **Table 4.23** shows the result of ANOVA to determine the effect of species, CP and particle size of sawdust used for the study as well as their interaction on the WR quality of briquette produced. The result indicates that species, CP and particle size as well as their interactions, at 5% level of significance, have significant effect on the WR quality of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE values of the ANOVA Model were 0.9682 and 0.2092. Thus, it could therefore be concluded that species, particle size and CP could explain about 96.82% of the variability in the WR quality of the briquettes produced.

Table 4.23: ANOVA of effect of biomass material, particle size and compacting pressure on water resistance quality of briquettes produced from sawdust of six timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
Species	5	252.6573309	50.5314662	1154.94	< 0.0001*
Particle size	2	41.0268290	20.5134145	468.85	< 0.0001*
CP	4	137.1602523	34.2900631	783.73	< 0.0001*
Species x CP	20	30.2651695	1.5132585	34.59	< 0.0001*
Species x Particle size	10	10.4610290	1.0461029	23.91	< 0.0001*
Particle size x CP	8	1.0184354	0.1273044	2.91	0.0037*
Species x Particle size x CP	40	6.4566907	0.1614173	3.69	< 0.0001*
Error	360	15.7509371	0.0437526		

*Statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure

In **Table 4.24** is presented the summarized result of multiple regression for determining the mathematical relationship between the dependent variable WR quality and the independent variables; species density, particle size and CP. The summarized results indicated in **Table 4.24** show the unstandardized (β) and standardized (Beta) regression coefficients, the multiple correlation coefficient (R), *adjusted* R^2, the value of t and its associated p-values for each of the variables. The result indicates that the species density, particle size and CP collectively explained 66.7% (*adjusted* R^2 = 0.667) of the variance in the WR quality of the briquettes produced. This suggests that the regression model is a good predictor of WR quality of briquettes produced (R^2 = 0.669, p-value = 0.000).

Table 4.24: Regression of water resistance quality of briquettes on species density, particle size and compacting pressure of briquettes produced from sawdust of six timber species

Variables	B	Beta	R	*Adjusted R^2*	t	p-value
Constant	4.265				26.936	0.000
Species density	-0.004	-0.571			-20.942	0.000
Particle size	-0.353	-0.274			- 10.074	0.000
Compacting pressure	0.038	0.518			18.994	0.000
			0.818	0.667		

The standardized regression coefficient values (Beta) for the three predictive variables suggest that both species density and CP explained the bulk of the variance in the WR quality of the briquette produced (Compacting pressure: Beta = 0.518, t = 18.994, p-value = 0.000; Species density: Beta = -0.571, t = -20.942, p-value = 0.000). However, species was the best predictor of WR quality of the briquette produced. Particle size of sawdust used also significantly contributed to the regression model (Particle size: Beta = 0.274, t = -10.074, p-value = 0.000). Considering the values of the unstandardized (β) regression coefficients, it could be established that the mathematical relationship between WR quality of the produced briquettes, and species (S), particle size (P) and CP is:

$$\text{Water resistance quality} = 4.265 - 0.004S - 0.353P + 0.038CP$$

Where;

S = Species density
P = Particle size
CP = Compacting pressure

4.8.6 Relationship between physico-chemical properties of six timber species, and relaxed density, compressive strength in cleft, impact resistance index and water resistance quality of briquettes produced

Table 4.25 present the Pearson's correlation coefficient (R) and coefficient of determination (R^2) values for correlation analysis performed to establish the relationship between the fibre length, species density, lignin, cellulose and hemi-cellulose on one hand, and the relaxed density, CS in cleft, IRI and WR quality of the briquettes produced. The result (**Table 4.25**) shows that at 5% level of significance there was a weak significant positive correlation between the fibre length of the three grades of sawdust used and CS in cleft, IRI and WR quality of the briquettes produced ($R_{FL\ X\ CS}$ = 0.297, p-value = 0.000; $R_{FL\ X\ IRI}$ = 0.115, p-value = 0.007; $R_{FL\ X\ WR}$ = 0.155, p-value = 0.000). On the contrary, there was a weak significant negative correlation between fibre length of the sawdust particles and relaxed density of the briquettes produced (R = -0.204, p-value = 0.000). This means that sawdust with longer fibre lengths are likely to produce briquettes with low density.

Table 4.25: Correlation between species characteristics, and relaxed density, CS in cleft, IRI, and WR quality of briquettes produced

Species Characteristics	Relaxed density		CS		IRI		WR	
	R	**R^2**	**R**	**R^2**	**R**	**R^2**	**R**	**R^2**
Fibre length	-.204*	.0416	.297*	0.0882	.115*	.0132	.155*	.0240
Species density	.160*	.0256	-.454*	.2061	-379*	.1436	-.571*	.3260
Lignin	.014†	.0002	.360*	.1296	.254*	.0645	-.041†	.0017
Cellulose	.082*	.0067	.103*	.0106	.106*	.0112	-.038†	.0014
Hemicellulose	-.029†	.0008	.105*	.0110	.074†	.0055	.036†	.0013

*Correlation significant at 0.05 level of significance (1-tailed); †Correlation not significant at 0.05 level of significance (1-tailed); N = 450

Legend: R = Pearson's correlation coefficient; R^2 = Coefficient of determination

On the contrary, it could be deduced that sawdust with longer fibre lengths, in other words sawdust with larger particle size, are likely to produce briquettes with higher CS in cleft, IRI and WR quality. This result could be due to the fact that increased fibre length resulting from higher proportion of larger particles in the biomass raw material could result in mechanical interlocking or folding of relatively long particles about each other (Pietsch, 1984, Rumpf, 1962 and Tabil, *et al*., 2011) therefore resulting in the formation of stronger bonds which leads to increased CS in cleft, IRI and WR quality of the briquettes formed.

As part of **Table 4.25** is also the result of correlation analysis depicting the relationship between the density of the timber species used for the study and, the relaxed density, CS in cleft, IRI and WR quality of the briquettes produced. The result indicates that at 5% level of significance the density of the species had a moderate significant positive correlation with the relaxed density of the briquettes produced (Pearson's R = 0.160, p-value = 0.000). However, the CS in cleft, IRI and WR quality of briquettes produced were found to have moderate significant negative correlation with the density of the species (SD) used ($R_{SD \ X \ CS}$ = -0.454, p-value = 0.000; $R_{SD \ X \ IRI}$ = -0.379, p-value = 0.000; $R_{SD \ X \ WR}$ = -0.571, p-value = 0.000). The above result suggest that when sawdust is densified at low CP level, that is CP level between 10 and 50 MPa the CS in cleft, IRI and WR quality of the briquettes produced will be better if low density species is used. The coefficient of determination values between species density and relaxed density (R^2 = 0.0256), species density and CS (R^2 = 0.2061), species density and IRI (R^2 = 0.1436) and species density and WR quality (R^2 = 0.3260) means that about 2.56%, 20.61%, 14.36% and 32.60% of the variability in the relaxed density, CS in cleft, IRI and WR quality, respectively of the briquette produced could be explained by the density of the species used.

Correlation analysis between percentage acid-insoluble lignin content of the timber species on one hand and, relaxed density, CS in cleft, IRI and WR quality of the briquettes produced on the other hand forms part of the results shown in **Table 4.25**. The result indicates that at 5% level of significance, the Klason lignin content of the timber species significantly and positively correlate with the CS in cleft and IRI of the briquettes produced ($R_{lignin\ X\ CS}$ = 0.360, p-value = 0.000; $R_{lignin\ X\ IRI}$ = 0.254, p-value = 0.000). Thus, timber species with higher percentage of Klason lignin are likely to have higher CS in cleft and IRI. The coefficient of determination values between percentage Klason lignin content and CS in cleft (R^2 = 0.1296), and percentage Klason lignin content and IRI (R^2 = 0.0645) suggest that about 12.96% and 6.45% of the variability in the CS in cleft and IRI respectively of the briquette produced could be explained by the percentage Klason lignin content of the timber species. Granada, *et al*. (2002) indicated that the adhesive properties of thermally softened lignin are thought to contribute considerably to the strength characteristics of briquettes made of lignocellulosic materials. At glass transition temperature the lignin content in wood softens. On cooling it forms a crystalline bridge between the particles (Granada, *et al*., 2002). This significantly contributes to the formation of bonds in the briquettes. Thus, it is most probable that timber species with higher percentage of lignin are likely to form more bonds therefore producing stronger briquettes. Even though the biomass raw material was not pre-heated before pressing and also the compaction was done at room temperature, localized heating resulting from particle-particle friction may have momentarily generated localized temperatures as high as 100 - 200^{o}C which resulted in the bonding mechanism (Pilpel, *et al*., 1991). On the contrary the percentage lignin content of the species used was found not to have any significant correlation with the relaxed density and WR quality of the briquettes produced ($R_{lignin\ X\ relaxed\ density}$ = 0.014, p-value = 0.383; $R_{lignin\ X\ WR}$ = -0.041, p-value = 0.190).

The relationship between alpha-cellulose, and the relaxed density, CS in cleft, IRI and WR quality of briquettes produced is part of the result presented in **Table 4.25**. The result indicates that at 5% level of significance, the percentage alpha-cellulose content of the timber species had a weak significant correlation with the relaxed density, CS in cleft and IRI of the briquettes produced ($R_{cellulose\ X\ relaxed\ density}$ = 0.082, p-value= 0.041; $R_{cellulose\ X\ CS}$ = 0.103, p-value = 0.014; $R_{cellulose\ X\ IRI}$ = 0.106, p-value = 0.013). Thus, the cellulose content of timber species used for the study had little influence on the relaxed density, CS in cleft and IRI of the briquettes produced. The coefficient of determination values for the relationships between; (1) cellulose content of the species and the relaxed density of briquettes produced (R^2 = 0.0067), (2) cellulose content of the species and CS in cleft (R^2 = 0.0106) and finally, (3) cellulose content of the species and IRI (R^2 = 0.0112) suggest that about 0.67%, 1.06% and 1.12% of the variability in the relaxed density, CS in cleft and IRI respectively of the briquette produced could be explained by the cellulose content of the wood species. However, the cellulose content of the timber species did not have any significant correlation with the WR quality of the briquettes ($R_{cellulose\ X\ WR}$ = -0.038, p-value = 0.212). Lastly, correlation between hemi-cellulose content of the species used, and relaxed density, CS in cleft and IRI of the briquettes produced as shown in **Table 4.25** indicates that at 5% level of significance there was no significant correlation between them. However there was a weak significant positive correlation between hemicellulose and CS in cleft of the briquettes produced.

4.8.7 Thermal properties of sawdust of six timber species

The main advantage of biomass fuel is that it can be used without damaging the environment (Nendel, *et al*., 1998). Its advantage lies not only in it contribution to CO_2 mitigation, but also extends to include other elements. According to Demirbas and Demirbas (2009), the fuel properties of wood can be summarized by elemental and proximate analyses and determination of heating value. In **Table 4.26** is presented the Gross calorific value (GCV), percentage ash content, organic carbon, nitrogen and sulphur content of of the species used. **Table 4.26** also includes the Austria and Germany standards for fuel pellets, Austria, ÖNORM M7135 and Germany DIN 51731/ DINplus respectively.

Calorific value

In the second colum of **Table 4.26** is presented the GCV of the six tropical hardwood species used for the study. *C. mildbreadii* had the least GCV of 20.16 MJ/kg whilst *T. superba* had the highest GCV of 22.22 MJ/kg. The GCV for the rest of the species studied lied within these two. From **Table 4.26** the GCV of the species studied could be considered to be adequate since they are greater than the minimum values suggested by the Austria and Germany standards for fuel pellets (Austria ÖNORM M7135, Calorific value ≥ 18.0 MJ/kg; Germany DIN 51731/DINplus, Calorific value 17.5 - 19.5 MJ/kg). Additionally, the GCV of all the species studied were higher than that suggested by Corder (1976), Stahl, *et al*. (2004) and Jain (1991) for woody biomass. Corder (1976) in his study on fuel characteristics of wood and bark and factors affecting heat recovery concluded that woody biomass has an average heating density of 19.8 MJ/kg. Stahl, *et al*. (2004) in a report on definition of a standard biomass stated that the calorific values for most woody materials are between 17 - 19 MJ/kg.

Table 4.26: Fuel properties of six tropical hardwood species and, Austria and Germany standards for fuel pellets

Species	Gross Calorific value (MJ/kg)	Ash (%)	Organic Carbon (%)	N (%)	S (%)
C. pentandra	20.33	4.7248	55.26	0.4817	0.0458
T. scleroxylon	21.60	2.0119	56.83	0.5600	0.0919
A. robusta	20.89	5.0407	55.08	0.4813	0.2142
T. superba	22.22	2.9574	56.29	0.6213	0.0561
P. africana	22.17	0.6075	57.65	0.7133	0.0475
C. mildbreadii	20.16	3.7077	55.85	0.6917	0.0572
Austria ÖNORM M7135	≥18.0	≤ 6.0	-	≤ 0.6	≤ 0.08
Germany DIN 51731 / DINplus	17.5-19.5	< 1.5%	-	< 0.3	< 0.08

Source of information for national standards for fuel pellets (Austria and Germany): Hahn, (2004)

Lastly, in a study of 22 commonly used tree species, Jain (1991) concluded that three quarters of the species studied had heating values between 14 - 19 MJ/kg of oven-dry wood. Furthermore, the heating values of the species studied besides being higher than that of other woody biomass has heating values greater than that of other biomass fuels like: Wheat straw = 17.51 MJ/kg; Rice straw = 14.56 MJ/kg; Maize straw = 17.70 MJ/kg and Sugarcane bagasse = 17.33 MJ/kg (Ebeling & Jenkins, 1985). Even though the species studied comparatively had higher heating values, their heating values are lower than that of fossil fuels like kerosene (46.5 MJ/kg), natural gas (37.3 MJ/kg) and hard coal (31.80 MJ/kg) (Payne, 1980). In spite of the lower heating values of the biomass fuels compared to that of fossil fuels it would increasingly continue to be an important source of energy because of it long term sustainability as a source of energy as well as it enormous social and environmental benefits.

A careful look at the result in **Table 4.26** indicates that the GCV of the species studied varies from each other although the variations were not much. This confirms the assertion by Ravindranath and Oakley Hall (1995) that there are no large differences of calorific value between species or between trees and shrubs. However, the small variations in the heating values of the species studied may be due to differences in their chemical and physical properties. Ravindranath and Oakley Hall (1995) stated that the calorific value of woody biomass positively correlate with the density of timber species. Cellulose has a smaller heating value than lignin because of its higher degree of oxidation. The hydrogen and carbon contents of fuel coupled with lower degrees of oxidation tend to raise the heating value of the biomass. Additionally, the presence of extractives in wood increases its heating values (Demirbas and Demirbas, 2009). Although *T. superba* is a medium density wood species it has high lignin content, high carbon content and high extractives content (**Table 4.3 and Table 4.26**). This might have contributed to its high GCV. Even though *C. mildbreadii* is a higher density species it has a very low lignin content, relatively low cabon content and also low extractives and these might explain its low heating value (**Table 4.3 and Table 4.26**).

Ash content

The inorganic minerals in wood are what is referred to as the wood ash. The problems of ash deposition on heat transfer surfaces in boilers and on internal surfaces in gasifiers (ash slagging) still remain. This phenomenon accelerate corrosion of hot heat exchanging tubes and also reduce it efficiency (Grover & Mishra, 1996). In the third colum of **Table 4.26** is presented the ash content of *C. pentandra*, *T. scleroxylon*, *A. robusta*, *T. superba, P. africana* and *C. mildbreadii*. The ash content of the mentioned species varied from as low as 0.6075% for *P. africana* to as high as 5.0407% for *A. robusta*. The ash content of all the species studied were lower than 6%, that is, the value considered to be adequate for biomass fuel according to the Austria ÖNORM M7135. With the exception of *A. robusta* and *C. mildbreadii* which had comparatively high percentage ash content, all the other species had ash content less than 4.0%. Grover and Mishra (1996) indicated that slagging of ash usually occurs with biomass fuels when the ash content is more than 4%. Thus, it is likely that when species like *P. africana*, *T. scleroxylon*, *T. superba and C. mildbreadii* are used as fuel no slagging would occur. On the contrarily, slagging may take place when *A. robusta* and *C. pentandra* are used as biomass fuel.

Organic carbon, Nitrogen and Sulphur of six tropical hardwood species

As part of the result in **Table 4.26** is the organic carbon, nitrogen and sulphur content of the species studied (**Colums 4, 5 and 6**). Fixed carbon gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Akowuah, *et al*., 2012). The organic carbon content of the species ranges from 55.26% for *C. pentandra* to 57.65% for *P. Africana*. The higher the carbon content of a biomass material the more likely is the formation of carbon monoxide, carbon dioxide (Extension, 2010). Carbon monoxide is a colourless, odourless gas that is poisonous at high levels. It can interfere with the delivery of oxygen in the blood to the rest of your body.

The nitrogen content of the species is as indicated in **Table 4.26**, **colum 5**. Nitrogen content is a good indicator of the amount of nitrogen-based toxic components that can be formed. The result shows that *A. robusta* had the least nitrogen content (0.4813%), followed by *C. pentandra* (0.4817%), *T. scleroxylon* (0.5600%), *T. superba* (0.6213%), *C. mildbreadii* (0.6917%) and *P. africana* (0.7133%) in increasing order. During combustion of wood fuel, nitrogen is oxidized into nitrogen oxides (NOx). When emitted from combustion facilities at relatively low levels, NOx may have a useful fertilizing effect on forests. However, as emission levels increase, NOx produces adverse health effects and increases the acidification of water and soils (Extension, 2010). Pollutants such as nitrogen dioxide (NO_2) and particulate matter are of significance because of the effect they have on the environment and human health. When NOx and volatile organic compounds (VOCs) react in the presence of sunlight, they form a photochemical smog, which is a significant form of air pollution (Sillman, 2003). Nitrogen oxides also play an important role in the atmospheric reactions creating ozone and acidic rain by the formation of nitric acid. Exposure to nitrogen oxides increases the risk of respiratory infections as they are highly toxic and irritating to the respiratory system (Sillman, 2003). The nitrogen content of *A. robusta* (0.4813%), *C. pentandra* (0.4817%) and *T. scleroxylon* (0.5600%) are lower than the limit set in the Austria national standard, Austria ÖNORM M7135 (i.e. Nitrogen content ≤ 0.6%) but higher than the limit set in the German national standard set for fuel pellet Germany DIN 51731 / DINplus (i.e. Nitrogen content ≤ 0.3%). However, the nitrogen content of *T. superba* (0.6213%), *C. mildbreadii* (0.6917%) and *P. africana* (0.7133%) are higher than the limits set in both the Austria and German standards for fuel pellet.

Sulphur emissions from combustion of fuels cause extensive damage to ecosystems and buildings, so fossil fuels are often graded by the amount of sulfur present. As with nitrogen, sulfur is oxidized during combustion to form sulfur oxides (SOx). This compound can have serious environmental effects and cause the acidification of soils and water

(Extension, 2010). The sulphur content of the species studied are as indicated in the last colum of **Table 4.26**. The result shows that *C. pentandra* had the least sulphur content (S = 0.0458%). The sulphur content of the other species are as follows: *P. africana* = 0.0475%, *T. superba* = 0.0561%, *C. mildbreadii* = 0.0572%, *T. scleroxylon* = 0.0919% and *A. robusta* = 0.2142%. The sulphur content of four of the species namely; *C. pentandra*, *P. africana, T. superba* and *C. mildbreadii* is lower than the limits set by the Austria and German national standards for fuel pellet; Austria ÖNORM M7135 (i.e. Sulphur content ≤ 0.08%), Germany DIN 51731 / DINplus (i.e. Sulphur content < 0.08%). However, *T. scleroxylon* and *A. robusta* had sulphur content more than the limits set by the Austria and German national standards for fuel pellet; Austria ÖNORM M7135 (i.e. Sulphur content ≤ 0.08%), Germany DIN 51731 / DINplus (i.e. Sulphur content ≤ 0.08%). This means that it is likely that when *T. scleroxylon* and *A. robusta* are used as fuels they would emit sulphur compounds more than the accepted limits into the atmosphere. This would have adverse effect on both the environment and human health.

4.9 Effect of biomass material and compacting pressure on physical and mechanical characteristics of briquettes produced from mixture of species

The tropical rain forest covers less than 6 percent of the Earth's land area. However, it contains the vast majority of the world's plant and animal genetic resources. The diversity of life in this forest type is astonishing. It has been estimated that generally one square kilometer of tropical rain forest may contain as many as 100 different tree species. On the contrarily, a typical temperate forest is characterized by about 3 - 4 tree species per square kilometer. The bio-diversity of the tropical rain forest translate into the nature and quality of sawdust generated in the sawmills situated in these areas. A typical sawmill in Ghana may process several tree species a day. This results in the production of sawdust which is a mixture of species. The implication of this is that the conversion of this waste into other useful product needs a lot of investigation due to the non homogeneous nature of the raw material. In this part of the study the researcher investigated into the effect of sawdust of mixed tropical hardwood species on the mechanical, physical and combustion characteristics of fuel briquettes produced at room temperature (25^{o}C) using low compacting pressure.

4.9.1 Particle size of sawdust used for this part of the study

Particle size and particle size distribution are variables that has been found to have significant effect on the quality of briquettes produced. In this part of the study the particle size of the biomass material used was P < 1mm. This particle size was selected because in the previous part of this study briquettes produced from this particle size showed greatest briquette qualities.

4.9.2 Effect of mixture of *P. africana* and *C. pentandra,* and compacting pressure on physical and mechanical characteristics of briquettes

Relaxed density of briquettes produced from mixture of *P. africana* and *C. pentandra*

Table 4.27 indicates the relaxed density of briquettes produced from sawdust of *P. africana* (high density species), *C. pentandra* (low density species), and their combination. Particle size of sawdust used for this part of the study was sizes that passed through a sieve with aperture 1mm. Briquettes were produced using compacting pressure (CP) levels ranging from 20 to 50 MPa at an interval of 10 MPa. Compacting pressure level 10 MPa was excluded from this study because in the preceding studies, almost all the briquettes produced using CP level 10 MPa had a very low mechanical strength properties (CS in cleft and IRI). The relaxed density of the briquettes produced from the mixture of *P. africana* and *C. pentandra* ranged from 534 to 766 kg/m^3 (**Table 4.27**). This relaxed density could be deemed adequate in that it is consistent with the suggestion by Tumuluru *et al*. (2010) that briquettes produced from hydraulic piston press are usually less than 1000 kg/m^3 and are usually between 300 - 600 kg/m^3 (Saeidy, 2004).

