CARBONIZATION AND BRIQUETTING OF SAWDUST FOR USE IN DOMESTIC COOKERS

BY

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This thesis has been submitted with our approval as the university supervisors.

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ABSTRACT

CARBONIZATION AND BRIQUETTING OF SAWDUST FOR USE IN DOMESTIC COOKERS

By

PAUL K. ROTICH

Sawdust represents a considerable amount of energy that is currently under-utilized. With an appropriate thermodynamic process this by-product can be converted into charcoal briquettes suitable for domestic use. In this study sawdust was carbonized in a traditional brick-lined metal kiln. Pyrolysis conditions were studied with particular reference to temperature, air flow rate and moisture content.

Charcoal yields of 28% (dry weight basis) was obtained from this system at pyrolysis temperatures of 450-550°C. Lower yields were obtained at temperatures below and above this range. Sawdust and wood containing moisture content of 40% and 35% respectively gave charcoal yields of 19.8% compared with 28% for input with moisture content of 30% (sawdust) and 26% (fuelwood) on dry weight basis.

The energy content of sawdust, wood and their carbonized products was determined using an adiabatic bomb calorimeter. Fully carbonized charcoal had calorific value between 28MJ/kg and 30 MJ/kg against 19 MJ/kg for uncarbonized sawdust. Partially carbonized or torrid sawdust had calorific value of 23-24 MJ/kg. Proximate analysis revealed that the percentage

fixed carbon of pyrolysis products increases with the degree of carbonization. The fixed carbon content was 56% and 70% for fully carbonized sawdust charcoal and wood charcoal respectively. Torrefied sawdust contained more volatiles but less fixed carbon (50%).

Densification of sawdust charcoal was done using a hand-operated hydraulic press and mechanical briquetter. The bulk density of briquettes could be increased from 160kg/m^3 of loose material to about 540 kg/m^3 using a compression pressure of 875N/cm^2 in conjunction with either 5% molasses or 3% starch binder. With a constant compression pressure of 350N/cm^2 the bulk density increased from 330 kg/m^3 to 450kg/m^3 on increasing the ratio of molasses from 0 to 20%, respectively. Fully carbonized sawdust charcoal was more friable and had better briquetting properties than torrefied sawdust.

Charcoal briquettes and ordinary lump charcoal were burned in ordinary cookers and their combustion characteristics compared. Charcoal briquettes caught fire more readily than ordinary charcoal when lighting and on average took 9 and 11 minutes respectively. Charcoal briquettes reached their peak glowing combustion 30 minutes after ignition but their fire died out within one and a half hours compared with 40 minutes and two hours respectively for ordinary charcoal.

DEDICATION

Dedicated to my wife Joan, daughter Rabby, sons Ronald, Rogers and Raphael from whom the time devoted to this thesis has been withdrawn. To my mother, Marcelline who denied herself the comfort of life for the sake of my education.

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Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF APPENDICES

Appendix

NOMENCLATURE

s/d	Sawdust
torr.	Torrefied
char.	charcoal
d.b	dry basis
d.w.b	dry weight basis
w.b	wet basis
o.d	oven dry
G.H.V	Gross heat value
M.C	moisture content
wt	weight
Cal.	Calorific
raw	uncarbonized material
Briq.	Briquette
Dens.	Density
S	Starch
M	Molasses
Rec.	Recorded

CHAPTER 1

INTRODUCTION

Biomass is widely used throughout the world as a source of timber, fibre, pulp, paper products, fuel and other uses. As a fuel, biomass accounted for 47% of total world energy production in 1978 (Fung, 1982). In Africa fuelwood represents over 60% of the total energy used (Bourgeois and Doat, 1985). Biomass as a domestic fuel is extensively used in most rural homes where other alternative sources are limited. Average consumption of fuelwood in developing countries for cooking is in the range of 62-69 GJ/annum per household which translates to about 3145kg of fuel wood per year (O'keefe *et al.* 1984). In Kenya, the average consumption of fuelwood per average family of 8 people is estimated to be 4680 kg per year (Central Bureau of Statistics, 1980). The progress in the development of wood as a source of timber has converted these once woodfuel into important source of high-value products making them too valuable to be used as fuel. Thus only woodwaste and residues that could not be utilized by current technology are best used as fuel (Hoi and Bridgwater, 1989).

Significant quantities of agricultural and forest residues are potentially available for converting into domestic energy source. These biomass wastes are currently under-utilized as fuel material due to their high moisture, low energy content and low mass density which makes them uneconomical to use. Biomass residues include tree trimmings, edgings, slabs, stumps, wood chips, bark, wood shavings, sawdust, straw, stover and corn cobs among others.

1.1 Sources of Biomass

The main sources of fuel for domestic use are forests, herbaceous and marine biomass. The use of forest products has put much pressure on the existing forests and may cause deforestation in the developing world. Developing countries therefore need to utilize their technologies for optimal use of forest biomass. The rational option is to derive maximum utility of this vital resource by using roundwood for its non-fuel purposes and then upgrading the woodwastes for energy purposes. FAO estimated that Kenya produced 38.6 million M^3 of roundwood in 1993 (FAO, 1993). The relative proportion of residues generated in sawmill industry are bark (10%), slabs and edgings (70%) and sawdust (20%) (Hoi and Bridgwater, 1989). Among the forest wastes, sawdust seems to be the most appropriate for conversion because of its local concentration and uniform size distribution suitable for densification. The amount of residues from forest industry can be estimated from the amount of timber production. Table I in Appendix A shows estimated amount of woodwaste from different wood working and types of wood. Resch (1982) avers that about 24-570m^3 of biomass waste may be produced by a large stationery sawmill. Most of this material is left to rot at the logging site or at sawmill yards, where it causes serious disposal problems. According to Mugo and Gichohi (1986) annual production of sawdust in Kenya is estimated to be 63,000 tones. It is therefore apparent that there is enough sawdust for exploitation as energy source.

1.2 Utilization of Wood and Sawdust-State of the art

The high cost of transporting fuelwood over long distance would diminish its relative low cost advantage as a fuel. According to Hoi and Bridgwater, (1989) the distance through which wood can be transported economically is about 100km. However the economic value of wood can be readily upgraded if it is converted into charcoal. According to Resch (1982) charcoal with calorific value of 30-32MJ/kg is about twice that of wood (16-20MJ/kg) but a fifth of its volume and thus can be easily transported over relatively longer distance. Another advantage of charcoal over wood is that it is a clean fuel which burn with less pollution and thus is preferred in major towns. Table II Appendix A gives comparison of energy content of some biomass and conventional fuel products. The use of wood as a fuel either directly or for making charcoal has depleted national forest resource because exploitation far exceeds replanting and growth rate. There is a need to diversify energy resources by including sawdust as domestic fuel.

Direct combustion of sawdust in domestic burners has been

practiced with slight modification of the cookers. However this is not suitable because sawdust tends to hold high moisture in its loose natural state and gives poor combustion efficiency. Special stoves adapted for burning sawdust are described by Arends (1985). Sawdust and other fine biomass have been used by industry in furnaces employing blowers where it is burnt in suspension form
(O'connor, 1980). Sawdust can also be densified into pellets, logs or briquettes to improve its handling, transport, and combustion characteristics as a domestic fuel (Sadakichi, 1982). But burning of sawdust briquettes, does not eliminate atmospheric pollution and efficiency of combustion is not sufficiently enhanced. However sawdust can be easily upgraded into charcoal through pyrolysis to improve its calorific value and combustion characteristics. But loose sawdust charcoal has to be densified before it can be used in domestic burners. Carbonization of sawdust, followed by briquetting of the charcoal would be the most attractive alternative for energy utilization of sawdust.

The main drawback in briquetting of sawdust charcoal is the necessity of a binder and the high energy input required during densification. This means high prices for charcoal briquettes relative to wood and charcoal. There is a need to establish an appropriate densification system which uses optimum pressure-binder ratio combination to produce a stable fuel that is cost effective and affordable to the users. In Thailand uncarbonized sawdust briquettes could not compete effectively with firewood because of high prices, but carbonized sawdust briquettes competed favourably with charcoal (Erickson and Prior, 1990). However it appears little documented data is available in literature on densification of carbonized sawdust. Conversion of the sawdust into charcoal briquettes provides a favourable economical option for saw-millers to dispose of the environmentally hazardous piles of sawdust. It is expected that handling and transportation of charcoal briquettes could be more economical than collection and transportation of fuelwood per unit of energy over similar distance.