Table 4.27: Relaxed density (kg/m^3) of briquettes produced from *P. africana*, *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	523	622	666	716
P. africana	Pure	567	637	679	741
P. africana : *C. pentandra*	80 : 20	578	645	701	766
P. africana : *C. pentandra*	60 : 40	564	626	677	732
P. africana : *C. pentandra*	40 : 60	560	620	672	730
P. africana : *C. pentandra*	20 : 80	534	614	654	719

It could be observed from the result (**Table 4.27**) that at mixing ratio 80 : 20 the relaxed density of all the briquettes produced from the mixture of *P. africana* and *C. pentandra* were higher than those produced from pure species of *P. africana* and *C. pentandra* at corresponding CP levels. Thus, mixing sawdust of *P. africana* and *C. pentandra* at mixing ratio 80 : 20 would produce briquettes that are denser than that produced from their corresponding pure species only. Additionally, with the exception of briquettes produced from mixing ratio 20 : 80, at CP levels 30 MPa and 40 MPa the relaxed density of the briquettes produced from the combination of *P. africana* and *C. pentandra* were higher than that of *C. pentandra* only. Thus, combining sawdust of *P. africana* and *C. pentandra* would enhance the relaxed density of briquettes produced from *C. pentandra* alone.

The result further indicates that generally for the entire CP levels briquettes' relaxed density decreased with decreasing amount of *P. africana* in the mixing ratio. This is corroborated by a result of correlation analysis between the proportions of *P. africana* in the mixture of *P. africana* and *C. pentandra,* and relaxed density of briquette produced which indicated a weak significant positive correlation between the two (Pearson's r = 0.218, p-value = 0.026; N =80; 1-tailed, α = 0.05). This trend is due to the fact that *P. africana* is a high density species (744.89 kg/m^3) whilst *C. pentandra* is a low density species (409.22 kg/m^3). Thus, increasing the amount of *P. africana* in the mixing ratio tends to increase the density of the raw material and therefore leading to increase in the relaxed density of the briquettes produced. This assertion is supported by the result in **Table 4.25** that species density positively correlates with relaxed density of briquettes. Additionally, the result indicates that for each of the mixing ratios the relaxed density of briquettes produced increased with increasing CP level. This is also collaborated by a strong positive correlation between CP and relaxed density of briquettes produced (Pearson's r = 0.964, p-value = 0.000; N = 80; 1-tailed, α = 0.05). This trend is due to the fact that the higher the CP level the closer would be the particles of the biomass materials pressed together due to reduction of the void spaces. This therefore would lead to formation of a denser briquette (Lindley & Vossoughi, 1989).

Two-way analysis of variance **(Appendix 1a)** to determine the effect of biomass raw material (*P. africana, C. pentandra* and their combination in the ratio of 80 : 20, 60 : 40, 40 : 60, 20 : 80) and CP on relaxed density of briquettes produced indicates that at 5% level of significance the biomass raw material, CP and their interactions have significant effect on relaxed density of the briquettes produced (p-value < 0.05). The multiple coefficient of determination value (R^2) and root mean square error (RMSE) of the ANOVA Model were 0.9829 and 9.97 respectively. The multiple coefficient of determination value of 0.9829 means that about 98.29% of the variability in the relaxed density of briquettes produced could be explained by the biomass raw material, CP and their interaction.

Least significant difference (LSD) was used to perform post hoc test to compare the means of relaxed density of briquette for the biomass raw material (*P. africana, C. pentandra* and their combination). The result as indicated in **Appendix 1b** shows that the relaxed density of briquettes made from mixing ratio 80 : 20 was significantly higher than that of the others (LSD > 6.2569). Even though in considering the raw materials used one would have expected the briquettes formed from pure *P. africana* to have the highest relaxed density due to the species density, the different particles of the two materials mixed together might have resulted in better rearrangement of the particle for the mixing ratio 80 : 20 therefore forming denser briquettes. The presence of different shape and size of particles improves the packing dynamics and also contributes to high static strength (Grover & Mishra, 1996). The result further indicates that the relaxed density of the briquettes made from mixing ratios 60 : 40 and 40 : 60 do not significantly differ (LSD < 6.256, $\alpha = 0.05$). Additionally, the relaxed density of briquettes made from *C. pentandra* only does not significant differ from that made from combination of 20% *P. africana* and 80% *C. pentandra*. This means that when 20% of sawdust of *P. africana* is introduced into 80% portion of sawdust of *C. pentandra* it would not have any significant effect on the relaxed density of the briquettes produced. Lastly, post hoc multiple comparison of means of the relaxed density of briquette produced for CP levels as shown in **Appendix 1c** indicates that the relaxed density of briquettes produced at the CP levels; 50, 40, 30 and 20 MPa were significantly different at 5% level of significance with that produced at CP level 50 MPa being the highest. The reason is that different CP level result in different degrees of packing of the particles of the sawdust and plastic deformation of the cell walls therefore resulting in varying densities of the briquettes formed.

Compressive strength in cleft of briquettes produced from mixture of *P. africana* and *C. pentandra*

Table 4.28 indicates the results of compressive strength in cleft (CS) of briquette produced from sawdust of *P. africana* (high density species), *C. pentandra* (low density species), and their combination and pressed at CP levels 20 to 50 MPa. The CS in cleft of the briquettes produced from this mixed species (*P. africana* and *C. pentandra*) ranged from 12.46 to 60.28 N/mm. At corresponding CP levels, all the briquettes produced from mixing ratio 20 : 80 (*P. africana : C. pentandra*) had CS in cleft higher than that produced from *P. africana* and *C. pentandra* only. The CS in cleft of briquettes produced for this mixing ratio (20 : 80) ranged from 30.18 to 60.28 N/mm. Thus, mixing sawdust of *P. africana* and *C. pentandra* in the ratio of 20 : 80 and pressing it at CP level as low as 20 MPa would produce briquettes with adequate CS in cleft (CS in cleft ≥ 19.6 N/mm). Rahman, *et al.* (1989), indicated that briquettes CS in cleft 19.6 N/mm is reasonably adequate for handling or used for domestic fuel purpose. Additionally, the result (**Table 4.28**) shows that at all corresponding CP levels all the CS in cleft of briquettes produced from mixture of *P. africana* and *C. pentandra* were higher than those produced from *P. africana* alone. Thus the addition of *C. pentandra* sawdust to that of *P. africana* will tremendously improve the CS in cleft of briquettes produced from *P.* africana. With the exception of briquettes produced from mixing ratio 80 : 20 and 60 : 40 at CP level 20 MPa all the briquettes produced from the mixed species had adequate CS in cleft i.e CS in cleft greater than 19.6 N/mm.

The result in (**Table 4.28**) also indicates that at all CP levels the CS in cleft of mixed biomass briquettes increased with increasing proportion of *C. pentandra* sawdust in the mixing ratio. This is supported by a correlation analysis which indicated a strong significant

Table 4.28: Compressive strength in cleft (N/mm) of briquettes produced from *P. africana*, *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	29.23	39.26	40.40	44.58
P. africana	Pure	5.95	10.13	17.06	21.14
P. africana : *C. pentandra*	80 : 20	12.46	20.43	27.03	39.66
P. africana : *C. pentandra*	60 : 40	18.95	27.19	34.87	48.53
P. africana : *C. pentandra*	40 : 60	27.08	37.08	43.96	56.33
P. africana : *C. pentandra*	20 : 80	30.18	39.34	46.45	60.28

negative correlation between the proportions of *P. africana* in the mixture of *P. africana* and *C. pentandra,* and CS in cleft of briquette produced (Pearson's $r = -0.561$, p-value = 0.000; $N = 80$; 1-tailed, $\alpha = 0.05$). The above result suggest that introducing *C. pentandra* sawdust into *P. africana* would significantly improve upon the CS in cleft of briquettes produced from *P. africana* sawdust and that the CS in cleft depends on the mixing ratio. This finding is consistent with that of Jindaporn and Songchai (2007). In their study of production and characterization of rice husk based charcoal briquettes, Jindaporn and Songchai (2007) found that the mixing ratio had a significant effect on the physical and mechanical properties of briquettes produced. In this study briquettes were compacted at low CP therefore increasing the proportions of high density species (*P. africana*) in the mixing ratio reduced the tendency of the samples to undergo plastic deformation. This will lead to the formation of weaker bonds. This explanation is supported by the result in **Table 4.25** which indicated that species density negatively correlate with the CS in cleft of briquettes. The briquettes produced also showed a consistent increase in CS in cleft with increasing CP levels for both the pure and the mixed biomass materials. This trend is also supported by a highly, significant and positively correlation between compressive strength in cleft of briquettes produced and CP (Pearson's r = 0.798, p-value = 0.000; N = 80; 1-tailed, α = 0.05).

Analysis of variance **(Appendix 2a)** to determine the effect of the biomass raw material (*P. africana, C. pentandra* and their combination in the mixing ratio: 80: 20, 60 : 40, 40 : 60, 20 : 80) and CP on the CS in cleft of briquettes produced indicates that at 5% level of significance the biomass raw material, CP and their interactions had significant effect on CS in cleft of the briquettes produced (p-value < 0.05). The multiple coefficient of determination value (R^2) and RMSE of the ANOVA Model were 0.9698 and 2.7612 respectively. The R^2 value of 0.9698 means that about 96.98% of the variance in the CS in cleft of the briquettes produced could be explained by the biomass material and CP.

Post hoc analysis to compare the means of CS in cleft of briquettes produced from the biomass raw material (*P. africana, C. pentandra* and their combination) as indicated in **Appendix 2b** shows that the CS in cleft of briquettes produced from these materials were significantly different at 5% level of significance (LSD > 1.7332). Thus, the different proportional mix of biomass raw materials had significant effect on the CS in cleft of the briquettes produced. It is also worth noting that briquettes produced from mixing ratios 20 : 80 and 40 : 60 (*P. africana* : *C. pentandra*) had CS in cleft significantly higher than that of *C. pentandra* only. This means that the CS in cleft of this mixed species briquette is also affected by factor order than the physical and chemical characteristics of the biomass material and these needs to be investigated. Post hoc multiple comparisons of means of CS in cleft for briquette CP as shown in **Appendix 2c** indicate that at 5% level of significance, CS in cleft of the briquettes produced significantly differs from each other (LSD > 1.4152).

Impact resistance index of briquettes produced from mixture of *P. africana* and *C. pentandra*

Briquettes' impact resistance index (IRI) is used to simulate the forces encountered during emptying of densified products from trucks onto ground. In **Table 4.29**, the result of briquettes' IRI for *P. africana*, *C. pentandra* and their combination is presented. The IRI of all the briquettes made from mixed species of *P. africana* and *C. pentandra*, using CP levels 20 to 50 MPa at an interval of 10 MPa ranged from 128 to 500%. All the briquettes produced for this combination had adequate IRI (IRI > 100%) in that according to the Italian standard for briquettes/pallets CTI-R04/5 briquettes durability greater or equal to 97.7% is considered adequate (Italian standard for briquettes/pallets CTI-R04/5 as cited in Hahn 2004). Besides, going by the following classification of briquettes durability by other researchers, that is, high durability (IRI > 80%), medium durability (IRI between 70 - 80%), and low durability (IRI < 70%) all briquettes produced could be considered to have high IRI (Tabil & Sokhansanj, 1996; Adapa, *et al*., 2003).

Table 4.29: Impact resistance index (%) of briquettes produced from *P. africana*, *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	200	283	316	350
P. africana	Pure	72	137	184	217
P. africana : *C. pentandra*	80 : 20	128	150	217	250
P. africana : *C. pentandra*	60 : 40	142	167	250	300
P. africana : *C. pentandra*	40 : 60	175	200	250	400
P. africana : *C. pentandra*	20 : 80	200	283	350	500

The result further indicates that for all corresponding CP levels the IRI of briquette made from combination of *P. africana* and *C. pentandra* were greater than that made from *P. africana* only. Thus, introduction of *C. pentandra* sawdust into that of *P. africana* could enhance the IRI of briquettes made from *P. africana.* Briquettes made from the mixing ratio 20 : 80 had IRI either equal to or more than their corresponding values for *C. pentandra.* Thus, the IRI of briquettes produced from *C. pentandra* could be enhanced by introducing 20% of *P. africana* into 80% of *C. pentandra*. Most of the briquettes produced from mixing ratios 80 : 20, 60 : 40, and 40 : 60 had IRI lower than their corresponding values for *C. pentandra*.

Correlation analysis between proportions of *P. africana* in the mixture of *P. africana* and *C. pentandra,* and IRI of briquette produced indicates that there exist a moderate significant negative correlation between the two parameters (Pearson's r = -0.466, p-value = 0.000; N = 80; 1-tailed, $\alpha = 0.05$). Thus the IRI of the briquettes produced decreased with increasing proportions of *P. africana* in the mixing ratio. This may be due to the relatively high species density of *P. africana*. In view of the fact that briquettes were formed using low CP and room temperature (25^{o}C) it was easier to press low density species to reach plastic deformation therefore enhancing bonding than high density species. CP was also found to be significantly and positively correlated with the IRI of briquettes produced (Pearson's r = 0.655, p-value = 0.000; N = 80; 1-tailed, $\alpha = 0.05$). This research finding is consistent with that of other research outcomes. Li and Liu (2000) studied the densification behaviors of oak sawdust, oak mulch, oak bark, oak chips, pine sawdust, cotton wood sawdust, and cotton wood mulch in the pressure range of 34 to 138 MPa. Li and Liu (2000) established that increasing CP resulted in increased abrasive resistance, impact resistance and compressive resistance briquettes produced from these biomass materials. Srivastava, *et al*. (1981) also found that increasing CP from 5 to 44 MPa increased the wafer (150-mm diameter) durability rating (based on an impact resistance test) of grass hay (mixed with 20% alfalfa) from 5 to 91%. The increase in IRI resulting from increased CP level could result from the fact that increased in CP enhances the formation of different binding mechanisms in densification. For instance, under high pressure, the natural binding components such as starch, protein, lignin, and pectin in the feed or biomass materials are squeezed out of the particles, which contribute to inter-particle bonding (Köser, *et al*., 1982; Thomas, *et al*., 1997). Additionally increased CP could enhance the bonding through Van der Waal's electrostatic force as well as the formation of stronger inter-locking bonds of the sawdust particles.

The result of a two-way ANOVA to determine the effect of biomass raw material (*P. africana, C. pentandra* and their combination), CP and their interaction on the IRI of briquettes produced is as presented in **Appendix 3a.** The result indicates that at 5% level of significance the biomass raw material and CP had significant effect on the IRI of briquettes produced (p-value < 0.05). Nevertheless, the interaction of biomass raw material and CP at 5% level of significance does not have any significant effect on the IRI of briquettes produced ($p > 0.05$). The multiple coefficient of determination (R^2) and the RMSE of the ANOVA Model were 0.6515 and 78.0276 respectively. The R^2 value of 0.6515 means that about 65.15% of the variance in the IRI of the briquettes produced could be explained by the biomass raw material and CP.

The result of post hoc analysis to compare the means of IRI of briquettes produced from the biomass raw material (*P. africana, C. pentandra* and their combination) is as indicated in **Appendix 3b.** Even though the IRI for mixing ratio 20 : 80 was the highest, it did not significantly differ from that of *C. pentandra* (LSD < 48.978). However, the IRI of briquettes produced from mixing ratio 20 ; 80 was significantly higher than that produced from the mixing ratios 40 : 60, 60 : 40 and 80 : 20. The differences in the IRI of the briquettes produce could be due to the different proportions of the species in the mixing ratios. Lastly, IRI of briquettes produced from *P. africana* at 5% level of significance did not significantly differ from that of *P. africana* sawdust mixed with 20% of *C. pentandra* at mixing ratio 80 : 20. Post hoc analysis to compare the means of IRI of briquettes produced from CP levels, 50, 40, 30 and 20 MPa **(Appendix 3c)** indicates that their mean IRI were significantly different at 5% level of significance (LSD > 39.991). This is due to the fact that higher levels of CP result in the formation of briquettes that are more compact and therefore reducing it tendency to break apart when dropped from a height.

Water resistance quality of briquettes produced from mixture of *P. africana* and *C. pentandra*

In **Table 4.30** is presented the result of briquettes' water resistance quality (WR) for *P. africana* and *C. pentandra* and their combination. The WR quality of briquettes produced ranged from 1.01 to 6.63 minutes. With the exception of WR quality of briquettes produced from combination of *P. africana* and *C. pentandra* at a mixing ratio of 20 : 80 and CP level 50MPa for which the WR quality was 6.63 minutes, the rest had WR quality considered as very low. Water resistance quality greater or equal to 5 minutes is the minimum value considered to be adequate (Križan, 2007). The medium WR quality of briquettes produced from combination of *P. africana* and *C. pentandra* at a mixing ratio of 20 : 80 and low CP level of 50 MPa provides a breakthrough in the production of briquettes with at least medium WR quality from wood waste at low CP. The result further indicates that for all CP levels the WR quality of briquette made from combination of *P. africana* and *C. pentandra* were higher than their corresponding values for *P. africana* only. Thus, adding sawdust of *C. pentandra* to that of *P. africana* could enhance the WR quality of briquettes produced from *P. africana* sawdust.

Table 4.30: Water resistance quality (minutes) of briquettes produced from *P. africana*, *C. pentandra* and their combination using compacting pressure levels 20 to 50MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	2.76	3.19	3.82	4.81
P. africana	Pure	0.62	0.69	0.69	0.70
P. africana : *C. pentandra*	80 : 20	1.01	1.29	1.31	1.40
P. africana : *C. pentandra*	60 : 40	1.17	1.53	1.59	1.76
P. africana : *C. pentandra*	40 : 60	1.51	2.06	2.28	3.20
P. africana : *C. pentandra*	20 : 80	2.92	3.38	4.68	6.63

Correlation analysis indicates that at 5% level of significance, the proportion *P. africana* in the mixing ratio was highly, significantly and negatively correlated with the WR quality of briquettes produced (Pearson's r = -0.768, p-value = 0.000; N =80; 1-tailed, α = 0.05). Thus, as the amount of *P. africana* in the mixing ratio increased the WR quality of the briquettes produced decreased. On the contrarily increasing the proportion of *C. pentandra* in the mixing ratio resulted in increased WR quality of briquettes produced. CP was also found to be, moderately, significantly and positively correlated with WR quality of briquettes produced (Pearson's r = 0.391, p-value = 0.000; N =80; 1-tailed, α = 0.05). This means that increased in the CP level resulted in the increase of WR quality of briquette.

In **Appendix 4a** is the result of a two-way analysis of variance to determine the effect of biomass raw material (*P. africana and C. pentandra* and their combination), CP and their interaction on the WR quality of the produced briquettes. The result indicated that at 5% level of significance the biomass raw material, CP and their interactions had significant effect on the water resistance quality of the briquettes produced (p-value < 0.05). The multiple coefficient of determination value (R^2) and the RMSE of the ANOVA Model were 0.9849 and 0.2088 respectively. Thus, the biomass raw material, CP and their interaction could explain about 98.49% of the variability in the WR quality of the briquettes produced.

Post hoc analysis to compare the means of WR quality of briquettes produced from the biomass raw materials (*P. africana*, *C. pentandra* and their combination) as indicated in **Appendix 4b** shows that the WR quality of briquettes produced from the different proportional mix of the biomass material together with their original material significantly differ at 5% level of significance (LSD > 0.1311). The differences in the WR quality of the briquettes could be attributed to the different characteristics of the constituent materials in the mixture especially the density of the species used. Post hoc analysis to compare the means of WR quality of briquettes produced for CP levels; 20MPa, 30MPa, 40MPa and 50MPa (**Appendix 4c)** also indicates that the mean of WR quality of briquettes produced were significantly different for the different CP levels ($\alpha = 0.05$; LSD > 0.107). The highest CP level produced briquettes with highest WR quality of 3.08 minutes whilst the lowest CP level produced briquettes with lowest WR quality of 1.67 minutes. When CP level is high particles are better pressed together. This will lead to the formation of stronger bonds therefore reducing the tendency of it falling apart when it comes into contact with water.

4.9.3 Effect of mixture of *P. africana* and *T. superba*, and compacting pressure on physical and mechanical characteristics of briquettes

This part of the study considered the effect of combining *P. africana* (high density species) and *T. superba* (medium density species) on the physical and mechanical characteristics of fuel briquettes. Physical and mechanical characteristics of briquettes considered were relaxed density, CS in cleft, IRI and WR quality. The combustion characteristics of the samples were also studied.

Relaxed density of briquettes produced from mixture of *P. africana* and *T. superba*

Table 4.31 indicates the relaxed density of briquettes produced from *P. africana* and *T. superba* as well as that of their combination. The CP levels used were 20, 30, 40 and 50 MPa. Briquettes' relaxed density ranged from 571 kg/m^3 (mixing ratio 20 : 80 at CP level 20 MPa) to 781 kg/m^3 (mixing ratio 80 : 20 at CP level 50 MPa). This range could be considered adequate based on the assertion by Tumuluru, *et al*. (2010) and Saeidy (2004) that briquettes made from hydraulic piston press usually have densities less than 1000 kg/m^3 and are usually between 300 and 600 kg/m^3. The result (**Table 4.31**) also indicates that at all corresponding CP levels the relaxed density of briquettes produced from combination of *P. africana* and *T. superba* were higher than that produced from *P. africana* and *T. superba* only.

Table 4.31: Relaxed density (kg/m^3) of briquettes produced from *P. africana* and *T. superba* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
T. superba	Pure	557	631	674	727
P. africana	Pure	567	637	679	741
P. africana : *T. superba*	80 : 20	594	665	726	781
P. africana : *T. superba*	60 : 40	589	661	719	778
P. africana : *T. superba*	40 : 60	570	658	715	757
P. africana : *T. superba*	20 : 80	571	653	712	755

Correlation between the proportions of *P. africana* in the mixture of *P. africana* and *T. superba*, and relaxed density of briquettes produced indicates that the proportions of *P. africana* in the mixture of *P. africana* and *T. superba* does not significantly correlate with the relaxed density of the briquettes produced (Pearson's r = 0.108, p-value = 0.171, N = 80; 1-tailed, $\alpha = 0.05$). However, CP was found to be strongly, positively and significantly correlate with relaxed density of briquettes produced from the mixed species of *P. africana* and *T. superba* (Pearson's r = 0.978, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$). Thus, as the CP level increased the relaxed density of briquettes produced also increased. This trend is due to the fact that in pressing biomass materials to form briquettes, as the CP is increased the pressed biomass material becomes more compact. This therefore results in a decrease in void space hence the volume of the raw material. Thus, for the same mass of sample decreased in volume result in increased density.