1.3 Thermochemical conversion of sawdust

Thermochemical process is the thermal degradation of biomass by heat to produce a variety of end-products whose proportions depend on the process employed. Thermochemical technologies employ different equipments and operate under different modes. There are four main thermochemical methods for converting biomass into a range of fuel products: combustion, liquefaction, gasification and pyrolysis. Among these technologies, pyrolysis appears to be the most promising process for large scale energy conversion of lignocellulosic material such as biomass into solid fuel (Grassi, 1989). A pyrolysis process produces gas, liquid and charcoal: whose relative fractions depend on the pyrolysis method and process parameters. The quality of charcoal from pyrolysis is influenced by carbonization temperature, moisture content and wood chemical composition. It has been noted (Gray *et al.* 1985; Beaumont and Schwob, 1984) that at pyrolysis temperatures above 340°C higher moisture content favours higher charcoal yield and vice versa for lower temperatures. It is therefore prudent to establish an optimal moisture content of the feed suitable for good charcoal yield.

Chembukulam *et al.* (1981) found that charcoal yield from teak wood sawdust reduced from 41% to 31% when pyrolysis temperatures were varied from 400 to 600°C and that good quality charcoal require minimum temperatures of 538°C. However charcoal quality is achieved at the expense of residual volatiles in the char which means less percentage total energy retained in the solid. It is necessary therefore to establish an optimal temperature which gives high charcoal yields of satisfactory quality charcoal for domestic use. According to Haggan (1985) partially carbonized fuel (torrefied wood) containing high volatiles but low fixed carbon is obtained at temperatures of 280-400°C. There is a need to determine a compromise temperature that would give optimal charcoal yields of reasonable quality for domestic purpose. According to Tatom *et al.* (1975) air flow rates affect pyrolysis temperatures and products yields. There appears to be no documented data showing the relationship of air flow with temperature and charcoal yield for traditional charcoal kilns

1.4 Objectives

The main objective of this research was to develop an appropriate process for converting agricultural and forest wastes into other forms of energy suitable for domestic utilization.

1.4.1 Specific Objective

i) To establish the optimum temperature-air flow rate combinations as function of charcoal yield and quality during carbonization of sawdust in a traditional kiln.
ii) To determine the effect of moisture content on charcoal yield during carbonization of sawdust in traditional kiln
iii) To determine the energy efficiency of converting sawdust into charcoal briquettes
iv) To determine the optimum densification pressure and binder ratio for converting carbonized sawdust into charcoal briquettes
v) To compare combustion characteristics of sawdust briquettes with those of commercial charcoal and uncarbonized sawdust.
vi) To demonstrate the feasibility of converting sawdust into charcoal briquettes for domestic cooking

CHAPTER 2

LITERATURE REVIEW

2.1 Historical background

Humankind has used direct combustion as a way of utilizing energy contained in plant matter for his domestic use from primitive ages. Besides direct combustion, various thermochemical processes are available for conversion of biomass into suitable energy forms. According to Mendis (1989) biomass gasification has been in use since the late 18th century but commercial applications of the technology were first recorded in 1830's. Mendis (1989) also reported that gasification technology was extensively used to run internal combustion engines in 1940's during World War II as a result of the scarcity of liquid petroleum fuels. These systems were however abandoned immediately after the war as the cheaper liquid petroleum fuels re-emerged in the market. With an expected rise in oil prices there is a potential of extensive utilization of biomass wastes as domestic fuel through briquetting and carbonization. In fact the oil crisis of 1970's sparked a renewed interest in biomass conversion technologies and a number of countries established implementation programmes for thermochemical energy conversion of biomass. These processes include gasification, liquefaction and pyrolysis and are described in sections 2.4

2.2 Biomass Feedstock

In developing countries the main source of energy in rural households is fuelwood, animal dung, straw, corn cobs, and woodwaste among other sources. Wood is also a leading feedstock for making charcoal, the main domestic fuel in urban areas. In Kenya 95% of charcoal produced is through earthen kiln which results in a loss of 75% of the initial energy. Though forest biomass is a renewable resource the rate of consumption of wood far exceeds planting and if this is not checked the forested areas are threatened by deforestation. The search for alternative energy supplies has generated interest in utilization of agricultural and forest wastes to supplement or replace conventional energy sources. Sawdust is one of the best agro-industry residues that can be turned into domestic energy sources.

2.3 Chemical Composition of Wood

Wood in general is composed of cellulose (48%), hemicellulose (19%), lignin (24%) extractive (7.5%), Ash (1.6%) and moisture (33%). Concentration of these compounds depend on the species of the plant and varies for different parts (Maschio *et al.* 1992; Shafizadeh, 1983; Munavu, 1976). Table III in Appendix A gives chemical components of some biomass species.

The cellulose component which is a macro molecule embedded in a matrix of hemicellulose and lignin form the major component of the cell wall and biomass in general. It consists of linearly linked (ß-1-4)-D-glucopyranose units in all types of biomass except that the degree of polymerization differ. The crystalline nature of these straight chain macromolecules make cellulose highly inert and inaccessible to chemical reagents in hydrolysis processes (Shafizadeh, 1980). Thus thermochemical conversion of cellulosic biomass seems to be the best alternative for upgrading biomass as an energy resource and therefore is the obvious choice in preference to acid or enzyme hydrolysis.

On the other hand hemicellulose are amorphous and have lower degree of polymerization and could be preferably hydrolysed under relatively mild conditions. The hemicellulose of softwood contain mainly D-mannose and D-galactose (glucomannans) while hardwood and agricultural wastes consists mainly of acetyl-4-O-methylglucuronoxylan (Xylan) (Shafizadeh, 1983). In contrast lignin is a randomly linked amorphous and high molecular weight phenolic compound. Soft wood lignin contains guaiacol propane units (phenolic groups with one methoxyl group) and is more polymeric and abundant. In addition, hardwood lignin has syringyl propane units (with two methoxyl groups). Thus pyrolysis of these components of wood proceeds through a series of complex, co-current and consecutive reactions and provide a variety of products. This phenomenon is observed on thermogravimetry of wood and its components.

Figure 2.1 shows the thermographimetry of cotton wood and its components which depicts the loss in weight with increase in temperature during pyrolysis. From the figure it can be seen that the residual weight of wood falls sharply at first but then attains constant weight as the temperature reaches 400°C. It is also seen that the xylan component of wood is converted faster than lignin and at 500°C has no residual charcoal.