Appendix 5a indicates the results of a two-way analysis of variance to determine the effect of biomass raw material (*P. africana* and *T. superba* and their combination), CP and their interaction on relaxed density of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP and their interaction had significant effect on the relaxed density of briquettes produced (p-value < 0.05). The multiple coefficient of determination value and the RMSE for the ANOVA model were 0.9798 and 11.1500 respectively. The multiple coefficient of determination value of 0.9798 means that about 97.98% of the variance in the relaxed density of the briquettes produced could be explained by the biomass material and the CP used for the pressing.Post hoc analysis to compare the means of the relaxed density of briquettes produced from the biomass raw material (**Appendix 5b**) indicates that the relaxed density of briquettes produced from the mixed species were significantly different (LSD > 6.6708) from that of their corresponding pure species. The relaxed density of the biomass raw material having mixing ratio 80 : 20 (*P. africana and T. superba*) was the highest however, it did not significantly differ from that of mixing ratio 60 : 40. Post hoc multiple comparison of means of relaxed density for CP levels 20, 30, 40 and 50 MPa as indicated in **Appendix 5c** also shows that at 5% level of significance the relaxed density for the briquettes produced for all the mixed species significantly differed (LSD > 6.6708). This result is consistent with that of the earlier findings in this study.

Compressive strength in cleft of briquettes produced from mixture of *P. africana* and *T. superba*

The CS in cleft of briquette produced from *P. africana* and *T. superba* as well as their combination are as shown in **Table 4.32.** The result indicates that, with the exception of briquettes' CS in cleft for mixing ratio 80 : 20 and pressed with CP level 20 MPa; and that for mixing ratio 60 : 40 and pressed with CP level 20 MPa for which the CS in cleft were lower than that of their corresponding values for briquettes produced from *T. superba* only, the rest of the briquettes produced from the mixed species had CS in cleft higher than that produced from pure species of *P. africana* and *T. superba* at all corresponding CP levels.

Table 4.32: Compressive strength in cleft (N/mm) of briquettes produced from *P. africana* and *T. superba* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
T. superba	Pure	6.16	10.44	13.64	18.92
P. africana	Pure	5.95	10.13	17.06	21.14
P. africana : *T. superba*	80 : 20	6.02	11.12	17.31	22.58
P. africana : *T. superba*	60 : 40	6.08	11.54	17.22	22.37
P. africana : *T. superba*	40 : 60	6.62	12.14	17.19	22.27
P. africana : *T. superba*	20 : 80	6.75	14.12	17.12	22.09

Briquettes produced showed a remarkable improvement in CS in cleft as a result of combining the two species. All the briquettes produced from the mixing ratio 80 : 20, 60 : 40, 40 : 60 and 20 : 80 using CP level 50 MPa had adequate CS in cleft for handling and packing (CS in cleft ≥ 19.6 N/mm). Therefore, briquettes with adequatte CS in cleft could be produced from a mixture of *P. africana* and *T. superba* when the two materials are combined at mixing ratios: 80 : 20, 60 : 40, 40 : 60 and 20 : 80 and pressed using CP level 50 MPa. Correlation analysis performed to establish the relationship between the proportions of *P. africana* in the mixing ratio of biomass material and, CS in cleft of briquettes produced indicated that there was no significant correlation between the proportions of *P. africana* in the mixture of *P. africana* and *T. superba* and CS in cleft of the briquettes produced (Pearson's r = -0.047, p-value = 0.340, N = 80; 1-tailed, α = 0.05). However, there was a significant positive correlation between CP levels and CS in cleft of the briquettes produced (Pearson's r = 0.977, p-value = 0.000, N = 80; 1-tailed, α = 0.05).

The result of ANOVA (**Appendix 6a**) to determine the effect of biomass raw material and CP on the CS in cleft of briquettes produced indicates that at 5% level of significance the biomass raw material, CP and their interaction had significant effect on CS in cleft of the produced briquettes. The multiple coefficient of determination and RMSE for the ANOVA model were 0.9647 and 1.2412 respectively. Thus, the two variables, biomass raw material and the CP could explain about 96.47% of the variability in the CS in cleft of briquettes produced. Post hoc analysis using LSD to compare the means of CS in cleft of briquettes produced from the biomass raw material (*P. africana*, *T. superba* and their combination) is as shown in **Appendix 6b.** The result shows that the CS in cleft of the briquette produced from the mixed species does not differ significantly from each other (LSD < 0.7791, α = 0.05).

Additionally, the CS in cleft of briquettes produced from *P. africana* was not significantly different from that produced from biomass material mixed at mixing ratio 60 : 40 and 80 : 20 (LSD < 0.7791, $\alpha = 0.05$). This result means that briquettes produced from a mixture of *P. africana* and *T. superba* at mixing ratios; 80 : 20, 60 : 40, 40 : 60, 20 : 80 would have no significant difference in their CS in cleft. Finally, briquettes made from *T. superba* were found to have significantly lower CS in cleft than that made from combination of *P. africana* and *T. superba*. Thus, the addition of *P. africana* to *T. superba* could considerably improve upon the CS in cleft of *T. superba* briquettes. In **Appendix 6c** is indicated Post hoc multiple comparisons of means of CS in cleft for CP levels using LSD. The result shows that the CS in cleft of briquettes produced from this mixed species were significantly different for each CP level (LSD > 0.6361, $\alpha = 0.05$). This result tends to reinforce the earlier findings in this study.

Impact resistance index of briquettes produced from mixture of *P. africana* and *T. superba*

In **Table 4.33** is presented the IRI of briquettes produced from *P. africana*, *T. superba* and their combinations). The result indicates that the IRI of briquettes produced from the mixed species ranges from 87 to 300%. The result further indicates that for the same CP level the IRI of all the briquettes produced from the mixed sawdust of *P. africana* and *T. superba* were lower or equal to those produced from *T. superba* only. The exception to this were briquettes produced from mixing ratio 40 : 60 and 20 : 80, and pressed at CP level 50 MPa for which the IRI of the briquettes produced was higher than that produced from *T. superba* only. Additionally, the IRI of briquettes produced from mixing ratios 40 : 60 and 20 : 80, and pressed using CP levels 40 and 50 MPa does not differ.

Table 4.33: Impact resistance index (%) of briquettes produced from *P. africana* and *T. superba* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
T. superba	Pure	133	192	233	283
P. africana	Pure	72	137	184	217
P. africana : *T. superba*	80 : 20	87	120	200	233
P. africana : *T. superba*	60 : 40	94	150	217	250
P. africana : *T. superba*	40 : 60	103	150	233	300
P. africana : *T. superba*	20 : 80	104	175	233	300

This means that both mixing ratios 40 : 60 and 20 : 80 could produce briquette with IRI 233% and 300% when pressed at CP level of 40 and 50 MPa respectively. The result further indicate that the IRI of all the briquettes produced from the combination of these two species, with the exception of that produced from mixing ratios 80 : 20 and 60 : 40 and pressed at CP level of 20 MPa, exceeded the targeted value of 100. Wilaipon (2009) stated that briquettes with impact resistance index value equal to 100 or more is considered as good briquettes. Additionally, according to the Italian standard for briquettes/pallets CTI-R04/5 briquettes durability greater or equal to 97.7% is adequate (Italian standard for briquettes/pallets CTI-R04/5 as cited in Hahn, 2004). It could also be concluded that briquettes' IRI is just not adequate but also high. Generally, researchers have classified the durability characteristics into high (> 0.8), medium (0.7 - 0.8), and low (< 0.7) (Tabil & Sokhansanj, 1996; Adapa, *et al*., 2003).

Correlation analysis between proportions of *P. africana* in the briquettes made from the mixed sawdust of *P. africana* and *T. superba* and, IRI indicated a low negative significant correlation between the two variables (Pearson's r = -0.202, p-value = 0.036, N = 80; 1-tailed, $\alpha = 0.05$). Thus, briquettes' IRI decreases with increasing proportions of *P. africana* in the mixing ratio. *P. africana* is a high density species therefore when compacting at a low CP of 50 MPa or less it does not easily undergo plastic deformation for strong bonds to be formed therefore resulting in the formation of briquettes with low IRI. This eventually leads to the formation of briquettes with weaker IRI as the proportions of *P. africana* in the mixing ratio increases. The result also indicates that there was a high significant correlation between CP levels and IRI of the briquettes produced from the mixed species of *P. africana and T. superba* (Pearson's r = 0.807, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$). This is consistent with the result obtained at the earlier part of this study as well as studies conducted by other researchers. Singh and Kashyap (1985) also found that increasing CP from 7.8 to 31.2 MPa increased the durability of rice husk briquettes from 80 to 95% where the briquettes were made from rice husk with an average particle size of 4.05 mm and added with 25% molasses. Increased CP level would increase the libration of natural binding chemicals in the biomass material therefore enhancing the formation of solid bridge bond hence resulting in increased IRI. Additionally, when CP is increased particles of the biomass material are brought closer to each other therefore enhancing the formation of intermolecular bond.

Appendix 7a indicates a two-way analysis of variance of the effect of biomass raw material (*P. africana* and *T. superba* and their combination), CP and their interaction on IRI of briquettes produced. The result shows that at 5% level of significance the biomass raw material and CP have significant effect on the IRI of the briquettes produced (p-value < .05). However, the interaction between the biomass raw material and the CP did not have any significant effect on the IRI of the briquettes produced. The multiple coefficient of determination and the RMSE for the ANOVA model were 0.6771 and 51.7129 respectively. The multiple coefficient of determination value of 0.6771 means that the biomass raw material and the CP could explain about 67.71% of the variability in the IRI of the briquettes produced.

Post hoc analysis to compare the means of IRI of briquettes produced from the biomass raw material (*P. africana, T. superba* and their combination), A**ppendix 7b**, shows that at 5% level of significance, the IRI of briquettes made from the mixing ratios 20 : 80, 40 : 60 and 60 : 40 did not significantly differed from that made from *T. superba* only (LSD < 32.461). Thus, the introduction of 20%, 40% and 60% of sawdust of *P. africana* into that of *T. superba* would not significantly change it IRI. Additionally, at 5% level of significance, the IRI of briquettes made from the mixing ratios of 60 : 40 and 80 : 20 did not significantly differ from that made from *P. africana* (LSD < 32.461). However, the IRI of briquettes made from *P. africana* at 5% level of significance was significantly lower than that made from mixing ratios of 20 : 80 and 40 : 60 (LSD > 32.461). This therefore imply that when sawdust of *P. africana and* T. superba are combined at mixing ratios 20 : 80 and 40 : 60 it would enhance the IRI of briquettes made than otherwise produced from *P. africana* alone. The result of Post hoc multiple comparison of means of IRI of briquettes produced using varying levels of CP (50, 40, 30 and 20 MPa) is as shown in **Appendix 7c**. The result indicates that the IRI of briquettes produced using CP levels 50, 40, 30 and 20 MPa differed significantly (LSD > 26.504; $\alpha = 0.05$). This is due to the fact that higher levels of CP result in the formation of briquettes that are more compact and strongly bonded together. Therefore, reducing it tendency to break apart when dropped from a height.

Water resistance quality of briquettes produced from mixture of *P. africana* and *T. superba*

Presented in **Table 4.34** is the result of WR quality of briquettes produced from *P. africana*, *T. superba* and their combination. The WR quality of the briquettes produced ranged from 0.59 to 0.86 minutes. The result further indicates that at all CP levels the WR quality of all the briquettes produced from the mixed species of *T. superba* and *P. africana* were lower than that produced from *T. superba* alone. Additionaly, with the exception of briquettes pressed at CP level 50 MPa, all the briquettes pressed from the mixing ratio 80 : 20 and 60 : 40 had WR quality lower than that of *P. africana*. However, the WR quality of all the briquettes pressed from mixing ratio 20 : 80 were found to be superior to that of *P. africana*. The above findings suggest that adding *P. africana* sawdust to that of *T. superba* could negatively affect the WR quality of briquettes produced from *T. superba*. On the contrarily adding sawdust of *T. superba* to that of *P. africana* could improve the WR quality of the briquettes produced from *P. africana*. Finally, it could be concluded that the WR quality of

Table 4.34: Water resistance quality (minutes) of briquettes produced from *P. africana* and *T. superba* and their combination using compacting pressure levels 20 to 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
T. superba	Pure	2.92	3.26	3.81	3.94
P. africana	Pure	0.62	0.69	0.69	0.70
P. africana : *T. superba*	80 : 20	0.59	0.61	0.62	0.75
P. africana : *T. superba*	60 : 40	0.60	0.65	0.67	0.77
P. africana : *T. superba*	40 : 60	0.62	0.69	0.70	0.82
P. africana : *T. superba*	20 : 80	0.74	0.76	0.81	0.86

all the briquettes produced from the mixed species of *P. africana* and *T. superba* could be classified as being low (WR quality < 5 minutes). According to Križan (2007) briquettes for which when dipped into water falls into pieces sooner than 5 minutes are considered as having a very low WR quality.

Correlation analysis to determine the relationship between proportions of *P. africana* in the mixture of *P. africana* and *T. superba,* and WR quality of the briquettes produced indicates that there was a significant negative correlation between the two variables (Pearson's r = -0.555, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$). Thus, as the proportions of *P. africana* in the mixture increased the WR quality of briquettes decreased. On the contrarily as the proportion of *T. superba* in the mixing ratio increased the WR quality of the briquettes produced increased. The implication of this result is that the WR quality of briquette made from *P. africana* could be improved by mixing it with *T. superba* as stated earlier. CP levels used in producing the briquette from this mixed species was also found to be moderately, positively and significantly correlated with the WR quality of briquettes produced (Pearson's r = 0.582, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$).

Appendix 8a indicates the results of a two-way analysis of variance performed to determine the effect of biomass raw material (*P. africana* and *T. superba* and their combination), CP and their interaction on WR quality of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP as well as their interactions had significant effect on WR quality of briquettes produced (p-value < 0.05). The coefficient of determination and RMSE for the ANOVA model was 0.9917 and 0.1075 respectively. The implication of the coefficient of determination value of 0.9917 is that the biomass raw material, CP and their interaction could explain about 99.17% of the variability in the WR quality of the briquettes produced. Post hoc multiple comparison of means of WR quality of briquettes produced from the biomass raw material (*P. africana*, *T. superba* and their combination) as shown in **Appendix 8b** shows that at 5% level of significance the WR quality of briquettes made from the mixing ratios 80 : 20, 60 : 40 and 40 : 60 do not significantly differ from each other (LSD < 0.0675, α = 0.05). Additionally, the WR quality of these briquettes does not significantly differ from that made from *P. africana* only. WR of briquettes produced from the mixed species were significantly lower than that of *T. superba only* (LSD > 0.0675, α = 0.05). The implication of the above result is that the addition of 40%, 60% and 80% of *T. superba* sawdust to that of *P. africana* would not significantly change the WR quality of briquettes produced from *P. africana* sawdust. However, a mixture of 20% *P. africana* sawdust and 80% *T. superba* sawdust would enhance the WR quality of briquette made from *P. africana*. Alternatively, addition of *P. africana* to *T. superba* would significantly reduce the WR quality of briquettes produced from *T. superba*. Post hoc analysis to compare the means of WR quality of briquettes produced from CP levels 50 MPa, 40 MPa, 30 MPa and 20 MPa, as shown in **Appendix 8c** indicates that WR quality of briquettes pressed at all the levels of CP significantly differed (LSD > 0.0551, α = 0.05). This result reaffirms that of the earlier studies.

4.9.4 Effect of mixture of *T. superba* and *C. pentandra*, and compacting pressure on physical and mechanical characteristics of briquettes

In this part of the study the result of the effect of mixing *T. superba* (medium density species) and *C. pentandra* (low density species) on the physical and mechanical characteristics of briquettes produced is presented and discussed. Physical and mechanical characteristics of briquettes studied were relaxed density, CS in cleft, IRI and WR quality.

Relaxed density of briquettes produced from mixture of *T. superba* and *C. pentandra*

The result in **Table 4.35** indicates the relaxed density of briquettes produced from *T. superba* and *C. pentandra* as well as their combination pressed using CP levels 20, 30, 40 and 50

MPa. The relaxed density of the briquettes produced from the mixture of *T. superba* and *C. pentandra* ranged from 555 kg/m^3 (mixing ratio 20 : 80 and CP 20 MPa) to 768 kg/m^3 (mixing ratio 80 : 20 and compacting pressure 50 MPa). With the exception of briquettes produced from mixing ratio 20 : 80 and at CP level 20 MPa for which the relaxed density was lower than it corresponding value for *T. superba* only all the briquette produced from this mixed species had relaxed density higher than their corresponding values for pure species of *T. superba*. The range for the relaxed density of briquettes produced (555 - 768 kg/m^3) could be considered adequate in that they were within the acceptable range of 300 to 1000 kg/m^3 as suggested by Tumuluru, *et al*. (2010) and Saeidy (2004). Tumuluru, *et al*. (2010) in his paper on review on biomass densification technologies for energy application asserted that briquettes made from hydraulic piston press are usually less than 1000 kg/m^3. Saeidy (2004), in his paper titled technological fundamentals of briquetting cotton stalks as a

Table 4.35: Relaxed density (kg/m^3)of briquettes produced from *T. superba*, *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	523	622	666	716
T. superba	Pure	557	631	674	727
T. superba : *C. pentandra*	80 : 20	572	651	709	768
T. superba : *C. pentandra*	60 : 40	564	650	706	756
T. superba : *C. pentandra*	40 : 60	559	645	699	749
T. superba : *C. pentandra*	20 : 80	555	641	696	746

biofuel stated that briquettes made from hydraulic piston press are usually between 300 - 600 kg/m^3 (Saeidy, 2004). From the above result it could be deduced that combining sawdust of *T. superba* and *C. pentandra* could greatly enhance the relaxed density of the briquettes produced. This could be due to better arrangement of the sawdust particles of the two species when mixed together and pressed.

Correlation analysis performed to establish the relationship between proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra*, and relaxed density of briquettes made shows that proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra* does not significantly correlate with the relaxed density of the briquettes produced (Pearson's $r = 0.081$, p-value = 0.239, $N = 80$; 1-tailed, $\alpha = 0.05$). However, at 5% level of significance CP was found to be strongly, positively and significantly correlated with the relaxed density of briquettes produced (Pearson's $r = 0.982$, p-value = 0.000, $N = 80$; 1-tailed). This is consistent with that of earlier findings of this study.

In **Appendix 9a** is indicated the results of a two-way analysis of variance to determine the effect of biomass raw material (*T. superba* and *C. pentandra* and their combination), CP and their interaction on the relaxed density of the briquettes produced. The result indicates that at 5% level of significance the biomass raw material and CP had significant effect on the relaxed density of briquettes produced (p-value < 0.05). However, the interaction between biomass material and CP did not have any significant effect on the relaxed density of the briquettes produced. The multiple coefficient of determination (R^2) and RMSE for the ANOVA model were 0.9823 and 10.6948 respectively. The R^2 value of 0.9823 means that about 98.23% of variability in the relaxed density of the briquettes produced could be explained by the biomass material, CP and their interaction. Post hoc multiple comparison of means of relaxed density of briquettes produced from the biomass raw material (*T. superba*, *C. pentandra* and their combination) as shown in **Appendix 9b** indicates that the relaxed density of briquettes made from the mixing ratio 40 : 60 does not significantly differs from that of mixing ratios 60 : 40 and 20 : 80 (LSD < 6.7132; α = 0.05). The relaxed density of briquettes obtained from mixing ratio 20 : 80 was significantly different from that obtained from 80 : 20 (LSD > 6.7132; α = 0.05). Further more, the relaxed density of all the briquettes made from mixing ratio of *T. superba* and *C. pentandra* were significantly higher than that produced from the pure species of *T. superba* and *C. pentandra* (LSD > 6.7132; α = 0.05). Post hoc multiple comparison of means of relaxed density of briquettes produced from CP levels 50, 40, 30 and 20 MPa, as shown in **Appendix 9c** indicates that the relaxed density of briquettes pressed at all CP levels differed significantly (LSD > 5.4813, α = 0.05). This may be due to better arrangement and bonding of the sawdust particles as CP level increases.

Compressive strength in cleft of briquettes produced from mixture of *T. superba* and *C. pentandra*

The CS in cleft of briquettes produced from *T. superba* and *C. pentandra* and their combination is presented in **Table 4.36**. The CS in cleft of briquettes produced from the mixed species of *T. superba* and *C. pentandra* ranged from 10.23 to 56.77 N/mm. Additionally, twelve out of sixteen of this briquettes had CS in cleft greater than 19.6 N/mm.

Table 4.36: Compressive strength in cleft (kg/m^3) of briquettes produced from *T. superba* and *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	29.23	39.26	40.40	44.58
T. superba	Pure	6.16	10.44	13.64	18.92
T. superba : *C. pentandra*	80 : 20	10.23	14.62	22.21	28.16
T. superba : *C. pentandra*	60 : 40	13.77	23.01	33.58	39.61
T. superba : *C. pentandra*	40 : 60	19.29	28.74	37.89	45.81
T. superba : *C. pentandra*	20 : 80	26.43	34.32	45.02	56.77

CS in cleft of 19.66 N/mm is the minimum value considered to be adequate for handling (Rahman, *et al*. (1989). The result also indicates that the CS in cleft of all the briquettes made from mixture of *T. superba* and *C. pentandra* were higher than that for their corresponding values of *T. superba* only. Therefore, when sawdust of *C. pentandra* is added to that of *T. superba* it could enhance CS in cleft of briquettes produced it. With the exception of briquettes produced from mixing ratio 40 : 60 and CP = 50 MPa; mixing ratio 20 : 80 and CP levels 40 MPa and 50 MPa, the CS in cleft of briquettes produced from the mixed species of *T. superba* and *C. pentandra* were lower than their corresponding values for *C. pentandra*. This result suggests that if sawdust of *C. pentandra* is mixed with that of *T. superba* at mixing ratio of 40 : 60 (*T. superba* : *C. pentandra*) and pressed at 50 MPa or mixed at ratio of 20 : 80 and pressed at 40 MPa or 50 MPa the quality of the CS in cleft of the briquette produced from *C. pentandra* sawdust would be enhanced.

Correlation analysis between the proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra*, and CS in cleft of briquettes produced indicated that at 5% level of significance the proportions of *T. superba* in the mixture significantly and negatively correlate with the CS in cleft of the briquettes produced (Pearson's r = -0.627, p-value = 0.000, N = 80; 1-tailed). Thus, increasing the proportions of *T. superba* in the mixture results in the decrease of CS in cleft of the briquettes formed. Species density is found to have negative correlation with CS in cleft of briquette produced (**Table 4.25**). Increased species density in the mixing ratio reduces the tendency of biomass material to reach elastic and plastic deformation. This therefore reduces the tendency for the formation of strong bonds through mechanical folding and inter-locking of sawdust particles. Additionally, CS in cleft of briquettes produced from combination of *T. superba* and *C. pentandra* was found to be highly, positively and significantly correlated with the CP levels used in making the briquettes (Pearson's r = 0.751, p-value = 0.000, N = 80; 1-tailed). According to Bilanski & Graham (1984), O'Dogherty and Wheeler (1984) and Briggs *et al*. (1999), application of higher compaction pressures during biomass densification can result in crushing the biomass particles, thus opening up the cell structure and exposing the protein and pectin that act as natural binders which assists in increasing the strength of the pelletized product. Additionally, increasing the CP level will leads to the particles of the sawdust being pressed closer to each other therefore resulting in the formation of stronger bonds through Van der Waals' forces and electrostatic force which is dependent on inter-particle distance.