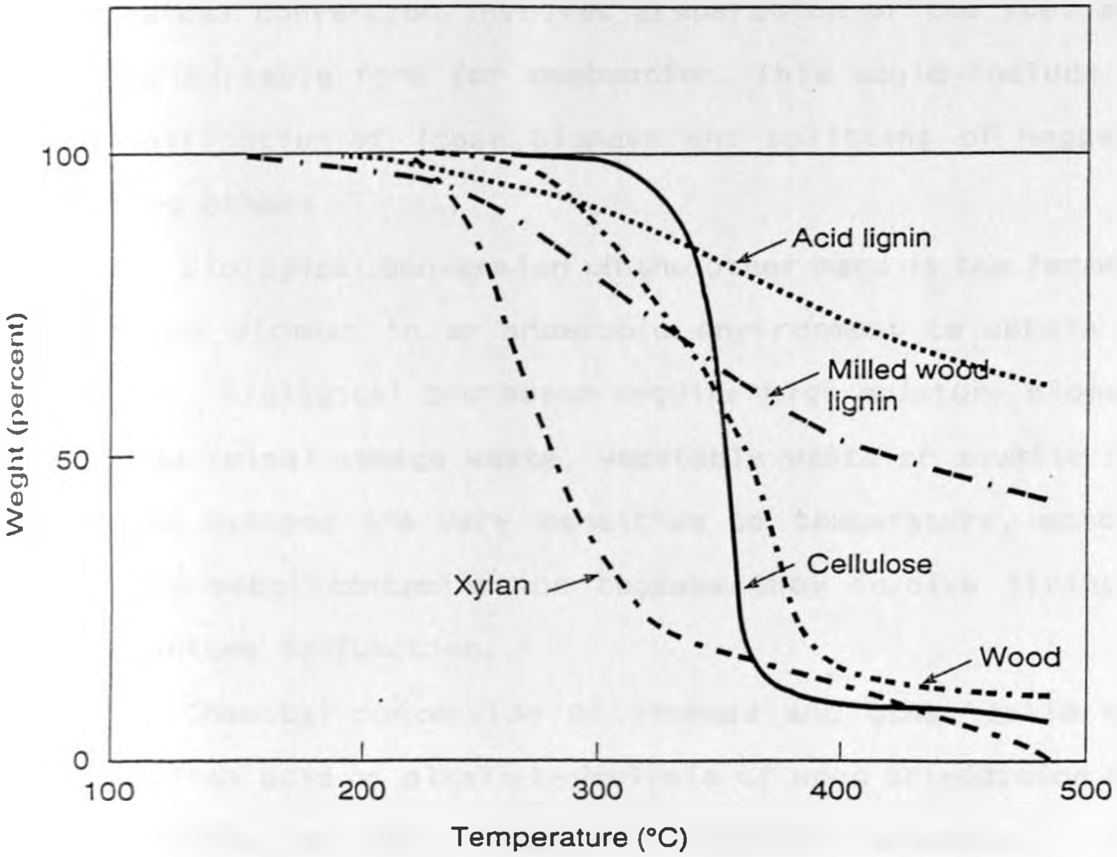

Fig. 2.1. Thermogravimetry of cottonwood and its components.

Source: Shafizadeh, (1980)

2.4 Biomass Conversion Technologies

The energy in biomass may be exploited either by direct combustion or by upgrading into more valuable and usable products such as wood gas, wood oil, charcoal or high-value products for chemical industry. This upgrading may be by physical, biological, chemical or thermal methods to give a solid, liquid, or gaseous fuel (Brigdwater and Brigde, 1991). Physical conversion involves preparation of the fuel material into suitable form for combustion. This would include drying, densification of loose biomass and splitting of hogged wood, among others.

Biological conversion on the other hand is the fermentation of wet biomass in an anaerobic environment to obtain gaseous fuel. Biological processes require high moisture biomass such as municipal sewage waste, vegetable waste or aquatic biomass. These systems are very sensitive to temperature, acidity and heavy metal contamination because they involve living micro-organisms to function.

Chemical conversion of biomass and other solid material involves acid or alkali hydrolysis of wood or addition of other chemicals to obtain fuels or chemical products. Chemical processes for energy conversion of biomass are very expensive. However they are important routes for converting wood into valuable chemical products for industrial uses.

Combustion is the direct burning of fuelwood in a hearth or fireplace to obtain heat energy for cooking or heating. This method however has low efficiency due to the high moisture content and the low heating value of wood. Smoke emission from a direct combustion process poses design problems and environmental pollution.

Liquefaction is the process used to obtain mainly liquid fuels from biomass through fast (or flash) pyrolysis at medium temperatures and moderate pressures (Bridgwater, 1989). Liquefaction however is currently not economically tenable under the present conditions as liquids fuels can be obtained from relatively cheap petroleum oils. Bio-oils products from liquefaction process are also highly corrosive and unstable, presenting difficulties in their handling, storage and use.

Gasification is the process of converting biomass into gaseous fuel and is achieved at high process temperatures with high heating rates. Gasification technology is limited by the low calorific value of the gas which has to be cleaned of dust, tar and vapours including moisture before it is used in internal combustion engines (Bridgwater, 1989). However the gas can be burnt in-situ to provide heat for any power system on site.

Pyrolysis is thermal degradation of biomass that may be carried out either in complete absence of oxygen or with too little oxidant to completely burn the substrate into ash but sufficient for partial gasification to provide heat of reaction. Pyrolysis as a route for conversion of biomass into suitable energy form is attractive because bulky biomass that is difficult and costly to manage can be readily converted into solid and liquid fuel products with higher energy density. The nature of the pyrolysis products from biomass is influenced by its chemical composition. Pyrolysis of biomass proceeds with successive degradation of its major components, namely:- hemicellulose, cellulose and lignin. In pyrolysis of wood partial combustion is necessary to provide the heat required to raise the temperature to the desired level unless heat is supplied externally. Charcoal is the most attractive product of conventional pyrolysis in handling, transport and storage. Liquid fraction presents problem due to its corrosiveness and instability, while the gas has low calorific value and is contaminated with dust, tars, vapours and moisture. Liquid and gases are best burnt on site to provide the process heat as they are too costly to purify and transport for use elsewhere. In recent years more attention has been focused on the optimization of operating conditions to maximize charcoal yield of good quality (Maschio *et al.* 1992). A typical pyrolysis conversion process of bone-dry wood at 400°C is given by Satonaka (1982) and is reproduced in Table 2.1.

Table 2.1: Calorific value of fuelwood and its products

products	Yields (%) on weight basis	Calorific value (MJ/kg)
charcoal	34	30-32
pyroligneous liquor	50	20
wood gas	16	5-9

From the table it can be seen that charcoal yield is in the range of 30% of initial dry feed and that its energy value between 30 and 32MJ/kg. The percentage yield, however will vary depending on many factors such as temperature, method of pyrolysis, starting material among others.

2.5 Pyrolysis Process

Carbonization is a slow pyrolysis process that requires slow heat supply rate at low temperatures that is designed to maximize solid fuel and limit production of the other pyrolysis products. Charcoal yields of up to 30-40% on dry weight basis can be obtained by slow pyrolysis of biomass (Brigdwater, 1989). The charcoal produced has higher volatile content because of the less severe pyrolysis. Upon heating in absence of air, wood undergoes physico-chemical degradation to form charcoal, pyroligneous liquid and gaseous products. This takes place between 200°C and 1100°C at atmospheric pressure (Palz and Charter, 1980).

According to Mezerette and Girard (1991), the reaction mechanisms during pyrolysis of biomass are complex and are not fully understood but five stages can be discerned:

(i) Upto 200°C:- mainly drying takes place but some volatilecompounds (oils and oleoresinous matter) are also lost.

(ii) 200-280°C:- thermally unstable hemicellulose is broken down giving off acids, furfural methanol and gases.

(iii) 280-350°C:- At 280°C a distinct exothermic reaction starts and temperature rises rapidly to 350°C without any additional energy.

Emission of carbon dioxide, carbon monoxide continues and some hydrocarbons such as methane (CH_4), ethane (C_2H_6), ethelyne (C_2H_4) , light tars and acids (acetic, formic, methanol and acetone).

(iv) 350-500°C:- An external source of energy is now required to maintain the process. At this stage cellulose breaks down producing water, carbon dioxide and charcoal or in rapid reaction process gives unstable intermediate substance (Levoglucosan) which in turn decomposes into substances similar to those from hemicellulose. Lignin also breaks down to phenolic compounds (phenol, creosols, and guaiacol) and methanol. Heavier tars are also produced at this stage.

(v) Above 500°C:- Complete carbonization has occurred. Any remaining lignin is turned into charcoal and the gas evolved becomes enriched in hydrogen.

2.6 Factors Affecting Charcoal Quality and Yield

It has been shown (Koufopanos,. *et al.* 1989; Grassi, 1989;) that the kinetics of pyrolysis of biomass is influenced by the following parameters:- nature and particle size of the feedstock, temperature, reaction rates, residence time, pressure of the system, moisture content and effect of catalyst. In practice it is easier to monitor the highest temperature, the pressure and residence time but more difficult to control the heating rates (Deglise and Magne, 1987). Yield and quality of charcoal are also influenced by the above parameters but depend more significantly on the carbonization temperature than moisture content or wood chemical composition. Similarly, products distribution appears to depend on the pyrolysis temperature than the nature and particle size of the feedstock (Maschio *et al.* 1992).

The actual course of reactions and final product fractions can be modified by changing operating conditions to maximize the desired product and its quality as discussed in the following sections.