In **Appendix 10a** is presented the ANOVA to determine the effect of mixed species, biomass raw material, CP and their interactions on the CS in cleft of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP and their interaction have significant effect on the CS in cleft of the briquettes produced. The multiple coefficient of determination and RMSE values for the ANOVA model were 0.9724 and 2.4926 respectively. Thus the two variables, biomass raw material and the CP could explain about 97.24% of the variability of the CS in cleft of the briquettes produced. Post hoc multiple comparison of means (**Appendix 10b**) of CS in cleft of briquettes produced from mixture of *T. superba* and *C. pentandra* in the ratios of 80 : 20, 60 : 40, 40 : 60, 20 : 80 using LSD shows that the CS in cleft of briquette produced from each biomass material mix differs significantly (LSD > 1.4952, $\alpha = 0.05$). The biomass material with mixing ratio 20 : 80 was strongest in terms of CS in cleft followed by that of 40 : 60, 60 : 40 and 80 : 20. Although the CS in cleft for the mixing ratios 40 : 60, 60 : 40 and 80 : 20 were lower than that of *C. pentandra* they were significantly higher than that of *T. superba*. The above result suggest that when sawdust of *C. pentandra* and *T. superba* are mixed in the mixing ratio of 20 : 80 it CS in cleft could improve significantly. Post hoc multiple comparison of means (**Appendix 10c**) of CS in cleft of briquettes produced from CP levels; 50MPa, 40MPa, 30MPa and 20MPa indicated that the CS in cleft of the briquettes produced from each of the CP levels differed significantly (LSD > 1.2775, α = 0.05). This further confirm the result obtained for the earlier part of this studies, that briquettes pressed at different CP level differs significantly in the CS in cleft.

Impact resistance index of briquettes produced from mixture of *T. superba* and *C. pentandra*

Presented in **Table 4.37** is the result of IRI of briquettes produced from a mixture of *T. superba*, *C. pentandra* and their combination. The IRI of briquettes produced from combination of *T. superba* and *C. pentandra* ranged from 133 to 500%. All the briquettes produced from this combination *T. superba* and *C. pentandra* had IRI greater than 100%, minimum value set for this study. According to Wilaipon (2009), IRI value of briquettes greater or equal 100% is considered as good. Additionally, the adequacy of IRI of briquettes

Table 4.37: Impact resistance index (%) of briquettes produced from *T. superba* and *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	200	283	316	350
T. superba	Pure	133	192	233	283
T. superba : *C. pentandra*	80 : 20	133	159	159	216
T. superba : *C. pentandra*	60 : 40	142	233	450	500
T. superba : *C. pentandra*	40 : 60	158	250	450	500
T. superba : *C. pentandra*	20 : 80	233	300	450	500

produced is supported by the Italian standard for briquettes/pallets CTI-R04/5 which indicates that briquettes durability greater or equal to 97.7 is adequate (Italian standard for briquettes/pallets CTI-R04/5 as cited in Hahn, 2004). The result also indicates that for mixing ratios 60 : 40, 40 : 60 and 20 : 80 the IRI of the briquettes produced were higher than that produced from pure sawdust of *T. superba*. All the briquettes produced from mixing ratios 60 : 40, 40 : 60 and 20 : 80 and at CP level 50 MPa did not show any sign of breaking when dropped five times from a height of two metres unto a concrete floor. Briquettes IRI was about 5 times greater than the targeted value of 100. Thus, mixing sawdust of *T. superba* with that of *C. pentandra* at mixing ratios 60 : 40, 40 : 60 and 20 : 80 could tremendously enhance the IRI of briquettes produced from *T. superba* sawdust.

Correlation between proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra* and IRI of briquettes produced indicates a moderate, significant negative correlation between the two variables (Pearson's r = -0.450, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$). This result suggests that increasing the proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra* will result in the production of briquette with weaker IRI. *T. superba* comparatively has higher density than *C. pentandra*. Species density is found to have negative correlation with IRI briquette produced (**Table 4.25**). Therefore, increasing *T. superba* in the mixing ratio will lead to increased in proportion of particles with higher density in the mixing ratio. As a result the tendency of the biomass material to reach elastic and plastic deformation is reduced. Additionally, for this same combination of biomass material, CP was found to be highly significantly and positively correlated with IRI of briquettes produced (Pearson's r = 0.673, p-value = 0.000, N = 80; 1-tailed, $\alpha = 0.05$). Thus, as CP level increased the IRI of the briquettes produced also increased. This result confirms that of Srivastava, *et al*. (1981) and Singh and Kashyap (1985). Srivastava, *et al*. (1981) found that increasing pressure from 5 to 44 MPa increased the wafer (150-mm diameter) durability rating (based on an impact resistance test) of grass hay (mixed with 20% alfalfa) from 5 to 91%. Singh and Kashyap (1985) also found that increasing pressure from 7.8 to 31.2 MPa increased the durability of rice husk briquettes from 80 to 95%. Increased CP level increases the strength of bonds formed through (1) mechanical folding and inter-locking of sawdust particles (2) electrostatic force of attraction and solid bridges through formation of solid bridges between sawdust particles.

Two-way analysis of variance of effect of biomass raw material (*T. superba* and *C. pentandra*, and their combination), CP and their interaction on IRI of briquettes produced is as shown in **Appendix 11a**. The result shows that at 5% level of significance the biomass raw material, CP and their interactions had significant effect on the IRI of briquettes produced (p-value < 0.05). The multiple coefficient of determination and the RMSE for the ANOVA model were 0.7379 and 82.7246 respectively. Thu it could be concluded that the two variables considered could explain about 73.79% of the variance in the IRI of the briquettes produced. Post hoc multiple comparison of means of IRI of briquettes produced from the biomass raw material (*T. superba*, *C. pentandra* and their combination) is as presented in **Appendix 11b**. The result shows that the IRI of briquettes produced from mixing ratios 20 : 80, 40 : 60 and 60 : 40 does not significantly differ at 5% level of significance (LSD < 51.927). Additionally, the IRI of briquettes produced from combination of 80% of *T. superba* and 20% of *C. pentandra* does not significantly differ from that made from only *T. superba* (LSD < 51.927, $\alpha = 0.05$). Post hoc multiple comparison of means of IRI for CP levels (**Appendix 11c**) also indicates that briquettes produced at these CP levels differed significantly (LSD > 42.398, α = 0.05). This is due to the fact that higher levels of CP result in the formation of briquettes that are more compact due to formation of stronger bonds. Therefore, briquettes formed has lower tendency to break apart when dropped from a height.

Water resistance quality of briquettes produced from mixture of *T. superba* and *C. pentandra*

In **Table 4.38** is the result of WR quality of briquettes produced from *C. pentandra* and *T. superba* and their combination. The WR quality of briquettes made from *T. superba* and *C. pentandra* ranged from 1.42 to 3.34 minutes. Additionally, the WR quality of the briquettes produced from mixed species, *C. pentandra* and *T. superba*, were less than that of their

Table 4.38: Water resistance quality (minutes) of briquettes produced from *T. superba* and *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	2.76	3.19	3.82	4.81
T. superba	Pure	2.92	3.26	3.81	3.94
T. superba : *C. pentandra*	80 : 20	1.42	1.44	1.45	1.63
T. superba : *C. pentandra*	60 : 40	2.00	1.95	2.10	2.14
T. superba : *C. pentandra*	40 : 60	2.12	2.16	2.27	2.38
T. superba : *C. pentandra*	20 : 80	2.70	2.65	2.86	3.34

corresponding values for *C. pentandra* and *T. superba* only. In conclusion the WR quality of briquettes produced from this mixed species was very low (WR quality < 5 minutes). According to Križan (2007) briquettes for which when dipped into water falls into pieces sooner than 5 minutes are considered as having a very low WR quality.

Correlation analysis between proportions of *T. superba* in the mixture of *T. superba* and *C. pentandra*, and WR quality of briquettes produced indicated that the proportions of *T.*

superba in the mixture was highly, negatively and significantly correlate with the WR quality of the briquettes produced. (Pearson's $r = -0.887$, p-value = 0.000, $N = 80$; 1-tailed, $\alpha = 0.05$). Thus, increasing the proportion of *T. superba* in the mixture resulted in decrease in the WR quality of the briquettes produced. This is due to the fact that increase proportion of *T. superba* in the mixing ratio result in the mixture having higher proportions of high density material. This therefore leads to the formation of weak bonds therefore resulting in the formation of briquettes with low WR quality. The WR quality of briquette produced from the combination of *T. superba* and *C. pentandra* was also found to be moderately, significantly and positively correlated with the CP levels (Pearson's $r = 0.214$, p-value = 0.028, $N = 80$; 1-tailed, $\alpha = 0.05$).

Appendix 12a is the results of a two-way analysis of variance of biomass raw materials (*T. superba* and *C. pentandra* and their combination), CP and their interaction on WR quality of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP and their interactions has significant effect on the WR quality of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and the RMSE values for the ANOVA model were 0.9567 and 0.2059 respectively. The R^2 suggest that the variables, biomass raw material and CP could explain about 95.67% of the variance in the WR quality of the briquettes produced. Post hoc multiple comparison of means of WR quality of briquettes produced for the biomass raw material (*T. superba* and *C. pentandra* and their combination) is as shown in **Appendix 12b**. The result indicates that the WR quality of all the briquettes made from the mixed species of *T. superba* and *C. pentandra* were significantly different from each other and from that made from pure sawdust of *T. superba* or *C. pentandra* (LSD < 0.1293, $\alpha = 0.05$). Additionally, Post hoc analysis to compare the means of WR quality of briquettes produced at CP levels 50 MPa, 40 MPa, 30 MPa and 20 MPa (**Appendix 12c**) showed significant difference for the varying CP levels (LSD < 0.1055, $\alpha = 0.05$).

4.9.5 Effect of mixture of *P. africana*, *T. superba* and *C. pentandra*, and compacting pressure on physical and mechanical characteristics of briquettes

In this part of the study the result of the effect of combining *P. africana* (High density species), *T. superba* (medium density species) and *C. pentandra* (Low density species) on the physical and mechanical characteristics of briquettes is presented and discussed. Physical and mechanical properties of briquettes considered were relaxed density, CS in cleft, IRI and WR quality.

Relaxed density of briquettes produced from mixture of *P. africana*, *T. superba* and *C. pentandra*

The result of relaxed density of briquette made from *P. africana*, *T. superba* and *C. pentandra* and their combination are shown in **Table 4.39**. The CP levels used were 20, 30, 40 and 50 MPa. The result indicates that the relaxed density of briquette produced from the mixed species ranged from 557 to 764 kg/m^3. The range of briquettes' relaxed density was within the acceptable range of 300 - 1000 kg/m^3 and therefore were deemed adequate. Tumuluru, *et al*. (2010) and Saeidy (2004) suggested that briquettes made from hydraulic piston press usually have densities less than 1000 kg/m^3 and are usually between 300 and 600 kg/m^3.

The result further indicate that for mixing ratios 40 : 30 : 30, 30 : 40 : 30, 30 : 30 : 40, 1 : 1 : 1 and at CP levels 40MPa and 50MPa the relaxed density of briquettes produced were higher than their corresponding values for *P. africana*, *T. superba* and *C. pentandra* only. The exception to this was that produced at mixing ratio 1 : 1 : 1 and at CP level 50MPa for which the relaxed density of the briquettes produced was equal to that of *T. superba*. At CP levels 20 MPa, 30 MPa, 40 MPa and 50 MPa the relaxed density of briquettes produced from the mixing ratio 40 : 30 : 30 were highest.

Table 4.39: Relaxed density (kg/m^3) of briquettes produced from *P. africana*, *T. superba* and *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure			
		20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	523	622	666	716
T. superba	Pure	557	631	674	727
P. africana	Pure	567	637	679	741
P. africana : *T. superba* : *C. pentandra*	40 : 30 : 30	582	649	726	764
P. africana : *T. superba* : *C. pentandra*	30 : 40 : 30	570	629	715	755
P. africana : *T. superba* : *C. pentandra*	30 : 30 : 40	563	636	705	751
P. africana : *T. superba* : *C. pentandra*	1 : 1 : 1	557	635	696	727

This may be due to the high proportions of *P. africana*, high density species, in the mixing ratio. The implication of this is that when briquettes are made from a mixture of *P. africana*, *T. superba* and *C. pentandra*, the one produced from mixing ratio of 40 : 30 : 30 would have the most superior quality of relaxed density. Briquettes' relaxed density for both the pure and the combined materials increased with increasing CP.

Appendix 13a indicates the results of a two-way ANOVA of the effect of biomass raw material (*P. africana*, *T. superba*, *C. pentandra* and their combination), CP and their interaction on relaxed density of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP and their interactions had significant effect on the relaxed density of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE for the ANOVA model were 0.9798 and 11.1500 respectively. The R^2 value of 0.9798 means that the variables considered i.e. biomass raw material and compacting pressure can explain about 97.98 percent of the variance in the relaxed density of the briquettes produced.

Post hoc multiple comparison of means of relaxed density of briquettes produced from the biomass raw material (*P. africana*, *T. superba*, *C. pentandra* and their combination) is as shown in **Appendix 13b**. The result indicates that the relaxed densities of briquettes produced from the mixing ratio 1 : 1 : 1 does not significantly differ from that produced from pure species of *P. africana* and *T. superba* (LSD < 6.9862, $\alpha = 0.05$). Briquettes produced from mixing ratios 30 : 40 : 30 and 30 : 30 : 40 at 5% level of significance differs from each other significantly (LSD > 6.9862). Lastly, the relaxed density of briquettes produce from all the mixed species was significantly higher than that of pure *C. pentandra*. This is due to the introduction of high density species (*P. africana*) and medium density species (*T. superba*) into *C. pentandra*. In a correlation analysis between density of species and relaxed density of briquettes produced (**Table 4.25**), density of species was found to have positive significant correlation with relaxed density of briquette. Post hoc multiple comparison of means of relaxed density of briquettes for CP levels 50, 40, 30 and 20 MPa (**Appendix 13c**) showed significant difference between the relaxed density of the briquettes produced (LSD > 5.2810, $\alpha = 0.05$). This result did not deviate from that obtain from the earlier part of this study. Increasing CP level, result in the particles of the biomass material being pressed closer to each other. Therefore, producing briquettes with higher density.

Compressive strength in cleft of briquettes produced from mixture of *P. africana*, *T. superba* and *C. pentandra*

In **Table 4.40** is presented the CS in cleft of briquette produced from *P. africana, T. superba*, *C. pentandra* as well as their combination. The result indicates that CS in cleft of briquettes produced from this mixed species ranged from 12 to 41.12 N/mm. All the briquettes produced for the mixed species of *P. africana*, *T. superba* and *C. pentandra* at CP level 20 MPa did not have adequate CS in cleft (CS in cleft < 19.6 N/mm). This means that producing briquettes from a mixture of *P. africana*, *T. superba* and *C. pentandra* using CP level 20MPa will not have adequate CS in cleft for packing. The result further indicates that briquettes produced for all the mixed species at CP level 40 and 50 MPa had adequate CS in cleft, that is, CS in cleft greater or equal to 19.6 N/mm. This suggest that briquettes produced from a mixture of *P. africana*, *T. superba*, *C. pentandra* sawdust using CP level 40 MPa or more would have adequate CS for packing.

Table 4.40: Compressive strength in cleft (N/mm) of briquettes produced from *P. africana*, *T. superba* and *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

		Compacting pressure			
Biomass material	Mixing ratio (weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	29.23	39.26	40.40	44.58
T. superba	Pure	6.16	10.44	13.64	18.92
P. africana	Pure	5.95	10.13	17.06	21.14
P. africana : *T. superba* : *C. pentandra*	40 : 30 : 30	14.16	23.77	33.08	40.45
P. africana : *T. superba* : *C. pentandra*	30 : 40 : 30	12.18	15.70	28.85	34.87
P. africana : *T. superba* : *C. pentandra*	30 : 30 : 40	17.60	26.43	33.36	41.12
P. africana : *T. superba* : *C. pentandra*	1 : 1 : 1	12.75	19.34	23.86	28.65

The CS in cleft of all the briquettes produced from combination of the three species were lower than their corresponding values for *C. pentandra* but higher than that of their corresponding values for *P. africana* and *T. superba* . This result suggests that mixing the three species (*P. africana*, *T. superba* and *C. pentandra*) could tremendously enhance the CS in cleft of briquettes produced from *P. africana* and *T. superba*. Lastly, briquettes CS in cleft for *T. superba* could be double when *P. africana, T. superba* and *C. pentandra* are combined at mixing ratio of 30 : 30 : 40 and pressed using CP levels 20, 30, 40 or 50 MPa.

The result of ANOVA, **Appendix 14a** to determine the effect of biomass raw material, CP and their interaction on the CS in cleft of briquettes produced indicated that at 5% level of significance the biomass raw material (ie *P. africana*, *T. superba* and *C. pentandra* as well as their combination), CP and their interaction had significant effect on the CS in cleft of the produced briquettes. The multiple coefficient of determination (R^2) and the RMSE for the ANOVA model were 0.9678 and 2.2997 respectively. Thus, the two variables, biomass raw material and the CP as well as their interaction could explain about 96.78% of the variability in the CS in cleft of briquettes produced. Post hoc multiple comparison of means of CS in cleft of briquettes produced from the biomass raw materials i.e. *P. africana*, *T. superba* and *C. pentandra* and their combination are idicated in **Appendix 14b.** This result shows that at 5% level of significance the CS in cleft of the briquette produced from combination of *P. africana*, *T. superba* and *C. pentandra* at the various mixing ratio differed significantly from each other (LSD > 1.4409, $\alpha = 0.05$). Additionally, the CS in cleft of all the briquettes produced from the mixture of the three species also differed significantly from that of the pure species (LSD > 1.4409, $\alpha = 0.05$). Post hoc comparison of means of CS in cleft of briquettes produced for CP levels 50, 40, 30 and 20 MPa (**Appendix 14c**) showed significant difference at 5% level of significance (LSD > 1.0892, $\alpha = 0.05$). This result is similar to that obtained for other materials in this study.

Impact resistance index of briquettes produced from mixture of *P. africana*, *T. superba* and *C. pentandra*

In **Table 4.41** is indicated the result of IRI of briquettes produced from *P. africana*, *T. superba* and *C. pentandra* as well as their combinations. The IRI of briquettes produced from the mixture of the three species ranged from 133% for mixing ratio 40 : 30 : 30 pressed with CP level 20 MPa to 400% corresponding to mixing ratio 30 : 30 : 40 and pressed at CP level

50 MPa. All the briquettes produced from the mixed sawdust of the three species were greater than the targeted value of 100%. Thus, briquettes produced from this mixed species had adequate IRI. The result also indicates that with the exception of briquettes produced from mixing ratio 40:30:30 and pressed at CP level 50 MPa all the briquettes produced from

Table 4.41: Impact resistance index (%) of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination using compacting pressure level 20 to 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure			
		20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	200	283	317	350
T. superba	Pure	133	192	233	283
P. africana	Pure	72	137	184	217
P. africana : *T. superba* : *C. pentandra*	40 : 30 : 30	133	150	192	217
P. africana : *T. superba* : *C. pentandra*	30 : 40 : 30	150	175	233	350
P. africana : *T. superba* : *C. pentandra*	30 : 30 : 40	175	233	300	400
P. africana : *T. superba* : *C. pentandra*	1 : 1 : 1	133	200	250	300

this mixed species had IRI greater than their corresponding values for that produced from pure species of *P. africana*. Thus, briquettes made from combination of the three species have better IRI than those made from only *P. africana*. Additionally, all the briquettes produced from the mixed species of *P. africana, T. superba* and *C. pentandra* had IRI lower than that produced from *C. pentandra* only. Thus, when sawdust of *C. pentandra* is mixed with *P. africana* and *T. superba* the IRI of the briquettes produced from the mixture is lowered. Nevertheless, even though the IRI is lowered it was still higher than the targeted value of 100%. It could also be observed from **Table 4.41** that briquettes' IRI for all the mixing ratios increased with increasing CP levels.

Appendix 15a indicates the result of a two-way analysis of variance of the effect of biomass raw material (*P. africana*, *T. superba* and *C. pentandra* as well as their combinations), CP and their interaction on the IRI of briquettes produced. The result indicates that at 5% level of significance the biomass raw material and CP has significant effect on the IRI of briquettes produced (p-value < 0.05). However, the interaction between biomass raw material and CP level at 5% level of significance did not have any significant effect on the IRI of briquettes produced (p-value > 0.05). The multiple coefficient of determination (R^2) and RMSE for the ANOVA model were 0.5514 and 77.7988 respectively. The R^2 value of 0.5514 means that about 55.14% of the variability in the IRI of the briquettes produced from the mixture of the three species could be explained by variables involved.

Post hoc multiple comparison of means of IRI of briquettes produced from the biomass materials (*P. africana*, *T. superba*, *C. pentandra* and their combinations) presented in **Appendix 15b** indicates that the IRI of briquettes produced from the mixing ratio 30 : 30 : 40 does not significantly differ from that made from *C. pentandra* only (LSD < 48.746, α = 0.05). This means that the IRI of briquettes made from mixing 30 : 30 : 40 will not significantly differ from that made from *C. pentandra* only. The IRI of briquettes made from mixing ratios of 30 : 40 : 30, 1 : 1 : 1 and 40 : 30 : 30 did not differ from each other as well as that made from *T. superba* only (LSD < 48.746, α = 0.05). This also means that the IRI of briquettes produced from mixing ratios 30 : 40 : 30, 1 : 1 : 1 and 40 : 30 : 30 will not significantly differ from that made from *T. superba* only. Post hoc multiple comparison of means of IRI of briquettes (**Appendix 15c**) for CP levels 50, 40, 30 and 20 MPa showed significant difference for the CP levels (LSD > 36.849, α = 0.05). This is due to the fact that higher levels of CP result in the formation of briquettes that are more compact and have stronger intermolecular bonds. This therefore reduces it tendency to break apart when dropped from a height.