2.6.1 Nature and Particle Size of Raw Material

The type and state of the biomass, determines its thermochemical reaction kinetics since different components making up the raw material will display different thermal properties which adds up to represent the average properties of the raw material (Shafizadeh, 1980). Chan Wai-Chun Ricky *et al.* (1978) reported that distribution and release rate of volatiles during pyrolysis are affected by particle size, thermal properties, wood anisotropy and porosity of the feedstock. The coarser the particle the slower the heating rate, and therefore pyrolysis occurs at low temperatures resulting in higher charcoal yield with low levels of liquid and gas fractions (Beamont and Schwob, 1984). Fine particles are preferred for production of liquids or gaseous products as they can attain higher heat transfer rates. Kryla (1985) found that particle size also has some effect on calorific value of pyrolysis products.

2.6.2 Charcoal Yields and Quality as Affected by Temperature

Pyrolysis products are affected by both the reaction temperature as well as the ultimate temperature reached. The reaction temperature is the temperature during which carbonization takes place and the ultimate temperature is the maximum temperature reached during pyrolysis. Low reaction temperatures (280-500°C) give higher charcoal yield but of lower quality as indicated by lower calorific value and percentage fixed carbon (Elder and Cutter, 1983). At temperatures of 280-320°C partially carbonized charcoal called torrefied wood is obtained which contains about 90% of the initial energy of the dry wood,and has high volatile content (Bourgeois and Doat, 1985). According to Caceres (1985) the lower the temperature the more the percentage charcoal yields obtained but the less the percentage fixed carbon content (see Table IV in Appendix A). The high-volatile-content ("soft") charcoal made at low temperatures (280-500°C) is mainly consumed by the domestic market while the high-grade ("white") charcoal produced at high temperatures (600-900°C)is preferred in the smelting industry as a reducing agent (Hollingdale *et al.* 1991). Research studies done elsewhere (Sadakata *et al.* 1987; Caceres, 1985; etc) on effect of temperature on carbonization of sawdust show that charcoal yields reduce from 492% wet basis obtained at between 300 and 400°C to 18.3% at temperatures of 800-900°C.

Figure 2.2 gives the yields of various pyrolysis products with temperature (Knight, 1976). At higher reaction temperatures (over 500°C) reaction rates are accelerated and more liquids and gases are obtained at the expense of solid fuel. It can be seen from the figure that gaseous products increase rapidly with temperatures above 500°C. It is also noted that charcoal yield as well as water vapour from pyrolysis system decrease with temperature. The production of oils and tars is not affected by the change in temperature but there is a general increase.

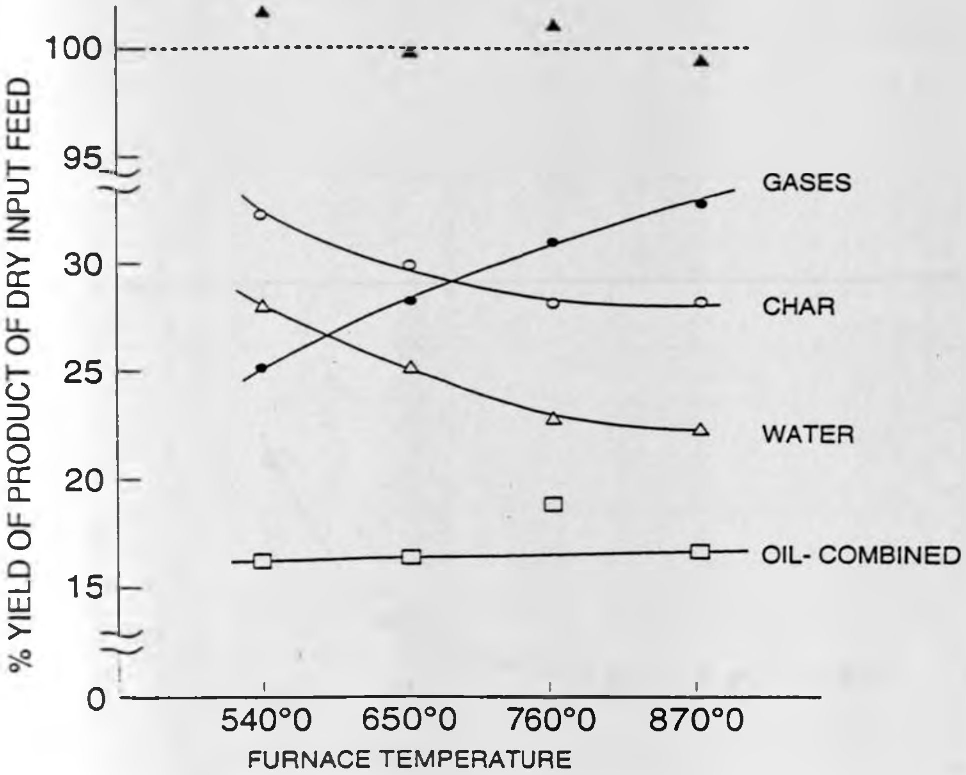

Fig. 2.2. Yields of the four major pyrolytic products versus temperature

Source: Knight, (1976)

Sadakata *et al.* (1987) gives the effects of temperature on pyrolysis of wood and its components and is illustrated in figure 2.3. The figure shows the effects of temperature on charcoal yields from pyrolysis of wood and its components namely: lignin and holocellulose (cellulose and hemicellulose). It is evident from the graph that charcoal yields generally decrease with increase in pyrolysis temperature for all the substances. It can also be noted that Lignin gives more charcoal than holocellulose or wood.

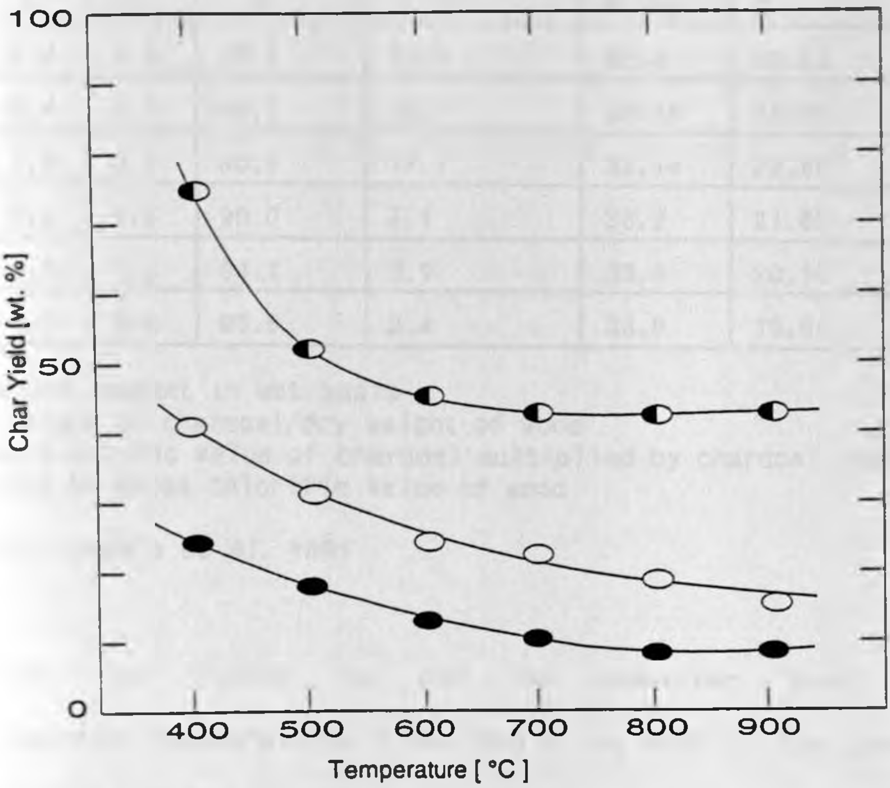

Fig. 2.3. Effect of temperature on char yields
○,Wood; ◐, lignin; ●, holocellulose

Source: Sadakata, *et al.*, (1987)

Hollingdale *et al.* (1991) reported values for energy content and proximate analysis of charcoal produced from Acacia at various temperature and are reproduced in Table 2.2

Table 2.2: properties of charcoal from *Acacia bussei* produced at different temperatures