Water resistance quality of briquettes produced from mixture of *P. africana*, *T. superba* and *C. pentandra*

In **Table 4.42** is presented the result of briquettes' WR quality for *P. africana*, *T. superba*, *C. pentandra* and their combination. The WR quality of the briquettes produced from the mixture of the three species ranged from 1.12 to 1.75 minutes. These values of WR quality could be classified as very low (WR quality < 5 minutes). According to Križan (2007) briquettes for which when dipped into water falls into pieces sooner than 5 minutes are considered as having a very low WR quality.

Table 4.42: Water resistance quality (minutes) of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination using compacting pressure levels 20 to 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure			
		20 MPa	30 MPa	40 MPa	50 MPa
C. pentandra	Pure	2.76	3.19	3.82	4.81
T. superba	Pure	2.92	3.26	3.81	3.94
P. africana	Pure	0.62	0.69	0.69	0.70
P. africana : *T. superba* : *C. pentandra*	40 : 30 : 30	1.12	1.23	1.31	1.50
P. africana : *T. superba* : *C. pentandra*	30 : 40 : 30	1.26	1.27	1.31	1.62
P. africana : *T. superba* : *C. pentandra*	30 : 30 : 40	1.43	1.39	1.47	1.75
P. africana : *T. superba* : *C. pentandra*	1 : 1 : 1	1.31	1.29	1.33	1.56

The result also indicates that all the briquettes made from the mixture of the three species had WR quality higher than that made from *P. africana* only. Thus, mixing sawdust of *P. africana* with that of *T. superba* and *C. pentandra* could enhance the WR quality of briquettes produced from *P. africana* sawdust. On the contrarily briquettes produced from mixing ratio 30 : 30 : 40, due to the higher proportions of *C. pentandra* in the mixture had the highest WR quality for all CP levels. WR quality of briquettes made from the combination of *P. africana*, *T. superba* and *C. pentandra* were lower than that produced from *T. superba* or *C. pentandra* only. This suggest that introduction of *P. africana* sawdust into that of a mixture of *T. superba* and *C. pentandra* and pressed with low compacting pressure at room temperature could tremendously reduce the water resistance quality of briquettes produced.

In **Appendix 16a** is presented the result of a two-way ANOVA of the effect of biomass raw materials (*P. africana*, *T. superba*, *C. pentandra* and their combination), CP and their interaction on WR quality of briquettes produced. The result indicates that at 5% level of significance the biomass raw material, CP and their interactions had significant effect on the WR quality of briquettes produced (p-value < 0.05). The multiple coefficient of determination value (R^2) and the RMSE of the ANOVA Model were 0.9864 and 0.1487 respectively. The R^2 value of 0.9864 means that about 98.64% of the variance in the WR quality of briquettes produced could be explained by the biomass materials, CP and their interactions. Post hoc multiple comparison of means of WR quality of briquettes produced from the biomass material and their combination in mixing ratios of 40 : 30 : 30, 30 : 40 : 30, 30 : 30 : 40 and 1 : 1 : 1 is as indicated in **Appendix 16b.** The result shows that the WR quality of briquettes produced from mixing ratios 1 : 1 : 1, 30 : 40 : 30 and 40 : 30 : 30 did not significantly differed from each other (LSD < 0.0932, $\alpha = 0.05$). However, at 5% level of significant the WR quality of the three significantly differed from that made from the mixing ratio 30 : 30 40 and that made from the pure species of *P. africana*, *T. superba* and *C. pentandra* (LSD > 0.0932, $\alpha = 0.05$). The above result suggests that producing briquettes from a mixture of *P. africana*, *T. superba* and *C. pentandra* at mixing ratio 1 : 1 : 1, 30 : 40 : 30 and 40 : 30 : 30 would have similar WR strength. However, the best WR quality of briquettes could be obtained from the combination of *P. africana*, *T. superba* and *C. pentandra* when the mixing ratio is 30 : 30 : 40. Post hoc Multiple comparison of means of WR quality of briquettes for CP levels 20, 30, 40 and 50 MPa (**Appendix 16c**) showed significant difference for the CP levels (LSD > 0.0704, $\alpha = 0.05$). This is result does not deviate from that obtained earlier. This trend is due to the fact that higher levels of CP result in the formation of briquettes that are more compact and have stronger bonds. This therefore reduces it tendency to fall apart when dropped into water.

4.10 Physical and mechanical characteristics of briquettes produced from combination of sawdust and maize cobs

There is no single solution that will solve the current and future energy needs of Ghana. Any attempt to rectify the energy needs of Ghana requires diversifying the energy source. According to Zych (2008), energy production methods should be best matched with the available natural resources in the region. Ghana is an agricultural country. It has been estimated that about 70% of her total workforce is employed in the agricultural sub-sector of its economy (Boateng, 2005). Most farmers engage in the cultivation of crops like millet, rice, maize, sugar cane and cocoa. After harvesting, the residue of these crops (rice husk, millet stalks, sugar cane baggasse and cocoa husk) are either left to decay or burnt and in some few occasions they are uneconomically utilized as fuel. FAOSTAT (2010) estimated that in 2010 Ghana produced about 1,872,000 tonnes of maize cobs. Generally, agricultural wastes have low bulk density and this limit its utilization as fuel. One of the methods used to overcome this limitation and to enable them to be economically used as fuel is by densifying then. Densifying maize cobs will result in improved energy density, lower volume (higher bulk density), and better mechanical handling (Bhattacharya, *et al*., 1989; O'Grady, *et al*., 1980). However, agricultural wastes are noted to have low lignin content, a chemical that is mainly responsible for bonding during briquetting. Therefore densifying such material would require a high CP and/or an external binder. This invariably would result in increased production cost which could hinder its utilization. Thus, it is most advisable that in searching for a technique that could be used in densifying agricultural waste care is taken to avoid selecting a technique that could substantially lead to increased cost of the finished product. In this part of the study the researcher investigated into the effect of combining maize cobs and sawdust on the quality characteristics of briquettes produced.

4.10.1 Particle size of mixture of sawdust and maize cobs used for this part of the study

Particle size is a variable that has been found to have significant effect on the quality of briquettes produced. This was also confirmed by the result obtained in the earlier part of this study. In this part of the study the particle size of the biomass material used for the study was particle size less than 1mm. This particle size was selected because in the first part of the study briquettes produced from particle size less than 1mm showed better briquettes quality.

4.10.2 Relaxed density (kg/m^3) of briquettes produced from maize cobs and sawdust of *C. pentandra*, *T. superba* and *P. africana* using compacting pressure 20 - 50MPa

Figures 4.4a, b and **c** indicate the relationship between relaxed density and CP of briquettes produced from maize cobs only, and combination of *C. pentandra*, *T. superba*, *P. africana* and maize cobs particles for mixing ratios 90 : 10, 70 : 30 and 50 : 50 (Sawdust : Maize cobs). For the same mixing ratio, graphs having different letters (a, b, c, d) differ significantly at 5% level of significance. From **Figures 4.4a, b** and **c** and **appendix 17a, b** and **c** it could be deduced that the relaxed density of briquettes produced from maize cobs only ranged from 541 to 659 kg/m^3 whilst that produced from a mixture of *C. pentandra* and maize cobs particles ranged from 565 to 774 kg/m^3.

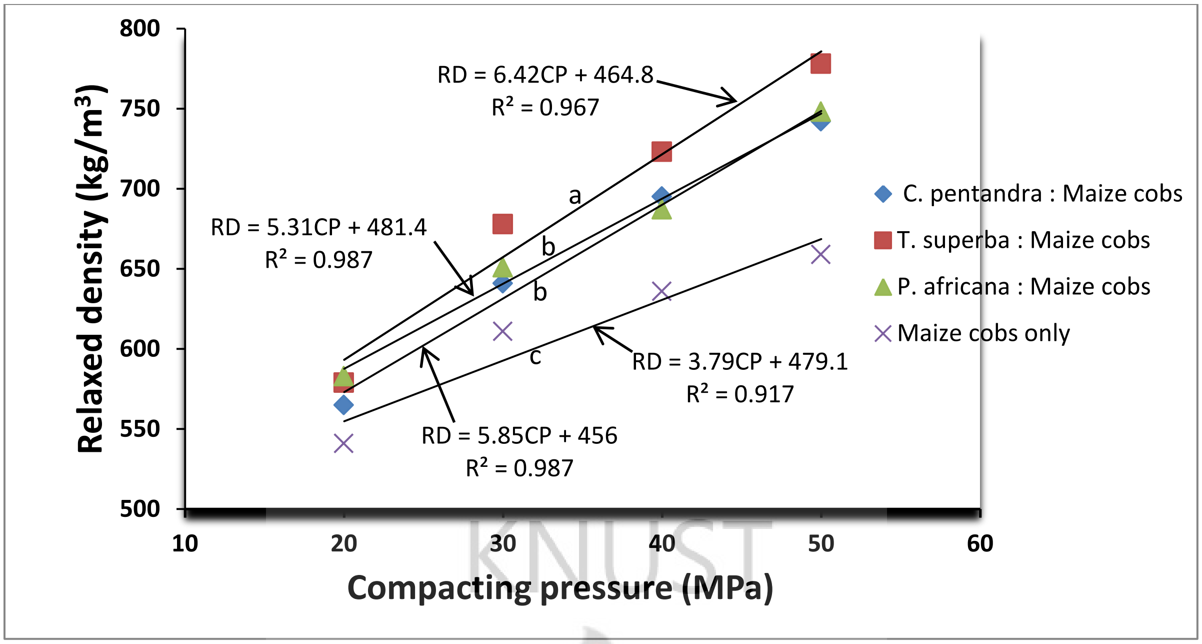


Figure 4.4a: Relationship between compacting pressure and relaxed density (RD) of briquettes produced from maize cobs particles and sawdust for mixing ratio 90 : 10

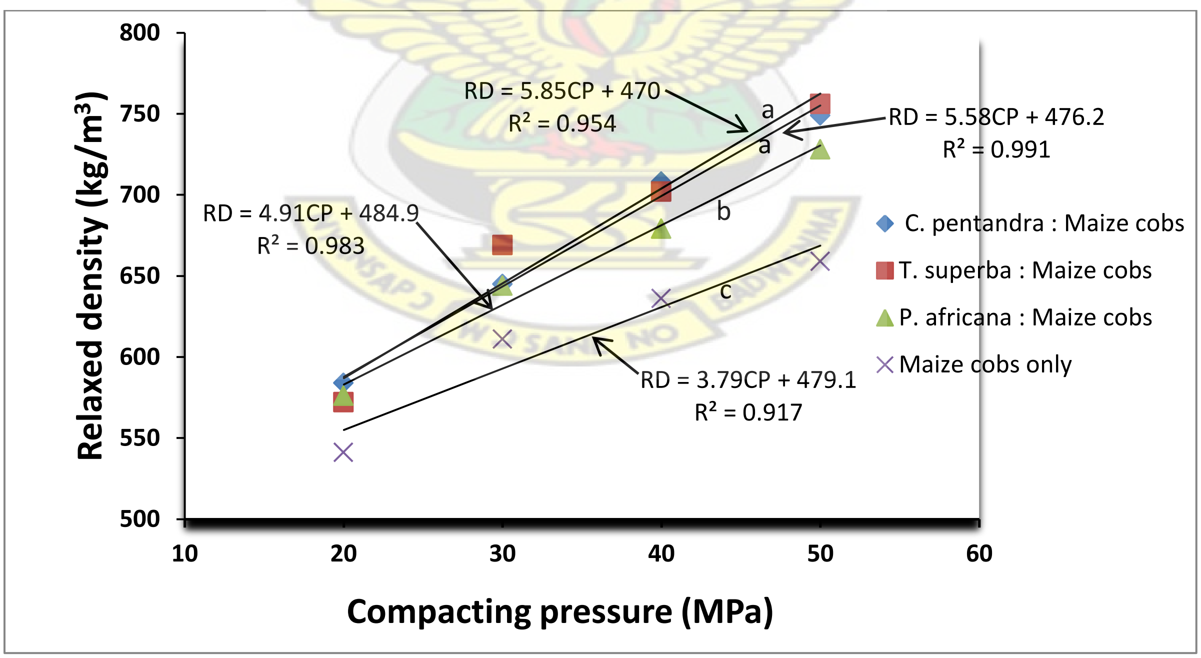


Figure 4.4b: Relationship between compacting pressure and relaxed density of briquettes produced from maize cobs particles and sawdust for mixing ratio 70 : 30

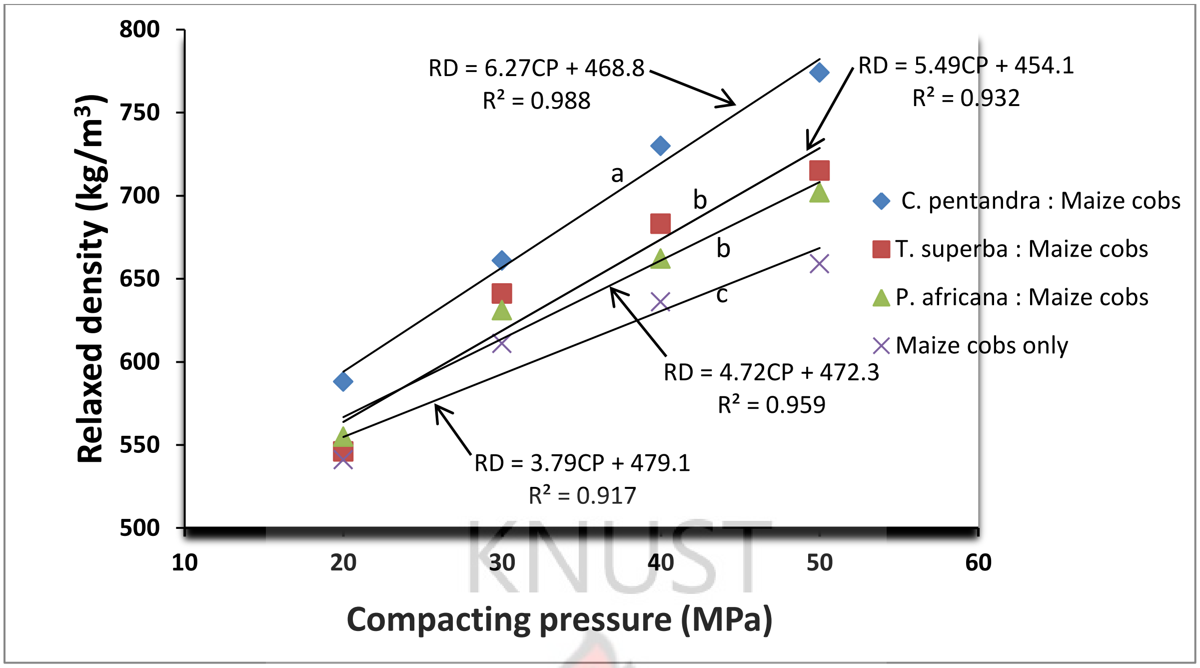


Figure 4.4c: Relationship between compacting pressure and relaxed density of briquettes produced from maize cobs particles and sawdust for mixing ratio 50 : 50

Additionally, the relaxed density of briquettes produced from combination of *T. superba* and maize cobs ranged from 546 to 778 kg/m^3 whilst that produced from combination of *P. africana* and maize cobs ranged from 555 to 748 kg/m^3. These values of relaxed densities for the briquettes produced could be considered adequate since they fall within the recommended values of relaxed density for briquette made using hydraulic press. Tumuluru *et al*. (2010) and Saeidy (2004) indicated that briquettes made from hydraulic piston press are usually less than 1000 kg/m^3 and are usually between 300 - 600 kg/m^3. It could also be deduced (**Figures 4.4a b & c**) that for all the three mixing ratios the relaxed density of briquettes produced from the mixed species were significantly higher than those produce from maize cobs particle only. This means that addition of sawdust of *C. pentandra*, *T. superba* or *P. africana* to maize cobs particles and pressed at low CP pressure without a binder could improve the relaxed density of briquettes produced from maize cobs. Furthermore, the graphs show that there exist a strong linear relationship between CP and relaxed density of briquettes produced. The R^2 values for the regression models of the graphs ranged from 0.917 to 0.997. This suggest that the regression models could predict more than 91% of the relaxed density of all the briquettes produced. The graphs also indicate that increase in CP resulted in an increase in relaxed density of briquettes produced. This is because for a fixed mass of biomass material increased in CP level will lead to the particles of the biomass material being closely packed. Therefore, leading to reduction in void spaces which resulted in increased density of the briquettes produced (Lindley & Vossoughi, 1989). Correlation analysis indicates that there was no significant correlation between proportions of *C. pentandra* and *P. africana* in the mixing ratio and relaxed density of briquettes produced (Pearson's $r_{(C.\ pentandra\ X\ RD)} = -0.166$, p-value = 0.102; N = 60, $\alpha = 0.05$, 1-tailed; Pearson's $r_{(P.\ africana\ X\ RD)} = 0.206$, p-value = 0.058; N = 60, $\alpha = 0.05$, 1-tailed). However, there was significant correlation between proportions of *T. superba* in the mixing ratio and relaxed density of briquettes produced (Pearson's $r_{(T.\ superba\ X\ RD)} = -0.248$, p-value = 0.028; N = 60, $\alpha = 0.05$, 1-tailed).

Analysis of variance **(Appendix 18)** to determine the effect of biomass material (i.e. Combinations of sawdust and maize cobs particles), mixing ratio, CP as well as their interaction on the relaxed density of briquette produced indicates that the biomass material, mixing ratio and CP at 5% level of significance, have significant effect on the relaxed density of briquettes produced (p-value < 0.05). Additionally, the interactions between biomass material and mixing ratio as well as biomass material and CP had significant effect on relaxed density of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE values of the ANOVA Model were 0.9667 and 13.69. There fore, it could be concluded that biomass material, mixing ratio and CP could explain about 96.67% of the variability in the relaxed density of the briquettes produced.

4.10.3 Compressive strength in cleft (N/mm) of briquettes produced from maize cobs and sawdust of *C. pentandra, T. superba, P. africana* using compacting pressure 20 - 50MPa

Presented in **Figures 4.5a, b** and **c** are graphs showing the relationship between CS in cleft and CP of briquettes produced from maize cobs only, and combination of *C. pentandra*, *T. superba*, *P. africana* and maize cobs particles for mixing ratios 90 : 10, 70 : 30 and 50 : 50 (Sawdust : Maize cobs). For the same mixing ratio, graphs having different letters (a, b, c, d) differ significantly in means of CS in cleft at 5% level of significance. From **Figures 4.5a, b** and **c** with the means indicated in **appendix 19a, b** and **c** it could be established that the

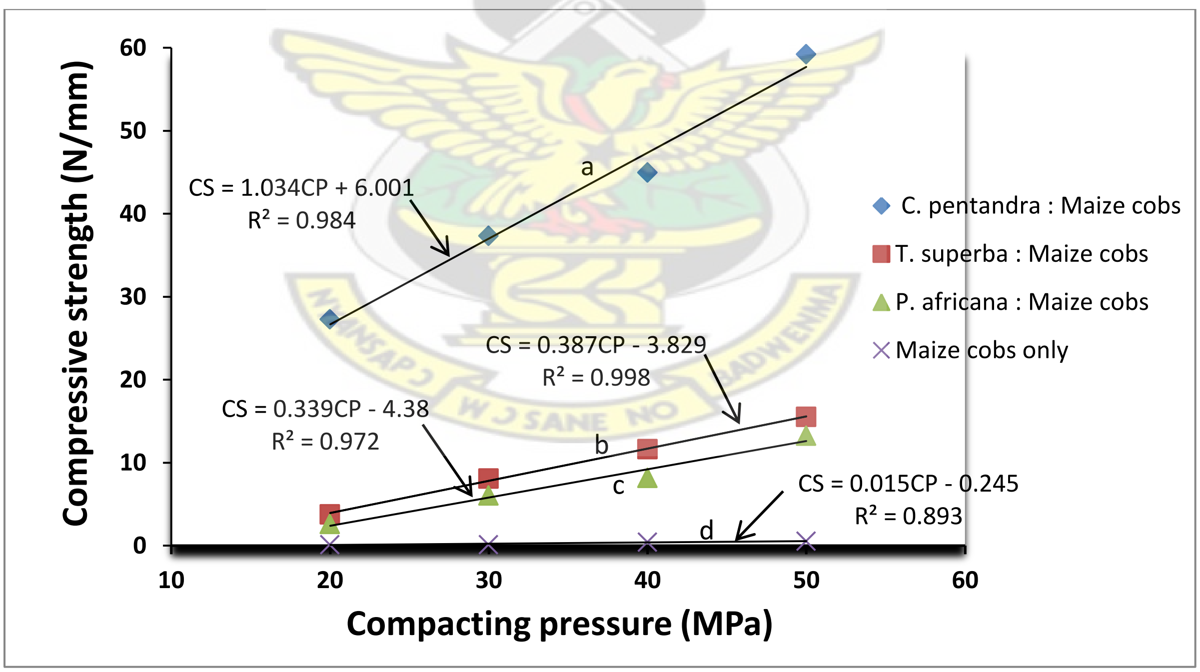


Figure 4.5a: Relationship between compacting pressure and compressive strength in cleft (CS) of briquettes produced from maize cobs particles and sawdust for mixing ratio 90 : 10

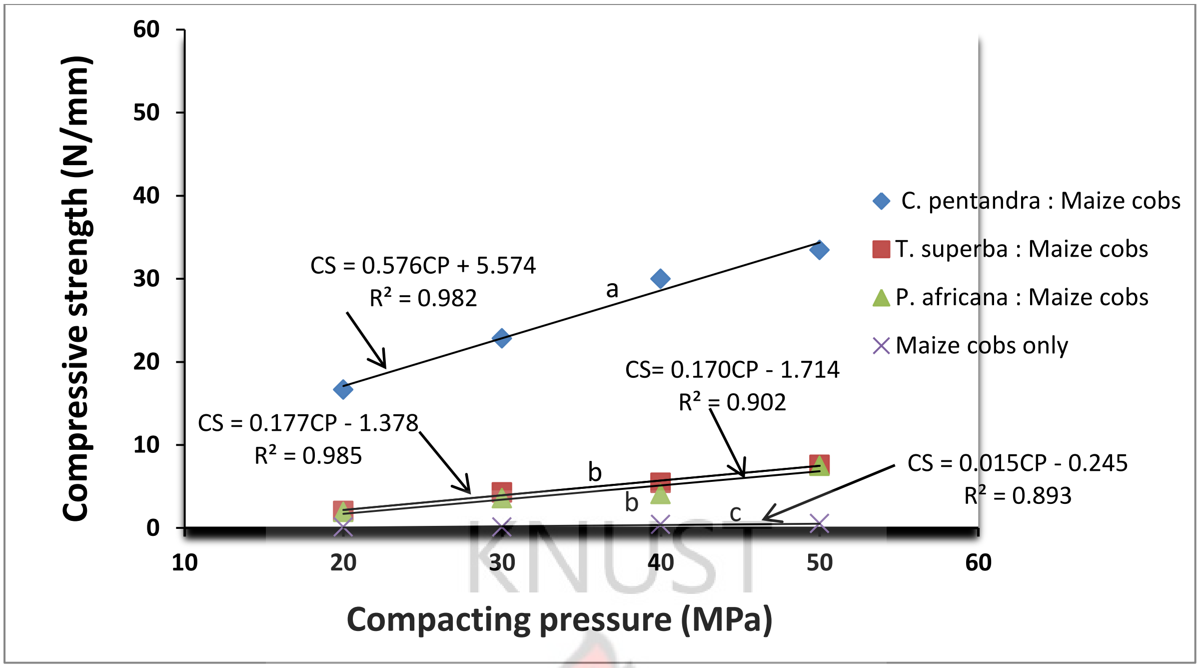


Figure 4.5b: Relationship between compacting pressure and compressive strength in cleft of briquettes produced from maize cobs particles and sawdust for mixing ratio 70 : 30