Temp ˚C	Ash %	M.C[a] %	Fixed carbon %	Volatiles %	Energy value MJ/kg	Charcoal yield[b] %	Energy yield[c] %
300	0.4	1.9	28.8	70.8	22.4	56.27	65.92
400	2.4	2.8	66.7	30.9	29.88	28.03	43.80
500	1.4	2.8	80.9	17.7	32.14	22.65	38.07
600	2.9	1.0	90.0	7.1	33.2	21.63	37.56
700	2.0	1.8	94.1	3.9	33.4	20.16	34.22
800	2.0	2.2	95.6	2.4	33.9	19.54	34.64

a Moisture content in wet basis
b Dry weight of charcoal/dry weight of wood
c Gross calorific value of charcoal multiplied by charcoal yield divided by gross calorific value of wood

Source Hollingdale *et al.* 1991

From the table it can be observed that raising carbonization temperature from 300˚C to 800˚C, the percentage fixed carbon and the energy value increase from about 29% to 96% and from 22 to 34MJ/kg respectively. On the other hand charcoal yields reduced from 56% at 300˚C to 19% at 800˚C. Similarly the energy yield is higher at lower temperatures with about 66% (at 300˚C) compared with 35% (at 800˚C). This is because gross energy yield of pyrolysis product depends on both calorific value and weight yield. At lower pyrolysis temperature low calorific value char is compensated by higher weight yield. Temperature is influenced by air flow rates with faster air flow enhancing higher temperatures. Experiments done at Georgia

Institute of Technology to determine the optimal conditions for pyrolysis revealed that high charcoal yield is obtained at low temperatures with low air flow rates but only upto a limiting value (Tatom *et al.* 1975). Commercial charcoal, with typical calorific value of 29-30 MJ/kg and is usually produced at 400-500°C with fixed carbon of 75-85% dry weight (Pyle, 1977). At temperatures beyond 500°C gaseous products dominate due to devolatilization and decomposition of charcoal resulting in lower charcoal yields though of higher percentage fixed carbon (Elder and Cutter, 1983; Pyle, 1977).

2.6.3 Effects of Heating Rates on Charcoal Quality and Yield

Pyrolysis process is influenced by the heating rate which control the rate of kinetic reactions (Beamont and Schwob, 1984). The heating rate in a pyrolysis process is the rate of heat gained by the charge with time. This heating rate depends on two main factors:- the type of reactor and the wood particle size. For a given particle size, the reactor type will determine the mode of heat transfer:- radiation, convection and conduction. At high temperatures pyrolysis process is controlled by the rate of heat transfer which become dominant rather than the kinetics of the chemical reaction (Shafizadeh, 1982). High heating rates of upto 100°C/sec (fast pyrolysis) at temperature below 650°C with rapid quenching leads to more liquid fraction. Fast or Flash pyrolysis is used to maximize either gas or liquid products depending on process temperature and pressure. On the other hand slow heating rates (<0.133°C/sec) at low temperature (less than 450°C) maximize charcoal production. The conventional pyrolysis normally uses slow heating process to make charcoal but liquids and gaseous products are also produced in small quantities as by-products.

2.6.4 Effect of Moisture Content on Charcoal Quality and Yield

The moisture content of the feedstock is the second most important factor after temperature that affects charcoal quality and yield. According to Hollingdale *et al.* (1991) wood with high moisture content gives charcoal of high friability resulting in increased proportion of char fines and less lump charcoal yields. It has also been found that higher moisture content promotes charring and lowers the formation of organic oils resulting more charcoal formation (Gray *et al.* 1985). But too high a moisture content (>25%) means increased dwell time of the charge as heat required for evaporation of moisture overloads the system. To maintain the pyrolysis process a greater portion of the wood charge would have to be sacrificed for the drying process and this leads to reduced charcoal yield. Generally, moisture content of the feedstock slows down the rate of heat gain and therefore pyrolysis of wet biomass takes place more slowly (Beamont and Schwob, 1984).

The effect of moisture content on charcoal yield is to lower the effective process temperature during pyrolysis of wet biomass. Gray *et al.* (1985) found that Woodex (pellets rich in bark constituents manufactured by compressing wood and extruding it without any binder) at 16% moisture content gave a higher charcoal yield at temperatures below 340°C than dry woodex. The results are reproduced in figure 2.4. From the figure it can be seen that wet woodex yields more charcoal because moisture tends to slow down heat transfer such that on the average, pyrolysis takes place more slowly favourable for more solid yields. At pyrolysis temperatures below 340°C dry woodex gave more charcoal than wet woodex. This might be attributed to the significant amount of heat required for vaporization of moisture which led to combustion of higher proportion of the woodex to maintain the pyrolysis process.

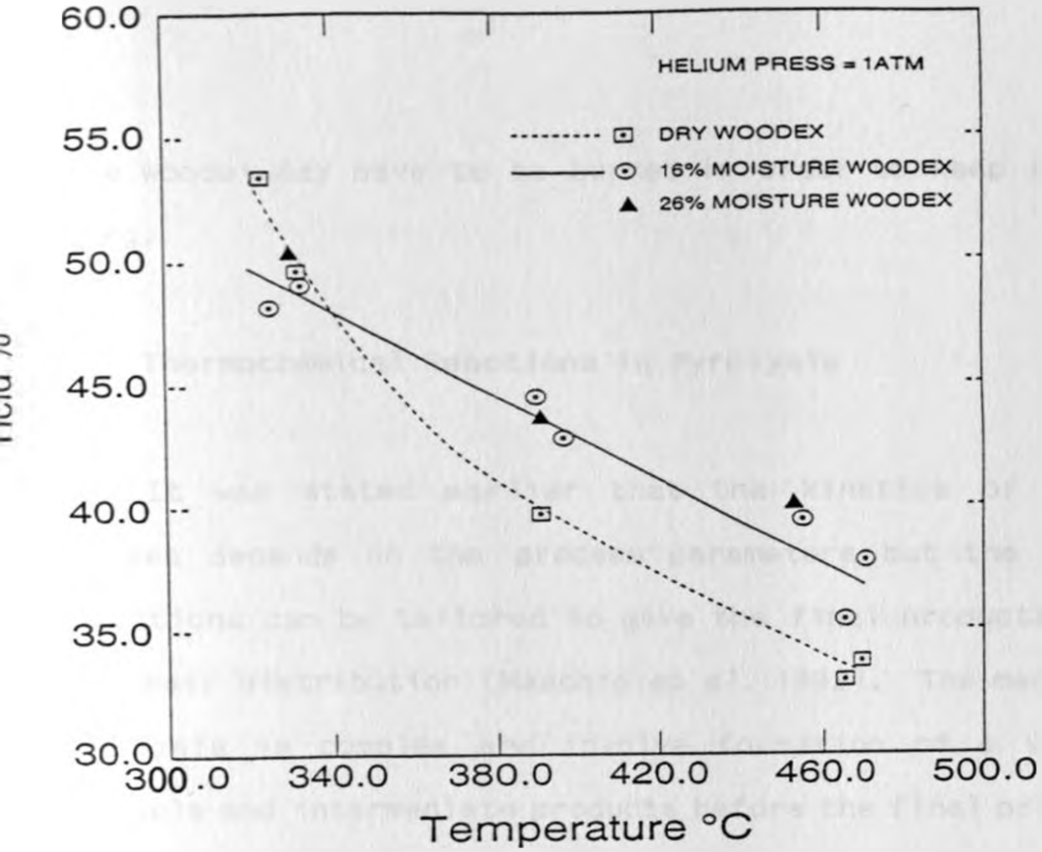

Fig. 2.4. Effects of moisture on the yields of char from untreated Woodex

Source: Gray, *et al.*, (1985)

Fig 2.4 illustrates the trend of charcoal yield on carbonization of woodex with different moisture content at temperatures between 300 and 500°C. From the figure it can be seen that generally wet woodex yields more charcoal than dry material at temperatures above 340°C but bellow this dry woodex gives more charcoal yield than wet woodex. This may be attributed to the cooling effects of moisture which reduces the rate of heat transfer at elevated temperatures thereby slowing down the rate of heat gain by pyrolysing substrate. This favours higher charcoal yield. At lower temperatures heat requirement for evaporating the moisture overload the system and more woodex may have to be burned in order to keep the system going.