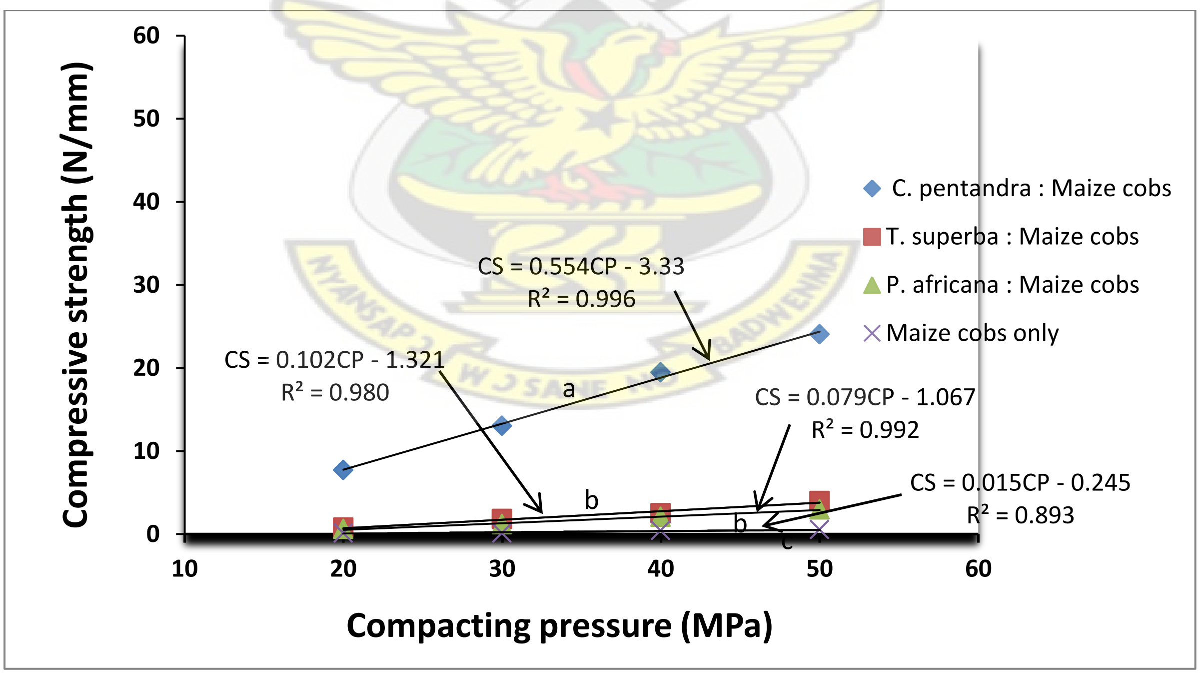


Figure 4.5c: Relationship between compacting pressure and compressive strength in cleft of briquettes produced from maize cobs particles and sawdust for mixing ratio 50 : 50

CS in cleft of briquettes produced from maize cobs only ranged from 0.12 to 0.54 N/mm whilst those from combination of *C. pentandra* and maize cobs ranged from 7.72 to 59.22 N/mm. Additionally, the CS in cleft of briquettes produced from combination *T. superba* and maize cobs ranged from 0.78 to 15.51 N/mm whilst that produced from combination *P. africana* and maize cobs 0.60 to 13.23 N/mm. From this result it could be concluded that briquettes produced from maize cobs particles using low CP without a binder will not have adequate CS in cleft for handling, storage and transporting (CS in cleft < 19.6 N/mm). With the exception of briquettes produced from mixing ratios 70 : 30 and pressed at CP level 20 MPa, all the briquettes produced from mixture of *C. pentandra* and maize cobs at mixing ratios 90 : 10 and 70 : 30 had adequate CS in cleft (CS in cleft > 19.6 N/mm). It could further be concluded from **Figure 4.5a, b** and **c** that for all the mixing ratios, briquettes produced from combination of *T. superba* and maize cobs, and *P. africana* and maize cobs did not have adequate CS in cleft (CS in cleft < 19.6 N/mm). The graphs depicted in **Figures 5a, b** and **c** indicate that for the same mixing ratio the mean CS in cleft of briquettes produced from *C. pentandra* and maize cobs combination was significantly greater than those produced from combination of *T. superba* and maize cobs, and *P. africana* and maize. The reason for this trend is that *C. pentandra* is a very low density species. Thus, particles of *C. pentandra* in the mixture has higher tendency to undergo plastic deformation when pressed using low CP therefore forming stronger bonds. This trend is consistent with the result in **Table 4.25** that species density negatively correlate with CS in cleft of briquettes produced.

Appendix 20 shows the result of ANOVA to determine the effect of biomass material, mixing ratio, CP as well as their interaction on the CS in cleft of briquette produced from combination of sawdust and maize cobs. The result indicates that the biomass material, mixing ratio and CP as well as their interactions at 5% level of significance, have significant effect on the CS in cleft of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE values of the ANOVA Model were 0.9925 and 1.34. Thus, it could therefore be concluded that biomass material, mixing ratio and CP could explain about 99.25% of the variability in the CS in cleft of the briquettes produced. **Figures 4.5a, b and c** also indicate that for each of the mixture there exist a strong linear relationship between CP and CS in cleft of the briquettes produced. The R^2 values for the regression models ranged from 0.893 to 0.998. Thus, there regression models could predict 89.3% or more of the CS in cleft of the briquettes produced from the various species mix and mixing ratios.

4.10.4 Impact resistance index (%) of briquettes produced from maize cobs and sawdust of *C. pentandra*, *T. superba*, *P. africana* using compacting pressure 20 - 50MPa

Indicated in **Figures 4.4a, b** and **c** are graphs that shows the relationship between IRI and CP of briquettes produced from maize cobs only, and combination of *C. pentandra*, *T. superba* or *P. africana* and maize cobs particles for mixing ratios 90 : 10, 70 : 30 and 50 : 50 (Sawdust : Maize cobs). At 5% level of significance graphs with the same letters (a, b, c, d), for each of the mixing ratios, do not significantly differ in means of IRI. It could be deduced from **Figures 4.6a, b** and **c**, and **appendix 21a, b** and **c** that the IRI of briquettes produced from maize cobs only was 0% whilst that produced from combination of *C. pentandra* and maize cobs ranged from 115 to 500%. Additionally, the IRI of briquettes produced from mixture of *T. superba* and maize cobs ranged from 0 to 300% whilst that produced from combination of *P. africana* and maize cobs ranged from 0 to 183%. The low IRI of briquettes produced from maize cobs particle only may be due to its low lignin content (5.6%), low water soluble carbohydrates (1.1%) and low protein (2.5%). These chemicals are largely responsible for forming solid bridge bonds during densification (Kaliyan & Morey, 2010; Mullen, *et al*. 2010).

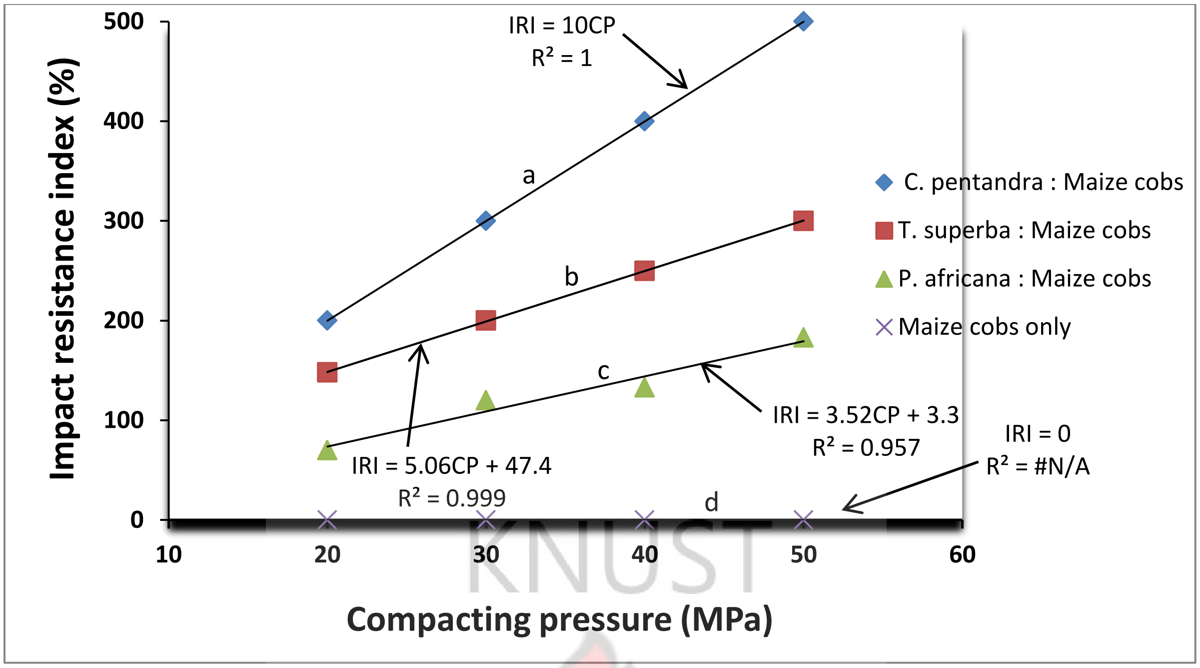


Figure 4.6a: Relationship between compacting pressure and impact resistance index (IRI) of briquettes produced from mixture of maize cobs particles and sawdust for mixing ratio 90 : 10

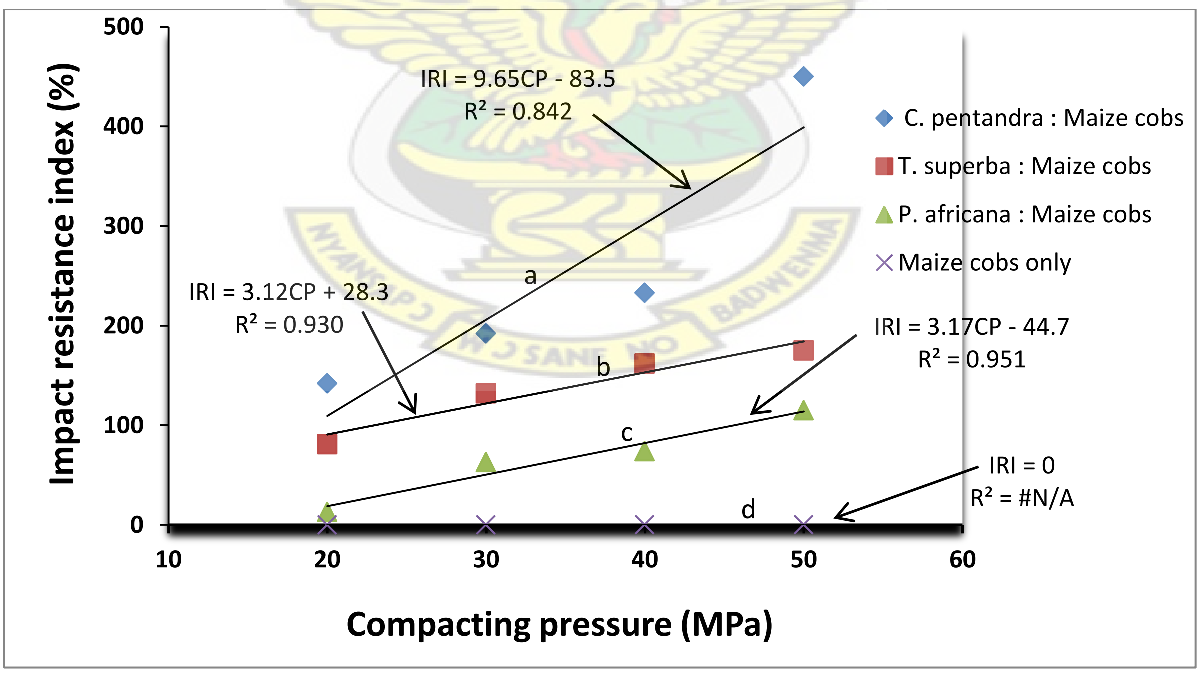


Figure 4.6b: Relationship between compacting pressure and impact resistance index of briquettes produced from mixture of maize cobs particles and sawdust for mixing ratio 70 : 30

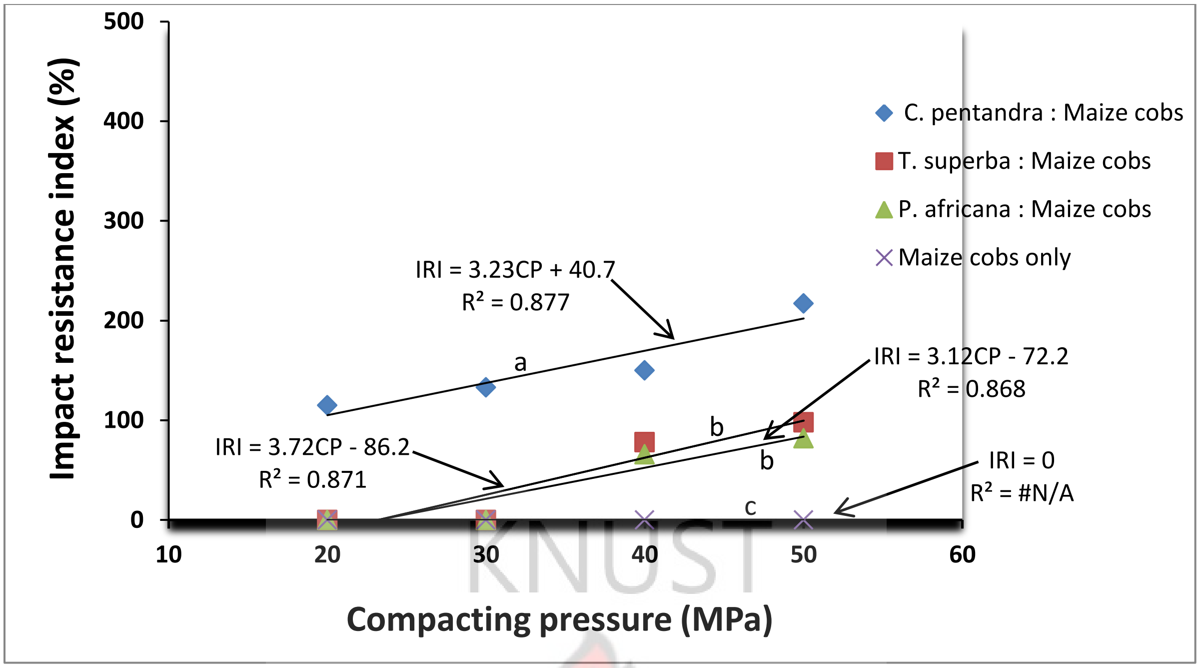


Figure 4.6c: Relationship between compacting pressure and impact resistance index of briquettes produced from mixture of maize cobs particles and sawdust for mixing ratio 50 : 50

All the briquettes made from combination of *C. pentandra* and maize cobs had adequate IRI (IRI > 100%). According to the Italian standard for briquettes/pallets CTI-R04/5, briquettes durability greater or equal to 97.7% is adequate for handling, storage and transporting (Italian standard for briquettes/pallets CTI-R04/5 as cited in Hahn, 2004). Therefore, it could be concluded that sawdust of *C. pentandra* could be added to maize cobs particles to improve the IRI of briquettes produced from maize cobs.

As show on **Figures 4.6a, b** and **c**, for all the three mixing ratios (90 : 10, 70 : 30 and 50 : 50), the mean IRI of briquettes produced from combination of *C. pentandra* and maize cobs was significantly higher than those produced from combinations of *T. superba* and maize cobs, and *P. africana* and maize cobs. This is due to the fact that the density of wood species negatively correlate with IRI of briquettes produced (**Table 4.25**) at low CP without a binder. Therefore, the low density of *C. pentandra* in the mixture contributed significantly to the higher IRI of briquettes produced from mixture of *C. pentandra* and maize cobs. There also exit a strong linear relationship between CP and IRI of briquettes produced from combination of sawdust and maize cobs for all the mixing ratios. The R^2 values for the regression models ranged from 0.842 to 1.0. Therefore, the regression models could predict more than 84% of the IRI of the briquettes produced.

Appendix 22 shows the result of ANOVA to determine the effect of biomass material, mixing ratio, CP as well as their interaction on the IRI of briquette produced from combination of sawdust and maize cobs. The result indicates that the biomass material, mixing ratio and CP as well as their interactions at 5% level of significance, have significant effect on the IRI of briquettes produced (p-value < 0.05). The multiple coefficient of determination (R^2) and RMSE values of the ANOVA Model were 0.8837 and 48.12. Thus, it could therefore be concluded that biomass material, mixing ratio and CP could explain about 88.37% of the variability in the IRI of the briquettes produced.

4.10.5 Thermal properties of *C. pentandra*, maize cobs and their combination

The gross calorific value (GCV), percentage ash content, organic carbon, nitrogen and sulphur content of maize cobs, sawdust of *C. pentandra,* and their mixture in varying ratio are presented in **Table 4.43**. **Table 4.43** also includes the Austria and Germany standards for fuel pellets, Austria ÖNORM M7135 and Germany DIN 51731 / DINplus respectively.

Calorific value

The result in (**Table 4.43**) indicates that the GCV of mixed species of maize cobs and *C. pentandra* ranged from 20.13 to 20.57 MJ/kg. The GCV for the individual mixing ratios (*C. pentandra* : maize cobs) are as follows: 90 : 10 = 20.13 MJ/kg, 70 : 30 = 20.39 MJ/kg and 50 : 50 = 20.57 MJ/kg. The GCV of the mixed species were higher than that obtained from maize cobs only which was 19.79 MJ/kg. The heating values of this mixed species could be considered to be adequate since they are greater than the minimum acceptable values suggested by the Austria and Germany standards for fuel pellets (Austria ÖNORM M7135, Calorific value ≥18.0 MJ/kg; Germany DIN 51731 / DINplus, Calorific value 17.5 MJ/kg - 19.5 MJ/kg).

Table 4.43: Fuel properties of *C. pentandra*, maize cobs, their mixture and Austria and Germany standards for fuel pellets

Biomass material	**Mixing ratio (Weight basis)**	**Gross calorific value (MJ/kg)**	**Ash (%)**	**Organic Carbon (%)**	**N (%)**	**S (%)**
Maize cobs	Pure	19.79	1.6362	57.05	0.6400	0.0722
C. pentandra	Pure	20.33	4.7248	55.26	0.4817	0.0458
C. pentandra : Maize cobs	90 : 10	20.13	4.1424	55.60	0.4130	0.0500
C. pentandra : Maize cobs	70 :30	20.39	3.2895	56.10	0.4100	0.0596
C. pentandra : Maize cobs	50 : 50	20.57	3.2772	56.09	0.5250	0.0678
Austria ÖNORM M7135		≥18.0	≤ 6.0	-	≤ 0.6	≤ 0.08
Germany DIN 51731 / DINplus		17.5 - 19.5	< 1.5	-	< 0.3	< 0.08

Source of information for national standards for fuel pellets (Austria and Germany): Hahn, (2004)

Additionally, the heating values of the sawdust of all the mixed species studied were higher than that suggested by Corder (1976), Stahl, *et al*. (2004) and Jain (1991) for woody biomass. Corder (1976) in his study on fuel characteristics of wood and bark and factors affecting heat recovery concluded that woody biomass has an average heating density of 19.8 MJ/kg. Stahl, *et al*. (2004) in a report on definition of a standard biomass stated that the calorific values for most woody materials are between 17 - 19 MJ/kg; for agricultural residues, the heating values are about 15 - 17 MJ/kg. The high calorific value of the mixture of the maize cobs and *C. pentandra* may be due to their low moisture content of between 8.90 to 9.65%. Biomass materials with higher moisture content are lower since part of the heat energy is used in drying out the moisture.

Ash content

In the fourth colum of **Table 4.43** is presented the ash content of maize cobs, *C. pentandra* and their combination (*C. pentandra*: maize cobs) in the mixing ratio of 90 : 10, 70 : 30 and 50 : 50. The ash content of the mixed species varied from 3.2772 to 4.1424%. The ash content for the individual mixing ratios (*C. pentandra*: maize cobs) are as follows: 90 : 10 = 4.1424%, 70 : 30 = 3.2895% and 50 : 50 = 3.2772%. These values are lower than 6%, that is, the value considered to be adequate for biomass fuel according to the Austria ÖNORM M7135. However, that for mixing ratio 90 : 10 is higher than 4% the value beyond which slagging would occur. Grover and Mishra (1996) indicated that slagging of ash usually occurs with biomass fuels when the ash content is more than 4%. Thus, it is likely that when maize cobs is mixed with *C. pentandra* at mixing ratio 90 : 10 and used as fuel slagging would occur.

Organic carbon, nitrogen and sulphur content of mixture of *C. pentandra* and maize cobs

The organic carbon, nitrogen and sulphur content of maize cobs, *C. pentandra* and their combination are presented in **Table 43**, **colums 5, 6** and **7** respectively. The organic carbon content of the mixed species ranges from 55.60% (mixing ratio 90 : 10) to 56.10% (mixing ratio 70 : 30). That for the remaining ratio 50 : 50 is 56.09%. Fixed carbon gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Akowuah, *et al*., 2012). The higher the carbon content the more heat it will generate. The carbon content of the mixed species is higher than that of the average value for woody biomass which was estimated to varies from about 47 to 53% due to varying lignin and extractives content (Ragland & Aerts, 1991).

The nitrogen content of the maize cobs *C. pentandra* mixed biomass materials is indicated in **Table 4.43**, **column 6**. The nitrogen content is a good indicator of the amount of nitrogen-based toxic components that can be formed during burning. The result shows that the nitrogen content of the mixed species ranged from 0.4100 (mixing ratio 70 : 30) to 0.5250% (mixing ratio 50 : 50). That for the remaining ratio 90 : 10 is 0.4130. For all the mixed materials the nitrogen content were lower than the safe limit set by the Austria national standard i.e. Austria ÖNORM M7135 (i.e. Nitrogen content ≤ 0.6%). However, they were high than the safe limit set by Germany DIN 51731 / DINplus (i.e. Nitrogen content < 0.3. High levels of nitrogen in fuels results in the formation of high levels of nitrogen oxides. Nitrogen oxide plays an important role in atmospheric reactions therefore creating ozone and acidic rain through formation of nitric acid. Exposure to nitrogen oxides increases the risk of respiratory infections as it is highly toxic and irritating to the respiratory system (Sillman, 2003).

In **Table 4.43** is indicated the sulphur content of the mixed biomass materials studied. The sulphur content of the mixed species are as follows: 90 : 10 = 0.0500, 70 : 30 = 0.0596, 50 : 50 = 0.0678. These values are lower than the limits set by the Austria and German national standards for fuel pellet; Austria ÖNORM M7135 (i.e. Sulphur content ≤ 0.08%), Germany DIN 51731 / DINplus (i.e. Sulphur content ≤ 0.08%) for biomass fuels. Thus, when these materials are used as fuels they would emit sulphur compounds less than the acceptable limits into the atmosphere. This would not have serious effect on both the environment and human health.

4.10.6 Thermal properties of *T. superba*, maize cobs, and their combination

In **Table 4.44** is presented the gross calorific value (GCV), percentage ash content, organic carbon, nitrogen and sulphur content of maize cobs, *T. superba* and their combination in mixing ratios 90 : 10, 70 : 30 and 50 : 50. It also includes the Austria and Germany standards for fuel pellets Austria, ÖNORM M7135 and Germany DIN 51731 / DINplus respectively.

Calorific value

The result in **Table 4.44** indicates that the GCV of mixed species of maize cobs and *T. superba* ranged from 20.95 to 21.64 MJ/kg. The GCV for the individual mixing ratios

Table 4.44: Fuel properties of *T. superba*, maize cobs, their mixture, and Austria and Germany standards for fuel pellets

Biomass material	Mixing ratio (Weight basis)	Gross calorific value (MJ/kg)	Ash (%)	Organic Carbon (%)	N (%)	S (%)
Maize cobs	Pure	19.79	1.6362	57.05	0.6400	0.0722
T. superba	Pure	22.22	2.9574	56.29	0.6213	0.0561
T. superba : Maize cobs	90 : 10	21.64	3.5284	55.95	0.6030	0.0568
T. superba : Maize cobs	70 : 30	20.95	2.8614	56.34	0.6100	0.0638
T. superba : Maize cobs	50 : 50	21.42	2.2813	56.68	0.6200	0.0653
Austria ÖNORM M7135		≥18.0	≤ 6.0	-	≤ 0.6	≤ 0.08
Germany DIN 51731 / DINplus		17.5-19.5	< 1.5%	-	< 0.3	< 0.08

Source of information for national standards for fuel pellets (Austria and Germany): Hahn, (2004) (*T. superba* : maize cobs) are as follows: 90 : 10 = 21.64 MJ/kg, 70 : 30 = 20.95 MJ/kg and 50 : 50 = 21.42 MJ/kg. The GCV of the mixed species were higher than that obtained from maize cobs only which was 19.79 MJ/kg. The heating values of the mixed species could be considered to be adequate since they are greater than the minimum acceptable values suggested by the Austria and Germany standards for fuel pellets (Austria ÖNORM M7135, Calorific value ≥18.0 MJ/kg; Germany DIN 51731 / DINplus, Calorific value 17.5 - 19.5 MJ/kg). Additionally, the heating values of all the mixed biomass materials studied were higher than that suggested by Corder (1976), Stahl, *et al*. (2004) and Jain (1991) for woody biomass. Corder (1976) in his study on fuel characteristics of wood and bark and factors affecting heat recovery concluded that woody biomass has an average heating density of 19.8 MJ/Kg. Stahl, *et al*. (2004) in a report on definition of a standard biomass stated that the calorific values for most woody materials are between 17 - 19 MJ/kg; for agricultural residues, the heating values are about 15 - 17 MJ/kg. The high calorific value of the mixture of maize cobs and *T. superba* may be due to the high calorific value of *T. superba* compared to that of maize cobs. Additionally, the mixture has a lower moisture content of between 9.22 to 9.27%. Biomass materials with high moisture content have lower calorific value since part of it heat energy is used in drying out the moisture.

Ash content

The ash content of maize cobs, *T. superba* and their combination are presented in **Table 4.44**. The ash content of the mixed biomass materials (maize cobs and *T. superba*) varied from 2.2813 to 3.5284%. The ash content for the mixing ratios (*T. superba* : maize cobs) are as follows: 90 : 10 = 3.5284%, 70 : 30 = 2.8614% and 50 : 50 = 2.2813%. The ash content of all the mixed species of *T. superba* and maize cobs were lower than 6%, that is, the value considered to be adequate for biomass fuel according to the Austria ÖNORM M7135. Additionally, the ash content of the mixed species were lower than 4%, the value beyond which slagging would occur. Grover and Mishra (1996) indicated that slagging of ash usually occurs with biomass fuels when the ash content is more than 4%. It is therefore likely that when maize cobs is mixed with *T. superba* and used as a fuel slagging would not occur.

Organic carbon, nitrogen and sulphur content of mixture of *T. superba* and maize cobs

The organic carbon, nitrogen and sulphur content of maize cobs, *T. superba* and their combination are presented in the **colums 5**, **6** and **7** respectively of **Table 4.44**. The organic carbon content of the mixed biomass materials ranged from 55.95% (mixing ratio 90 : 10) to 56.68% (mixing ratio 50 : 50). That for the mixing ratio 70 : 30 is 56.34%. Fixed carbon gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Akowuah, *et al*., 2012). The higher the carbon content the more heat it will generate. The carbon content of the mixed species is higher than that of the average value for woody biomass which was estimated to vary from about 47 to 53% due to varying lignin and extractives content (Ragland & Aerts, 1991).

The nitrogen content of maize cobs and *T. superba* mixed biomass materials is indicated in **Table 4.44**, **column 6**. The nitrogen content is a good indicator of the amount of nitrogen-based toxic components that can be formed during burning. The result shows that the nitrogen content of the mixed species ranged from 0.6030 (mixing ratio 90 : 10) to 0.6200% (mixing ratio 50 : 50). The nitrogen content for the mixing ratio 70 : 30 = 0.6100. The nitrogen content for all the mixed material were lower than the safe limit set by the Austria national standard i.e. Austria ÖNORM M7135 (i.e. Nitrogen content ≤ 0.6%). However, they were higher than the safe limit set by Germany DIN 51731 / DINplus (i.e. Nitrogen content < 0.3. High levels of nitrogen in fuels results in the formation of high levels of nitrogen oxides. Nitrogen oxide plays an important role in atmospheric reactions therefore creating ozone and acidic rain by the formation of nitric acid. Exposure to nitrogen oxides increases the risk of respiratory infections as it is highly toxic and irritating to the respiratory system (Sillman, 2003).

Sulfur is oxidized during combustion to form sulfur oxide (SOx). This compound can have serious environmental effects and causes the acidification of soils and water (Extension, 2010). The sulphur content of the mixed species as indicated in **Table 4.44** are as follows: 90 : 10 = 0.0568, 70 : 30 = 0.0638 and 50 : 50 = 0.0653. The sulphur contents of all the mixed species were lower than the limits set by the Austria and German national standards for fuel pellet; Austria ÖNORM M7135 (i.e. Sulphur content ≤ 0.08%), Germany DIN 51731/ DINplus (i.e. Sulphur content ≤ 0.08%) for biomass fuels. Thus, when these materials are used as fuels they would emit sulphur compounds less than the acceptable limits into the atmosphere. This would not have serious effect on both the environment and human health.

4.10.7 Thermal properties of *P. africana*, maize cobs, and their combination

The gross calorific value (GCV), percentage ash content, organic carbon, nitrogen and sulphur content of maize cobs, sawdust of *P. africana*, and their mixture in ratio of 90 : 10, 70 : 30, 50 : 50 are presented in **Table 4.45**. **Table 4.45** also includes the Austria and Germany standards for fuel pellets, Austria ÖNORM M7135 and Germany DIN 51731/DINplus respectively.

Calorific value

The result, **Table 4.45 colum 3** indicates that the GCV of mixed species of maize cobs and *P. africana* ranged from 22.12 to 23.68 MJ/kg. The GCV for the individual mixing ratios (*P. africana* : maize cobs) are as follows: 90 : 10 = 23.68 MJ/kg, 70 : 30 = 22.96 MJ/kg and 50 : 50 = 22.12 MJ/kg. The GCV of the mixed species were higher than that obtained from both maize cobs and *P. africana* only which were 19.79 MJ/kg and 22.17 M/kg respectively. The heating values of this mixed species could be considered to be adequate since they are greater

Table 4.45: Fuel properties of *P. africana*, maize cobs, their mixture and Austria and Germany standards for fuel pellets/briquettes

Biomass material	**Mixing ratio (Weight basis)**	**Gross calorific value (MJ/kg)**	**Ash (%)**	**Organic Carbon (%)**	**N (%)**	**S (%)**
Maize cobs	Pure	19.79	1.6362	57.05	0.6400	0.0722
P. africana	Pure	22.17	0.6075	57.65	0.7133	0.0475
P. africana : Maize cobs	90 : 10	23.68	1.0713	57.38	0.6300	0.0515
P. africana : Maize cobs	70 : 30	22.96	1.0196	57.41	0.6180	0.0678
P. africana : Maize cobs	50 : 50	22.12	1.4287	57.17	0.618	0.0703
Austria ÖNORM M7135		≥ 18.0	≤ 6.0	-	≤ 0.6	≤ 0.08
Germany DIN 51731 / DINplus		17.5 - 19.5	< 1.5%	-	< 0.3	< 0.08

Source of information for national standards for fuel pellets (Austria and Germany): Hahn, (2004)

than the minimum acceptable values suggested by the Austria and Germany standards for fuel pellets (Austria ÖNORM M7135, Calorific value ≥18.0 MJ/kg; Germany DIN 51731 / DINplus, Calorific value 17.5 - 19.5 MJ/kg). Additionally, the heating values of the mixture of maize cobs and *P. africana* were higher than that suggested by Corder (1976), Stahl, *et al*. (2004) and Jain (1991) for woody biomass. Corder (1976) in his study on fuel characteristics of wood and bark and factors affecting heat recovery concluded that woody biomass has an average heating density of 19.8 MJ/kg. Stahl, *et al*. (2004) in a report on definition of a standard biomass stated that the calorific values for most woody materials are between

17 - 19 MJ/kg; for agricultural residues, the heating values are about 15 - 17 MJ/kg. The high calorific value of the mixture of the maize cobs and *P. africana* may be due to their low moisture content of between 9.24 to 9.78%. Biomass materials with higher moisture content have relatively lower calorific value since part of it heat energy is used in drying out the moisture.

Ash content

The fourth colum of **Table 4.45** is indicated the ash content of maize cobs, *P. africana* and their combination (*P. africana* : maize cobs) in the mixing ratio of 90 : 10, 70 : 30 and 50 : 50. The ash content of the mixed species varied from 1.0196 to 1.4287%. That for the individual mixing ratios (*P. africana* : maize cobs) are as follows: 90 : 10 = 1.0713%, 70 : 30 = 1.0196% and 50 : 50 = 1.4287%. These values are lower than 6%, that is, the maximum value of ash considered to be adequate for biomass fuel according to the Austria ÖNORM M7135. Additionally, the ash content for all the mixed species were lower than 4%, the value beyond which slagging would occur. Grover and Mishra (1996) indicated that slagging of ash usually occurs with biomass fuels when the ash content is more than 4%. Thus, it is likely that when maize cobs is mixed with *P. africana* and used as fuel slagging would not occur.

Organic carbon, nitrogen and sulphur content of *P. africana,* maize cobs and their mixture

The organic carbon, nitrogen and sulphur content of *P. africana*, maize cobs and their combination are presented in **Table 4.45**, **colums 5**, **6** and **7** respectively. The organic carbon content of the mixed species ranges from 57.17% (mixing ratio 50 : 50) to 57.41% (mixing ratio 70 : 30). That for the remaining ratio which is 90 : 10 is 57.38%. Fixed carbon gives a rough estimate of the heating value of a fuel and acts as the main heat generator during burning (Akowuah, *et al*., 2012). The higher the carbon content the more heat it will generate. The carbon content of the mixed species is higher than that of the average value for woody biomass which was estimated to varies from about 47 to 53% due to varying lignin and extractives content (Ragland & Aerts, 1991).

In **Table 4.45, column 6** is presented the nitrogen content of *P. africana*, maize cobs and their combinanation. The result shows that the nitrogen content of the mixture of *P. africana* and maize cobs ranged from 0.6180% (mixing ratio 70 : 30, 50 : 50) to 0.6300% (mixing ratio 90 : 10). The nitrogen content for all the mixed species as well as the pure once were higher than the safe limit set by the Austria national standard i.e. Austria ÖNORM M7135 (i.e. Nitrogen content ≤ 0.6%). Nitrogen content is a good indicator of the amount of nitrogen-based toxic components that can be formed during burning. High levels of nitrogen in fuels results in the formation of high levels of nitrogen oxides. Nitrogen oxides plays an important role in atmospheric reactions therefore creating ozone and acidic rain by the formation of nitric acid. Exposure to nitrogen oxides increases the risk of respiratory infections as it is highly toxic and irritating to the respiratory system (Sillman, 2003).

In **Table 4.45 colum 7** is presented the sulphur content of the mixed species studied as well as their individual materials of maize cobs and *P. africana*. The sulphur content of the mixed species are as follows: 90 : 10 = 0.0515, 70 : 30 = 0.0678, 50 : 50 = 0.0703. That of maize cobs and *P. africana* is 0.0722 and 0.0475 respectively. The sulphur content of all the mixed materials as well as the pure once are lower than the limits set by the Austria and German national standards for fuel pellet; Austria ÖNORM M7135 (i.e. Sulphur content ≤ 0.08%), Germany DIN 51731 / DINplus (i.e. Sulphur content ≤ 0.08%) for biomass fuels. Thus, when these materials are used as fuels they would emit sulphur compounds less than the maximum limits set by the Austria and German national standards for fuel pellet.

Thus, fuel from maize cobs, *P. africana* and their mixture would not have serious effect on both the environment and human health when burnt.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

This study researched into densification of sawdust of six tropical hardwood species and maize cobs at room temperature using low compacting pressure. The following are the conclusions drawn from the study:

- Generally good quality briquettes could be produced from sawdust of tropical hardwoods and agricultural materials at low compacting pressure and room temperature ($25^{o}C$) without a binder.
- With the exception of WR quality of briquettes produced, generally all the chemical constituent of the six timber species used for the study (Lignin, cellulose, hemicellulose) had significant positive correlation with the CS in cleft and IRI of the briquettes produced.
- At low CP (i.e. CP level between 10 MPa and 50 MPa) and laboratory temperature briquettes produced from sawdust of low density wood species are likely to have higher CS in cleft, IRI and WR quality but lower relaxed density than those produced from higher density wood species.
- The percentage change in length and diameter of briquettes produced from sawdust of *T. scleroxylon*, *C. pentandra*, *A. robusta*, *T. superba*, *C. mildbreadii*, *P. africana* using low CP and laboratory temperature increased with increasing CP level and particle size of sawdust. Additionally, the mathematical relationship between percentage change in length and, species density(S), particle size (P) and compacting pressure (CP) is: Percentage change in length = 16.950 – 0.016S + 0.432P + 0.059CP

- The mathematical relationship between percentage change in diameter and, species density (S), particle size (P) and compacting pressure (CP) is:

  Percentage change in diameter = 0.105 - 0.001S + 0.116P + 0.011CP

- The relaxed density of briquettes produced from sawdust of the six timber species at low CP using laboratory temperature was adequate and ranged from 32 4 kg/m^3 to 741 kg/m^3 with mathematical relationship between relaxed density and, species density (S), particle size (P) and compacting pressure (CP) as:

  Relaxed density = 334.628 + 0.125S - 23.986P + 6.639CP

- The CS in cleft of briquettes produced from the six species ranged from as low as 1.30 N/mm (*C. mildbreadii*, P < 1 mm, CP = 10 MPa) to 52.60 N/mm (*C. pentandra*, 1 mm ≤ P < 2 m, CP = 50MPa) with the mathematical relationship between CS in cleft and, species density (S), particle size (P) and compacting pressure (CP) as:

  Compressive strength = 19.923 - 0.046S + 2.957P + 0.637CP

- The IRI of the briquettes produced from: *T. scleroxylon*, *C. pentandra*, *A. robusta*, *T. superba*, *C. mildbreadii*, *P. africana* ranged from 0 to 450% with mathematical relationship between IRI and, species density (S) and compacting pressure (CP) is:

  IRI = 174.770 - 0.270S + 4.263CP

- Generally, the WR quality of all the briquettes produced from the six species at room temperature using low CP was low. Therefore, they need to be protected from moisture

- The mathematical relationship between WR quality of briquettes produced, and species density (S), particle size (P) and CP is:

  Water resistance quality = 4.265 - 0.004S - 0.353P + 0.038CP

- Generally, the fuel characteristics of the six timber species used for the study were adequate.
- The relaxed density of briquettes produced from mixed species of *P. africana, C. pentandra*, and *T. superba* were adequate and they ranged from 534 to 781 kg/m^3. Additionally, in some cases their relaxed densities were better than that of their corresponding pure species.
- The CS in cleft of briquettes produced from mixed species of *P. africana, C. pentandra*, and *T. superba* ranged from 6.02 to 60.28 N/mm. CS in cleft of briquettes produced from combination of *P. africana* and *C. pentandra* were higher than their corresponding values for *P. africana* only.
- With the exception of briquettes produced from mixture of *P. africana* and *T. superba*, at mixing ratios 80 : 20 and 60 : 40 and pressed at CP level 20 MPa, all the briquettes produced from combination of *P. africana, C. pentandra*, and *T. superba* had adequate IRI.
- With the exception of WR quality of briquettes produced from combination of *P. africana* and *C. pentandra* at a mixing ratio of 20 : 80 and CP level 50MPa for which the WR quality was moderate (6.63 minutes) all the briquettes produced from combinations of *P. africana, C. pentandra*, and *T. superba* had a low WR quality.
- Generally, for briquettes produced from combinations of *P. africana, C. pentandra*, and *T. superba*, CP and biomass raw material have significant effect on relaxed density, CS in cleft, IRI and WR quality of briquettes produced.

- The relaxed density of briquettes produced from combination of maize cobs and, *P. africana*, *C. pentandra*, and *T. superba* at low CP and laboratory temperature was adequate and ranged from 565 to 778 kg/m^3.
- All the briquettes produced from pure maize cobs at room temperature had a very weak CS in cleft and IRI. Briquettes produced from combination of *C. pentandra* and maize cobs had the best CS in cleft and IRI. Thus, briquettes with best CS in cleft and IRI could be produced from combination of *C. pentandra* and maize cobs.
- There exist a linear model between the CP and, relaxed density, CS in cleft and IRI of briquettes produced from combination sawdust and maize cobs particles.
- The gross calorific values of biomass materials prepared from combination of maize cobs and sawdust of *P. africana, C. pentandra*, and *T. superba* from which briquettes were prepared were adequates and ranged from 20.13 to 23.68 MJ/kg.
- Generally, at low CP and room temperature irrespective of the biomass raw material used the relaxed density, CS in cleft, IRI and WR quality of briquettes produced increased with increasing CP.

5.2 Recommendation

The following recommendations are made from the study conducted:

- It is recommended that when producing briquettes from sawdust of *C. pentandra*, the application of CP level 20 MPa or more would be adequate to produce briquette that is strong enough for handling, transporting and storage.
- This work has revealed that for all the briquettes produced from mixed species at room temperature using low CP, their CS in cleft, IRI and WR quality increased with increasing proportions of *C. pentandra* in the mixing ratio therefore it is

recommended that when producing briquettes from sawdust *T. superba*, *P. africana* and maize cobs sawdust of *C. pentandra* must be added in order to improve it physical and mechanical properties.

- This work has also revealed that briquettes can be formed from tropical hardwood and maize cobs therefore the biomass briquettes industry must move towards producing briquettes at room temperature and low CP in order to reduced energy input in this production process which tends to significantly increase production cost.
- The study has also revealed that generally briquettes produced from biomass materials at room temperature using low CP has low WR quality therefore it is recommended that briquettes produced under such condition should be protected from moisture.
- It is recommended that further studies must be conducted into the bonding mechanism between maize cobs and sawdust particles for which this study did not cover.