2.7 Thermochemical Reactions in Pyrolysis

It was stated earlier that the kinetics of pyrolysis process depends on the process parameters but the operating conditions can be tailored to give the final products required and their distribution (Maschio *et al.* 1992). The mechanism of pyrolysis is complex and involve formation of a variety of unstable and intermediate products before the final products are formed namely: charcoal, liquids, and gases. Though the chemical reactions associated with biomass pyrolysis are complex and have not been fully fathomed by man, some of the reactions that are known to occur are given below.

1 $C + O_2 \longrightarrow CO_2$ - 394 MJ/kg-mol
2 $C + CO_2 \longrightarrow 2CO$ + 168 MJ/kg-mol
3 $C + H_2O \longrightarrow CO + H_2$ + 126 "
4 $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ - 84 "
5 $C + 2H_2 \longrightarrow CH_4$ - 281 "
6 $CO + H_2O \longrightarrow CO_2 + H_2$ - 33.6 "
7 $CO + \frac{1}{2}O_2 \longrightarrow CO_2$ - 252 "
8 $C_nH_4 \longrightarrow M/4CH_4 + (n-m)/4C$
9 $CH_4 + H_2O \longrightarrow CO + 3H_2$
10 $C + \frac{1}{2}O_2 \longrightarrow CO$ - 111 MJ/kg

Reaction 1 through 4 involve gasification of the fixed carbon in the biomass. Reaction 1 is the combustion of carbon to carbon dioxide which is highly exothermic and complete. Reactions 2 and 3 are endothermic and reversible, 4 is exothermic and unfavourable at high temperatures. The oxidation reactions 5 and 7 are exothermic and substantially irreversible whilst the water-gas shift reaction 6 is exothermic and reversible. Volatiles evolved in pyrolysis are further decomposed on heating to methane and higher hydrocarbons as in 8. More reactions of the hydrocarbons with steam 9 gives the synthesis gases (CO + H_2). The exothermic reactions above supplies the heat required to sustain the pyrolysis process.

2.8 Gross Calorific Value and Proximate Analysis

2.8.1 Gross Calorific Value

The gross calorific value (G.C.V) of a substance is the heat released on combustion of that substance in an oxygen-filled bomb calorimeter at constant volume. The conditions of combustion are such that the products of combustion are ash, gaseous carbon dioxide, liquid water, sulphur dioxide and nitrogen. The terms higher heating value and energy content are alternatively used for G.C.V. The energy content of fuel material is influenced by the type of biomass, moisture content and pyrolysis conditions for carbonized fuels. Wood has heating value of about 15-17 MJ/kg on wet basis but range from 19-22 MJ/kg for oven dry material (Hellwig and Tu-Munich, 1985). For carbonized fuels, energy content will depend on the chemical composition of the original biomass and the method of pyrolysis. Partially carbonized charcoal (torrefied wood) has calorific value of 23.0 - 24.0 MJ/kg, depending on the relative percentage fixed carbon, volatile and ash contents (Bourgeois and Doat 1985; Hollingdale et al 1991). Charcoal carbonized at higher temperatures (>400°C) has calorific value of between 29 and 32 MJ/kg of dry fuel (Diebold & Scahill, 1985; Pyle, 1977; Musonda, 1985).

2.8.2 Proximate Analysis

Proximate analysis is a method of describing the composition of a fuel material, assuming that it is made up of four main components:- fixed carbon, volatile matter, ash and moisture content. The percentage proportion of these components depends on the type of material and the pyrolysis process used to obtained the fuels. Charcoal produced at low carbonization temperatures (torrefied wood) has low fixed carbon but the overall charcoal yield by weight is high. Torrefied wood has high volatiles content (60-70%) compared to about 25% for fully carbonized (black) charcoal (Bourgeois and Doat, 1985). Charcoal from wood that is completely carbonized at high temperatures (normally 400-700°C) in traditional earth mould kilns is here referred to as Black charcoal (as opposed to the brownish torrefied charcoal). The advantage that could be exploited by briquetting torrefied sawdust is that softened lignin could act as an intrinsic binder during densification. Characteristics of torrefied wood and black charcoal are presented in Table 2.3

Table 2.3: Characteristics of Wood and its pyrolysis products

Property	Uncarbonized wood	Torrefied wood	Black charcoal
Process temp.	direct comb.	280-300°C	400-500°C
Fixed carbon	15%	25-40%	60-90 %
Carbon content[1]	50%	45%	15%
Charcoal yield[2]	-	75%	35%
Energy value[3]	100%	80-90%	30-50%
Calorific value MJ/kg	19-22	23-25	30-32
Volatile %	85[a]	70	20-25[b]

1-ratio of carbon to the initial fuel material

2- figures on wet weight basis.

3- % of initial energy content

sources Bourgeois and Doat (1985)
a - Resch (1982)
b - Fusako (1982)

The higher the pyrolysis temperature the lower the volatile content of the resulting solid residue (Sadakata *et al.* 1987; Hollingdale *et al.* 1991). Biomass in general has low ash content and normally in the range of 1 to about 10 % depending on the species and the part of the plant (Diebold and Scahill, 1985; Chembukulam *et al.* 1981). Volatile matter, moisture and ash contents of a fuel can be determined directly and fixed carbon found by difference. The methods of determination of volatile and ash use empirical procedures and therefore values obtained depends on the condition of the particular standard procedures followed for each test (Hollingdale *et al.* 1991). This involves heating the substance at a particular temperature for a specific period of time and then measuring the residual material to get the proportion of ash or carbonized residue. Proximate analysis of different biomass fuels are presented in table 2.4

Table 2.4: Proximate analysis of some biomass fuel

Type of fuel		Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)
Sawdust	1	7.0	0.14	78.8	14.1
	2	DRY	2.3	79.9	17.84
Torrefied wood	3	DRY	0.55	71.9	27.7
	4	DRY	0.35	68.7	30.9
Charcoal	5	DRY	1.0	15.0	73.0
	6	DRY	18.5	24.1	57.4

Sources

1. Wan and Cheng (1978) - for white pine sawdust
2. Chembukulam *et al.* 1981 - sawdust from mango wood.
3. Bourgeois and Doat, 1985 - using Pinus spp.
4. Hollingdale *et al.* 1991 - results for Eucalyptus spp.
5. Musonda, 1985 -for Eucalyptus species using brick kiln.
6. Chembukulam *et al.* 1981- Charcoal from teakwood sawdust carbonized at 450°C.

It should be noted here that moisture content represents physically bounded water while water released from thermo-chemical reaction of pyrolysis process constitutes the volatiles together with other gaseous hydrocarbons. From the table it can be noted that percentage fixed carbon increases whereas the volatile matter content decreases with stage of carbonization of biomass material. The fixed carbon content of uncarbonized sawdust (1 & 2) is between 14 and 18%, for torrefied wood it ranges from 27-30% (3 & 4) and that of fully carbonized charcoal is 73% and 57% (5 & 6) respectively for Eucalyptus and Teakwood charcoal. The ash content of biomass material is generally low ranging from o.14% to 2.3% except for teakwood sawdust charcoal with ash content of 18.5%. This high value for percentage ash content is caused by the (free) ash from the burnt out portion of the charge which is not separable from the fine sawdust charcoal.

2.9 Briquetting

Briquetting is the compaction or densification of low density material into hard solids of regular shapes called briquettes. Briquetting technology has been used successfully in many countries to amalgamate loose biomass into hard solids of regular shapes such as briquettes, pellets, or cubes depending on the densification equipment employed. The physical dimensions of briquettes commonly encountered in practice are diameter 30-80 mm and length 20-40 mm with density of about 500 Kg/m^3, (Eriksson and Prior, 1990).

2.9.1 Briquetting Material

In many developing countries large quantities of forest and crop residues that are presently under-utilized are available for conversion into charcoal briquettes for domestic purposes (Hislop, 1992). The suitability of the loose biomass material for briquetting will depend on the nature and type of biomass as this will have a bearing on the quality of the end product. The factors that affect the density and strength of charcoal briquettes are:-

i) Particle size distribution. Most densification equipment requires that the feedstock particle length be no more than one quarter of the diameter of the resulting briquette/pellet. In some cases size reduction using hammer mill is necessary and this further increases the cost of the briquettes. In addition to biomass size reduction cost, other costs associated with pre-processing of the loose feedstock include drying, cleaning or removal of metal /stones and other foreign matter (Hollingdale *et al.* 1991)

ii) Densification pressure. The pressure employed in briquetting and the retention time of the pressure will determine the density of briquette obtained. This densification pressure depends on the equipment but usually range from 5-100 MPa (Eriksson and Prior,1990). Resch (1982) states that the energy requirement for densification of sawdust varies from 0.12 to 0.44 MJ/kg of pellets depending on the equipment and the wood species. The energy demand for briquetting process implies that briquettes will be more expensive than other biomass fuels. Briquetting sawdust at elevated temperature (180-300°C) may achieve self-bonding due to softened lignin in the material, but briquettes have to cool under pressure, implying more retention time (Arends, 1985).

iii) Type and Ratio of binder used. There are many binders that have been used in briquette making some of which are gums, molasses sugar, wood/coal tar, starch, sulphite liquor, waste cement and polyvinyl acetate. The proportion of the binder used will influence the consistency of briquettes. For example, starch required for loose biomass with initial density of 270-320 Kg/m^3 range form 5-7% and that of 160 kg/m^3 range form 11-12% starch, (Hollingdale *et al.* 1991). Heat treatment (250-300°C) can also be used to soften the lignin of uncarbonized biomass to achieve self-bonding. But densification of charred biomass would require a binder because the lignin component would be destroyed during pyrolysis stage.

iv) Initial moisture content and density of the loose material. In general most densification equipment requires that the feedstock should have moisture content of 10-20% (w.b). But the resulting briquettes must be dried to less than 10% M.C to avoid decomposition and disintegration of briquettes during storage and handling. The combustion and storage characteristics of briquettes are influenced by nature and type of feedstock and humidity of storage environment. Briquettes made from high density charcoal have greater crushing strength than that from low density biomass (Hollingdale *et al.* 1991)

2.9.2 Briquetting Equipment

Many commercial briquetting plants exist in the market and they are mainly in four categories:- Piston press, screw press, pelletizing mill and roll briquetter (Bourgeois and Doat,1990). With the exception of small-scale manual operations these briquetting machines are capital intensive and usually associated with high operation cost and are only viable when operated on large industrial scales. It is generally considered that economies of scale do not favour turnover of less that 1 Ton/hour of charcoal briquettes produced on continuous basis (Hollingdale *et al.* 1991). The availability and price of the raw material will determine the price of the output and thus the importance of locating the briquetting plant near the source of biomass. In these system drying of sawdust is achieved by open air sun-drying or solar drying units (Mathews, 1987). It has been found that roll briquetters and pelletizing mills have lowest cost per ton of densified material but the quality of briquettes may not equal that of either piston or screw press but nevertheless give good charcoal for domestic use. Replacement of fuelwood in domestic and industrial sectors with more capital intensive fuel products like sawdust briquettes is technically feasible but the economic and social implications on the prospective users is adverse. The new fuel products would be expensive and the user will have to adopt their domestic cookers to charcoal briquette which must be competitive in prices compared with conventional fuels.

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CHAPTER 3

EXPERIMENTAL FACILITY AND METHODOLOGY

3.1 The Kiln

Carbonization of sawdust was done in a square cross-section brick-lined metal kiln built on the ground with 18G metal sheet. This kiln was built initially for another project that was to use natural convection current to fire and maintain pyrolysis process. Thus the dimensions of the of the kiln were already fixed and they were sides 1mx1m and height 1.5m inclusive of the plenum space below a raised floor. The raised floor was 0.4m from the ground level and was plastered with brick work and clay mortar, save for the central position occupied by 46cmx46cm ash tray. The top cover was made of 18G metal shed and had no brick linings. Bolts were used to fasten the lid onto the top of the kiln walls. At the centre of the top cover was a round hole 102mm diameter for smoke emission. A straight pipe 152mm diameter was used as smoke stack or chimney during firing phase and placed on top of the hole. When a steady fire had developed this chimney was removed and replaced with a 102mm diameter pipe that was bent so as to direct the gaseous products to one side. The bent pipe was necessary for ease in controlling the exhaust gases by adjusting a throttle valve attached to the pipe. Also condensates from the gaseous products could drain out easily through the bent pipe. If the straight pipe pointing upwards was used Liquids and tar condensing would drip back into the kiln rewetting the sawdust in the kiln.

Bridging of sawdust caused complete combustion along some cavities and lack of carbonization in some patches within the sawdust. This was overcome by occasional stoking of the substrate with an iron bar through the top outlet hole ensuring that the thermcouples were not disturbed. The carbonization equipment used is shown in plate I A and B in Appendix D. An illustration of the equipment kiln is also shown in Fig. 3.1 below.

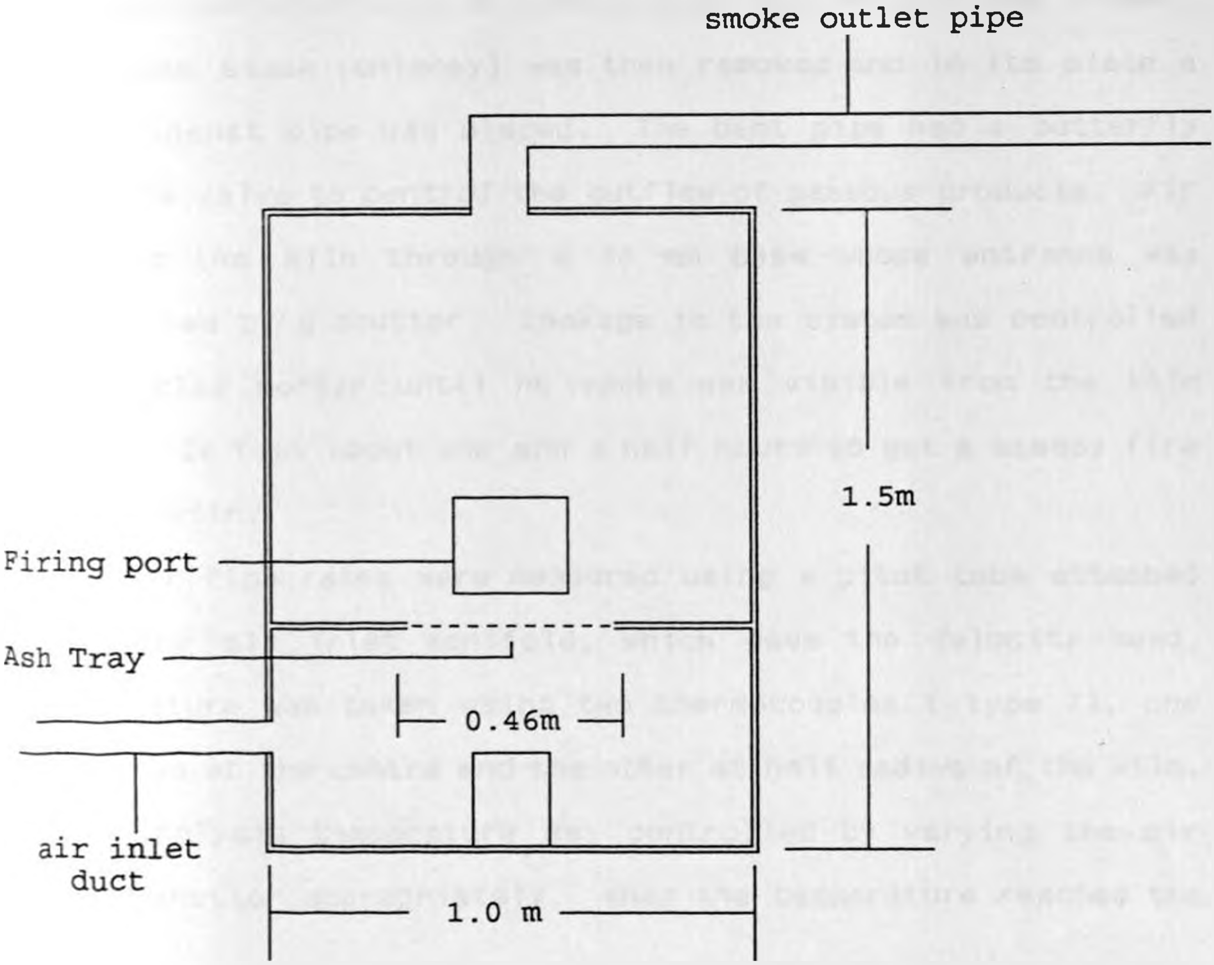


Fig. 3.1 Carbonization Kiln

3.2 Procedure

A batch of 50 kg of sawdust was weighed for experimental test runs. A small sample was taken from the batch for moisture analysis. The same weight of wood logs was taken and placed in kiln and ignited with the aid of fire sticks, before putting the sawdust. When the fire in the kiln had burned steadily the batch of 50 kg sawdust was carefully placed on the fire without extinguishing it. The top cover was then attached to the kiln and a smoke stack placed on top of a hole on the lid to enhance firing. When the material in the kiln had achieved steady burning characteristic a side door or firing port was closed. The smoke stack (chimney) was then removed and in its place a bent exhaust pipe was placed. The bent pipe had a butterfly throttle valve to control the outflow of gaseous products. Air entered the kiln through a 58 mm pipe whose entrance was controlled by a shutter. Leakage in the system was controlled using clay mortar until no smoke was visible from the kiln sides. It took about one and a half hours to get a steady fire in the kiln.