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APPENDICES

Appendix 1a: ANOVA of effect of biomass material and compacting pressure on relaxed density of briquettes produced from sawdust of *P. africana, C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	25476.142	5095.228	51.28	< .0001*
CP	3	519735.625	173245.2083	1743.64	< .0001*
Biomass material x CP	15	3875.425	258.3617	2.60	< .0026*
Error	96	9538.400	99.3583		

*Statistically significant at 0.05 level of significance

Appendix 1b: Post hoc multiple comparison of the means of relaxed density of briquette for biomass raw material *P. africana, C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana : C. Pentandra*)
A	672.70	20	80 : 20
B	656.35	20	*P. africana*
C	649.70	20	60 : 40
C	645.40	20	40 : 60
D	631.60	20	*C. pentandra*
D	630.15	20	20 : 80

A, B, C, D: means with different group letters differs significantly (LSD = 6.2569; α = 0.05)

Appendix 1c: Post hoc multiple comparison of the means of relaxed density of briquette for compacting pressure of briquettes produced from *P. africana, C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	734.00	30	50
B	674.90	30	40
C	627.37	30	30
D	554.30	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 5.1087; α = 0.05)

Appendix 2a: ANOVA of effect of biomass material and compacting pressure on compressive strength in cleft of briquettes produced from sawdust of *P. africana*, *C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	13168.875	2633.7751	345.45	< .0001*
CP	3	9540.080	3180.0266	417.10	< .0001*
Biomass material x CP	15	831.690	55.4460	7.27	< .0001*
Error	96	731.924	7.6242		

*Statistically significant at 0.05 level of significance

Appendix 2b: Post hoc multiple comparison of means of compressive strength in cleft of briquette for biomass raw material *P. africana*, *C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana : C. Pentandra*)
A	44.06	20	20 : 80
B	41.11	20	40 : 60
C	38.37	20	*C. pentandra*
D	32.38	20	60 : 40
E	24.90	20	80 : 20
F	13.57	20	*P. africana*

A, B, C, D, E, F: means with different group letters differs significantly (LSD =1.7332; α = 0.05)

Appendix 2c: Post hoc multiple comparison of means of compressive strength in cleft of briquette compacting pressure of briquettes produced from *P. africana*, *C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	45.09	30	50
B	34.96	30	40
C	28.91	30	30
D	20.64	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 1.4152; α = 0.05)

Appendix 3a: ANOVA of effect of biomass material and compacting pressure on impact resistance index of briquettes produced from sawdust of *P. africana, C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	449210.942	89842.1883	14.76	< .0001*
CP	3	557825.958	185941.9861	30.54	< .0001*
Biomass material x CP	15	85703.092	5713.5394	0.94	0 .5253†
Error	96	584477.600	6088.3080		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance **Legend:** DF = Degree of freedom

Appendix 3b: Post hoc multiple comparison of means of impact resistance index of briquette for biomass raw material *P. africana, C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana : C. Pentandra*)
A	333.40	20	20 : 80
AB	287.60	20	*C. pentandra*
BC	256.35	20	40 : 60
CD	214.70	20	60 : 40
DE	186.35	20	80 : 20
E	152.25	20	*P. africana*

A, B, C, D, E: means with different group letters differs significantly (LSD = 48.978; α = 0.05)

Appendix 3c: Post hoc multiple comparison of means of impact resistance index of briquette for compacting pressures

Groupings	Mean	N	Compacting pressure
A	336.13	30	50
B	261.20	30	40
C	203.50	30	30
D	152.93	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 39.991; α = 0.05)

Appendix 4a: ANOVA of effect of biomass material and compacting pressure on water resistance quality of briquettes produced from sawdust of *P. africana, C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	211.499	42.2998	970.14	< .0001*
CP	3	33.060	11.0198	252.74	< .0001*
Biomass material x CP	15	29.022	1.935	44.37	< .0001*
Error	96	4.186	0.0436		

*Statistically significant at 0.05 level of significance
Legend: Degree of freedom

Appendix 4b: Post hoc multiple comparison of means of water resistance quality of briquette for biomass raw materials *P. africana, C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana : C. Pentandra*)
A	4.40	20	20 : 80
B	3.64	20	*C. pentandra*
C	2.26	20	40 : 60
D	1.51	20	60 : 40
E	1.25	20	80 : 20
F	0.68	20	*P. africana*

A, B, C, D, E, F: means with different group letters differs significantly (LSD = 0.1311; α = 0.05)

Appendix 4c: Post hoc multiple comparison of means of water resistance quality of briquette for compacting pressures of briquettes produced from *P. africana, C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	3.08	30	50
B	2.40	30	40
C	2.02	30	30
D	1.67	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 0.1070; α = 0.05)

Appendix 5a: ANOVA of effect of biomass material and compacting pressure on relaxed density of briquettes produced from sawdust of *P. africana* and *T. superba* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	29119.5417	5823.9083	51.57	< .0001*
CP	3	542277.625	180759.2083	1600.52	< .0001*
Biomass material x CP	15	3109.625	207.308	1.84	0.0403*
Error	96	10842.000	112.9375		

*Statistically significant at 0.05 level of significance

Appendix 5b: Post hoc multiple comparison of means of relaxed density of briquettes for biomass raw material *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana : T. superba*)
A	691.60	20	80 : 20
A	686.80	20	60 : 40
B	675.15	20	40 : 80
B	672.80	20	20 : 80
C	656.35	20	*P. africana*
D	647.55	20	*T. superba*

A, B, C, D: means with different group letters differs significantly (LSD = 6.6708; α = 0.05)

Appendix 5c: Post hoc multiple comparison of means of relaxed density of briquette for compacting pressure of briquettes produced from *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Compacting pressure
A	756.57	30	50
B	704.53	30	40
C	650.77	30	30
D	574.97	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 5.4467; α = 0.05)

Appendix 6a: ANOVA of effect of biomass material and compacting pressure on compressive strength in cleft of briquettes produced from sawdust of *P. africana* and *T. superba* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	92.213	18.4426	11.97	< .0001*
CP	3	3887.908	1295.9694	841.27	< .0001*
Biomass material x CP	15	62.999	4.1999	2.73	0 .0016*
Error	96	147.887	1.5405		

*Statistically significant at 0.05 level of significance

Appendix 6b: Post hoc multiple comparison of means of compressive strength in cleft of briquettes for biomass raw materials *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana* : *T. superba*)
A	15.02	20	20 : 80
A	14.56	20	40 : 60
AB	14.30	20	60 : 40
AB	14.26	20	80 : 20
B	13.57	20	*P. africana*
C	12.29	20	*T. superba*

A, B, C: means with different group letters differs significantly (LSD = 0.7791; α = 0.05)

Appendix 6c: Post hoc multiple comparison of means of compressive strength in cleft of briquette for compacting pressure of briquettes produced from *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Compacting pressure
A	21.56	30	50
B	16.59	30	40
C	11.59	30	30
D	6.26	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 0.6361; α = 0.05)

Appendix 7a: ANOVA of effect of biomass material and compacting pressure on impact resistance index of briquettes produced from sawdust of *P. africana* and *T. superba* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	57004.867	11400.9733	4.26	0.0015*
CP	3	468114.833	156038.2778	58.35	< .0001*
Biomass material x CP	15	13178.267	878.5511	0.33	0.9810†
Error	96	256725.200	12674.2208		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Appendix 7b: Post hoc multiple comparison of means of impact resistance index of briquettes for biomass raw material *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana* : *T. superba*)
A	210.50	20	*T. superba*
AB	203.20	20	20 : 80
AB	196.70	20	40 : 60
BC	177.80	20	60 : 40
C	160.05	20	80 : 20
C	152.25	20	*P. africana*

A, B, C: means with different group letters differs significantly (LSD = 32.461; α = 0.05)

Appendix 7c: Post hoc multiple comparison of means of impact resistance index of briquette for compacting pressure of briquettes produced from *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Compacting pressure
A	263.93	30	50
B	216.80	30	40
C	154.03	30	30
D	98.90	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 26.504; α = 0.05)

Appendix 8a: ANOVA of effect of biomass material and compacting pressure on water resistance quality of briquettes produced from sawdust of *P. africana* and *T. superba* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	129.5197	25.9040	2241.66	< .0001*
CP	3	1.441	0.4802	41.56	< .0001*
Biomass material x CP	15	2.273	0.1515	13.11	< .0001*
Error	96	1.109	0.0116		

*Statistically significant at 0.05 level of significance

Appendix 8b: Post hoc multiple comparison of means of water resistance quality of briquettes for biomass raw materials *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio (*P. africana* : *T. superba*)
A	3.48	20	*T. superba*
B	0.79	20	20 : 80
C	0.71	20	40 : 60
C	0.68	20	*P. africana*
C	0.67	20	60 : 40
C	0.64	20	80 : 20

A, B, C: means with different group letters differs significantly (LSD = 0.0675; α = 0.05)

Appendix 8c: Post hoc multiple comparison of means of water resistance quality of briquette for compacting pressure of briquettes produced from *P. africana* and *T. superba* and their mixture

Groupings	Mean	N	Compacting pressure
A	1.31	30	50
B	1.22	30	40
C	1.11	30	30
D	1.02	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 0.0551; α = 0.05)

Appendix 9a: ANOVA of effect of biomass material and compacting pressure on relaxed density of briquette produced from *T. superba*, *C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	24967.142	4993.4283	43.66	< .0001*
CP	3	582471.225	194157.0750	1697.49	< .0001*
Biomass material x CP	15	2366.825	157.7883	1.38	0.1731†
Error	96	10980.400	114.3792		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Appendix 9b: Post hoc multiple comparison of means of relaxed density of briquettes for biomass raw materials *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	675.10	20	80 : 20
AB	668.95	20	60 : 40
BC	663.25	20	40 : 60
C	659.70	20	20 : 80
D	647.55	20	*T. superba*
E	631.60	20	*C. pentandra*

A, B, C, D, E: means with different group letters differs significantly (LSD = 6.7132; α = 0.05)

Appendix 9c: Post hoc multiple comparison of means of relaxed density of briquette for compacting pressure of briquettes produced from *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	743.70	30	50
B	691.80	30	40
C	640.30	30	30
D	554.97	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 5.4813; α = 0.05)

Appendix 10a: ANOVA of effect of biomass material and compacting pressure on compressive strength in cleft of briquettes produced from *T. superba, C. pentandra* and their mixture

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	12435.995	2487.1990	400.33	< .0001*
CP	3	7655.873	2551.9576	410.76	< .0001*
Biomass material x CP	15	900.876	60.0584	9.67	< .0001*
Error	96	596.429	6.2128		

*Statistically significant at 0.05 level of significance

Appendix 10b: Post hoc multiple comparison of means of compressive strength in cleft of briquette for biomass raw materials *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	40.63	20	20 : 80
B	38.37	20	*C. pentandra*
C	32.93	20	40 : 60
D	27.50	20	60 : 40
E	18.81	20	80 : 20
F	12.29	20	*T. superba*

A, B, C, D, E, F: means with different letters differs significantly (α = 0.05; LSD = 1.5646)

Appendix 10c: Post hoc multiple comparison of means of compressive strength in cleft of briquette for compacting pressure of briquettes produced from *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	38.98	30	50
B	32.12	30	40
C	25.07	30	30
D	17.52	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 1.2775; α = 0.05)

Appendix 11a: ANOVA of effect of biomass material and compacting pressure on impact resistance index of briquettes produced from *T. superba* and *C. pentandra*, and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	640414.567	128082.9133	18.72	< .0001*
CP	3	933379.933	311126.6444	45.46	< .0001*
Biomass material x CP	15	275900.567	18393.3711	2.69	0.0019*
Error	96	656962.800	6843.3630		

*Statistically significant at 0.05 level of significance

Appendix 11b: Post hoc multiple comparison of means of impact resistance index of briquette for biomass raw materials *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	370.85	20	20 : 80
A	345.83	20	40 : 60
AB	331.25	20	60 : 40
B	287.60	20	*C. pentandra*
C	210.50	20	*T. superba*
C	166.67	20	80 : 20

A, B, C: means with different group letters differs significantly (LSD = 51.927, α = 0.05)

Appendix 11c: Post hoc multiple comparison of means of impact resistance index of briquette for compacting pressure of briquettes produced from *T. superba, C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	391.70	30	50
B	343.13	30	40
C	236.23	30	30
D	166.80	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 42.398, α = 0.05)

Appendix 12a: ANOVA of effect of biomass material and compacting pressure on water resistance quality of briquettes produced from *T. superba* and *C. pentandra* and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	5	72.615	14.5231	342.44	< .0001*
CP	3	9.222	3.0740	72.48	< .0001*
Biomass material x CP	15	8.017	0.5344	12.60	< .0001*
Error	96	4.071	0.0424		

*Statistically significant at 0.05 level of significance

Appendix 12b: Post hoc multiple comparison of means of water resistance quality of briquette for biomass raw material *T. superba* and *C. pentandra* and their combination

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	3.64	20	*C. pentandra*
B	3.48	20	*T. superba*
C	2.89	20	20 : 80
D	2.23	20	40 : 60
E	2.05	20	60 : 40
F	1.49	20	80 : 20

A, B, C, D, E, F: means with different group letters differs significantly (LSD = 0.1293, α = 0.05)

Appendix 12c: Post hoc multiple comparisons of means of water resistance quality of briquette for compacting pressure of briquettes produced from *T. superba*, *C. pentandra* and their mixture

Groupings	Mean	N	Compacting pressure
A	3.04	30	50
B	2.72	30	40
C	2.44	30	30
D	2.32	30	20

A, B, C, D: means with different group letters differs significantly (LSD = 0.1055, α = 0.05)

Appendix 13a: ANOVA of effect of biomass material and compacting pressure on relaxed density of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	6	28622.486	4770.4143	38.37	< .0001*
CP	3	640406.136	213468.7119	1717.07	< .0001*
Biomass material x CP	18	7793.5143	432.9730	3.48	< .0001*
Error	112	13924.000	124.3214		

*Statistically significant at 0.05 level of significance

Appendix 13b: Post hoc multiple comparison of means of relaxed density of briquette for biomass raw materials *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	680.10	20	40 : 30 : 30
B	667.40	20	30 : 40 : 30
B	663.70	20	30 : 30 : 40
C	656.35	20	*P. africana*
CD	653.85	20	1 : 1 : 1
D	647.55	20	*T. superba*
E	631.60	20	*C. pentandra*

A, B, C, D, E: means with different group letters differs significantly (LSD = 6.9862, α = 0.05)

Appendix 13c: Post hoc multiple comparison of means of relaxed density of briquette for compacting pressure of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Compacting pressure
A	740.29	35	50
B	694.57	35	40
C	634.11	35	30
D	559.91	35	20

A, B, C, D: means with different group letters differs significantly (LSD = 5.2810, α = 0.05)

Appendix 14a: ANOVA of effect of biomass material and compacting pressure on compressive strength in cleft of briquette produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	6	10149.014	1691.5023	319.84	< .0001*
CP	3	6933.120	2311.0066	436.97	< .0001*
Biomass material x CP	18	701.204	38.9558	7.37	< .0001*
Error	112	592.331	5.2887		

*Statistically significant at 0.05 level of significance

Appendix 14b: Post hoc multiple comparison of means of compressive strength in cleft of briquette for biomass raw materials *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	38.37	20	*C. pentandra*
B	29.63	20	30 : 30 : 40
C	27.87	20	40 : 30 : 30
D	22.90	20	30 : 40 : 30
E	21.15	20	1 : 1 : 1
F	13.57	20	*P. africana*
F	12.30	20	*T. superba*

A, B, C, D, E, F: means with different group letters differs significantly (LSD = 1.4409, α = 0.05)

Appendix 14c: Post hoc multiple comparison of means of compressive strength in cleft of briquette for compacting pressure of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Compacting pressure
A	32.82	35	50
B	27.18	35	40
C	20.73	35	30
D	14.01	35	20

A, B, C, D: means with different group letters differs significantly (LSD = 1.0892, α = 0.05)

Appendix 15a: ANOVA of effect of biomass material and compacting pressure on impact resistance index of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	6	295249.171	49208.1952	8.13	< .0001*
CP	3	488535.336	162845.1119	26.90	< .0001*
Biomass material x CP	18	49553.514	2752.9730	0.45	0.9711†
Error	112	677897.200	6052.654		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Appendix 15b: Post hoc multiple comparison of means of impact resistance index of briquette for biomass raw materials *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	287.60	20	*C. pentandra*
A	277.15	20	30 : 30 : 40
B	227.20	20	30 : 40 : 30
CB	220.90	20	1 : 1 : 1
CB	210.50	20	*T. superba*
CD	173.05	20	40 : 30 : 30
D	152.25	20	*P. africana*

A, B, C, D: means with different group letters differs significantly (LSD = 48.746; α = 0.05)

Appendix 15c: Post hoc multiple comparison of means of impact resistance index of briquette for compacting pressure of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Compacting pressure
A	302.43	35	50
B	244.14	35	40
C	195.86	35	30
D	142.51	35	20

A, B, C, D: means with different group letters differs significantly (LSD = 36.849, α = 0.05)

Appendix 16a: ANOVA of effect of biomass material and compacting pressure on water resistance quality of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Source	DF	ANOVA SS	Mean square	F-Ratio	p-value
Biomass raw material	6	162.662	27.1103	1225.96	< .0001*
CP	3	8.057	2.6856	121.44	< .0001*
Biomass material x CP	18	8.697	0.4832	21.85	< .0001*
Error	112	2.477	0.0221		

*Statistically significant at 0.05 level of significance

Appendix 16b: Post hoc multiple comparison of means of water resistance quality of briquettes for biomass materials *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Biomass raw material/Mixing ratio
A	3.64	20	*C. pentandra*
B	3.48	20	*T. superba*
C	1.51	20	30 : 30 : 40
D	1.37	20	1 : 1 : 1
D	1.37	20	30 : 40 : 30
D	1.29	20	40 : 30 : 30
E	0.68	20	*P. africana*

A, B, C, D, E: means with different group letters differs significantly (LSD = 0.0932; α = 0.05)

Appendix 16c: Post hoc multiple comparison of means of water resistance quality of briquette for compacting pressure of briquettes produced from *P. africana*, *T. superba*, *C. pentandra* and their combination

Groupings	Mean	N	Compacting pressure
A	2.27	35	50
B	1.96	35	40
C	1.76	35	30
D	1.63	35	20

A, B, C, D: means with different group letters differs significantly (LSD = 0.0704, α = 0.05)

Appendix 17a: Relaxed density (kg/m^3) of briquettes produced from maize cobs and combination of sawdust and maize cobs (90 : 10) pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	541	611	636	659
C. pentandra : Maize cobs	90 : 10	565	641	695	742
T. superba : Maize cobs	90 : 10	579	678	723	778
P. africana : Maize cobs	90 : 10	583	651	687	748

Appendix 17b: Relaxed density (kg/m^3) of briquettes produced from maize cobs and combination of sawdust and maize cobs (70 : 30) pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	541	611	636	659
C. pentandra: Maize cobs	70 : 30	584	645	708	749
T. superba : Maize cobs	70 : 30	572	669	702	756
P. africana : Maize cobs	70 : 30	576	644	679	728

Appendix 17c: Relaxed density (kg/m^3) of briquettes produced from maize cobs and combination of sawdust and maize cobs (50 : 50) pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30MPa	40 MPa	50 MPa
Maize cobs	Pure	541	611	636	659
C. pentandra: Maize cobs	50 : 50	588	661	730	774
T. superba: Maize cobs	50 : 50	546	641	683	715
P. africana : Maize cobs	50 : 50	555	631	662	702

Appendix 18: ANOVA of effect of biomass material, mixing ratio and compacting pressure on relaxed density of briquettes produced from mixture of maize cobs and sawdust of three timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
BM	2	13278.01	6639.01	35.44	< 0.0001*
Mixing ratio	2	7254.34	3627.17	19.36	< 0.0001*
CP	3	720049.08	240016.36	1281.25	< 0.0001*
BM x Mixing ratio	4	29340.36	7335.09	39.16	< 0.0001*
BM x CP	6	8409.50	1401.58	7.48	< 0.0001*
Mixing ratio x CP	6	1565.03	260.84	1.39	0.2215†
BM*Mixing ratio x CP	12	2085.73	173.85	0.93	0.5211†
Error	144	26975.60	187.33		

*Statistically significant at 0.05 level of significance; †Not statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure
BM = Biomass material

Appendix 19a: Compressive strength in cleft (N/mm) of briquettes made from *C. pentandra*, maize cobs and their combination, pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	0.12	0.12	0.41	0.54
C. pentandra : Maize cobs	90 : 10	27.29	37.33	44.98	59.22
T. superba : Maize cobs	90 : 10	3.77	8.07	11.64	15.51
P. africana : Maize cobs	90 : 10	2.62	6.02	8.14	13.23

Appendix 19b: Compressive strength in cleft (N/mm) of briquettes produced from *T. superba*, maize cobs and their combination pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	0.12	0.12	0.41	0.54
C. pentandra: Maize cobs	70 : 30	16.66	22.82	30.00	33.47
T. superba : Maize cobs	70 : 30	2.06	4.29	5.42	7.61
P. africana: Maize cobs	70 : 30	1.94	3.58	4.08	7.47

Appendix 19c: Compressive strength in cleft (N/mm) of briquettes produced from *P. africana*, maize cobs and their combination pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	Compacting pressure 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	0.12	0.12	0.41	0.54
P. africana : Maize cobs	50 : 50	7.72	13.02	19.46	24.04
P. africana : Maize cobs	50 : 50	0.78	1.82	2.51	3.97
P. africana : Maize cobs	50 : 50	0.60	1.20	2.07	2.95

Appendix 20: ANOVA of effect of biomass material, mixing ratio and compacting pressure on compressive strength in cleft of briquettes produced from mixture of maize cobs and sawdust of three timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
BM	2	21101.09	10550.54	5890.18	< 0.0001*
Mixing ratio	2	5287.00	2643.50	1475.82	< 0.0001*
CP	3	3260.42	1086.81	606.74	< 0.0001*
BM x Mixing ratio	4	2617.98	654.49	365.39	< 0.0001*
BM x CP	6	1317.88	219.65	122.62	< 0.0001*
Mixing ratio x CP	6	519.36	86.56	48.33	< 0.0001*
BM x Mixing ratio x CP	12	110.03	9.17	5.12	< 0.0001*
Error	144	257.93	1.79		

*Statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure
BM = Biomass material

Appendix 21a: Impact resistance index (%) of briquettes made from *C. pentandra*, maize cobs and their combination pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	0	0	0	0
C. pentandra : Maize cobs	90 : 10	200	300	400	500
T. superba: Maize cobs	90 : 10	148	200	250	300
P. africana: Maize cobs	90 : 10	70	120	133	183

Appendix 21b: Impact resistance index (%) of briquettes produced from *T. superba*, maize cobs and their combination pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs	Pure	0	0	0	0
C. pentandra: Maize cobs	70 : 30	142	192	233	450
T. superba : Maize cobs	70 : 30	81	132	162	175
P. africana: Maize cobs	70 : 30	13	63	74	115

Appendix 21c: Impact resistance index (%) of briquettes produced from *P. africana*, maize cobs and their combination pressed using compacting pressure levels 20 - 50 MPa

Biomass material	Mixing ratio (weight basis)	**Compacting pressure** 20 MPa	30 MPa	40 MPa	5 0MPa
Maize cobs	Pure	0	0	0	0
C. pentandra: Maize cobs	50 : 50	115	133	150	217
T. superba : Maize cobs	50 : 50	0	0	78	98
P. africana : Maize cobs	50 : 50	0	0	66	82

Appendix 22: ANOVA of effect of biomass material, mixing ratio and compacting pressure on impact resistance index of briquettes produced from mixture of maize cobs and sawdust of three timber species

Source	DF	ANOVA SS	Mean Square	F-Ratio	p-value
BM	2	964832.48	482416.24	208.34	< 0.0001*
Mixing ratio	2	726213.21	363106.61	156.81	< 0.0001*
CP	3	558962.06	186320.69	80.47	< 0.0001*
BM x Mixing ratio	4	68972.06	17243.01	7.45	< 0.0001*
BM x CP	6	101304.99	16884.17	7.29	< 0.0001*
Mixing ratio x CP	6	43960.26	7326.71	3.16	0.0060*
BM x Mixing ratio x CP	12	68517.94	5709.83	2.47	0.0059*
Error	144	333436.00	2315.53		

*Statistically significant at 0.05 level of significance

Legend: DF = Degree of freedom
CP = Compacting pressure
BM = Biomass material