Air flow rates were measured using a pitot tube attached into the air inlet manifold, which gave the velocity head. Temperature was taken using two thermocouples (type T), one attached at the centre and the other at half radius of the kiln. The pyrolysis temperature was controlled by varying the air inlet shutter appropriately. When the temperature reached the required ultimate point the air flow rate through the duct was reduced to maintain the temperature. To make the system more sensitive the throttle valve in the outlet duct was also changed either to reduce or increase smoke emission which in turn affected the air entry. Pyrolysis process took 25-30 hours per batch from the time of ignition, depending on moisture content of the charge and the pyrolysis temperature. To stop the process and allow cooling, both the inlet and outlet ducts were closed completely and all leakages thoroughly sealed. The carbonized material was removed after further 6 hours of cooling after completion of pyrolysis. The pyrolysed solid residue was then removed and separated according to the extent of carbonization. The different categories of charred material were weighed and recorded.

The first run was made using the sawdust as received from the sawmill yard. A sample of the sawdust was taken for moisture analysis using oven dry method. The hot junctions of thermcouples were then inserted in the kiln before placing the top cover while ensuring they lay within the sawdust. The carbonized material was then removed from the kiln and carefully separated into four categories: - wood charcoal, completely carbonized and partially carbonized sawdust charcoal, uncarbonized material and ash mixed with fine char. Any fire that was still smouldering was put off with water. The solid residues were weighed separately and a small sample from each was taken for moisture content determination. It was noted that the ash residue containing some unrecoverable fine charcoal were formed at the bottom near the ash tray (sieve). Wood charcoal was separated from sawdust charcoal by sieving using a tray wire. The weights as recorded in kilogram were later converted to dry weight by correcting for moisture content. Yields for the different pyrolysis test runs were obtained in the same way and recorded. Results from carbonization process at different temperatures on percentage weight yields and energy content for eight experimental runs are tabulated in Appendix C.

3.3 Temperature measurement

Thermocouples used for temperature measurement were made locally from constantan and copper wires, (Type T). The thermocouples were first calibrated using a furnace that could reach a temperature of 600°C. To read the voltage developed between the hot and cold junctions the wires were connected to the terminals of a digital voltmeter. The digital multimeter powered by rechargeable dry cadmium cells and marketed under the trade name SOLARTRON (number 7045) was used for voltage readings (in mV). The multi-meter had a sensitivity of upto 0.001mV and could be used to read amperes and the ambient temperature if required.

The temperature of the system was monitored using two thermocouples whose hot junctions were placed in the sawdust, one at the centre and the other at half radius. The cold junctions were inserted in ice/water mixture in a thermos flask outside the kiln. They were connected to the voltmeter (the *solartron*) which gave the electromotive force generated between the cold and the hot junction. The voltage was taken every 15 minutes and an average for the hour calculated. The voltages read were converted to temperature using a calibration chart. The apparatus for temperature measurement as well as air flow rate manometer is shown in Plate II in Appendix D.

Close monitoring was necessary so that the temperatures could be maintained within the required temperature range. Air flow rate into the system was varied accordingly to control the temperature. When temperatures rose beyond the top temperature limit air entry at the inlet duct was reduced by closing a shutter and vice versa if the temperature fell below the lower set temperature point.

A rapid rise of temperatures was noted when the temperature reached about 400°C. This was attributed to the dominant exothermic reactions at this temperature that sustained the process. In addition a lot of tar and aqueous liquids, including oil were evolved at this stage. A fraction of this liquid condensed inside the outlet pipe but some of it evaporated with the smoke. To maintain the temperatures below 450°C the system was sealed completely on reaching 400°C as it was found to continue to rise slowly to about 450°C.

3.4 Air flow measurement

The airflow at the air inlet duct was controlled by a shutter valve and at the same time exhaust gases were controlled by a butterfly valve attached inside the outlet pipe. A manometer attached in the air inlet duct measured the air flow rate. The air flow measuring apparatus consisted of a pitot-static tube, type MK 5, complete with its manometer liquid reservoir and capillary tube. It had allowance for changing the angular position of the capillary tube from the vertical to alter the scale with corresponding multiplication factor. This arrangement enabled the reading of the velocity head with a sensitivity of 0.05mm when the capillary stem was at the lowest position. This was necessary for the small velocity head encountered. The velocity head recorded was used to evaluate the air flow rate through the air inlet duct.

3.5 Gross Calorific Value Determination

The gross calorific values of the various biomass fuels were determined using an adiabatic bomb calorimeter as described in ASTM standards Milne *et al.* (1990). The adiabatic bomb calorimeter system type IKA C400 K was used for energy content determination of fuel biomass. The substance to be burned was weighed in air and then burned in a bomb-calorimeter in pure oxygen at 30kN/m^2 by being brought into intimate contact with an ignition wire. The heat evolved by burning of specimen raises the temperature of the calorimeter system and this is used to work out the heat of combustion (calorific value) of the substance.

3.6 Densification Tests

Densification experiments were carried out using two different machines: (1) hand operated hydraulic press and (2) mechanical hand briquetter.

3.6.1 Hand Operated Hydraulic Tensile Testing Machine

Densification of the sawdust charcoal was done using a Tensile testing machine (T.I.C) normally used for material testing. It gives the pressure applied on the load in a dial gauge attached to it. Compression force was varied from 1 kN to 5 kN which translated to a compression pressure of 175 - 900 N/cm^2 and a retention time was about 1 minute for tests performed with this hydraulic press. An improvised pipe mould with a fitting piston ram had an internal diameter 28.5 mm and length 125 mm whose inside was polished as much as possible to reduce friction forces. The dimensions were chosen to be as close as possible to the existing manual press which was 27.0 mm and similar in size to those found in practice. It was reported in section 2.9 that dimensions of briquettes made by different workers are diameter 30 - 80 mm and length 20 -50 mm. The length of the mould was chosen to fit the position of the hydraulic press and determined the amount of loose charcoal to be compressed at once. The sawdust charcoal being briquetted was first mixed with the binder and a little water to enhanced consistence properties. The binders used in the study were starch and molasses. For starch the required amount of water was first boiled before mixing to enhance its binding properties. Different compression tests were applied for different binder ratios for all categories of sawdust charcoal obtained. Plate III A in Appendix D show the hydraulic press (T.I.C) machine used.

3.6.2 Mechanical Hand briquetting Machine

A mechanical hand briquetting machine fabricated by Appropriate Technology Centre Nairobi, was used for hand briquetting. The machine had two compartments consisting of two hoppers and pipe moulds each 27.0 mm diameter with a fitting compression rod. Densification was achieved by putting the loose charcoal fines in the hoppers whose base was grooved to join a section of the 27.0 mm diameter pipe along which the compression rod moved pushing some material into the pipe mould whose end had a removable stopper. The mechanical linkage was such that the force developed on the piston was twice the effort applied by the hand on the lever. To measure the applied force a spring balance was attached to the hand lever and pulled. The human's effort that could be applied by an ordinary man range from 300-500N. This translated to a loading of between 600N and 1000N with the given arrangement. On average the force applied by human effort was 450N or a compression force of 900N. Since there were twin briquetting moulds at the same time, the load applied to one was 450N on average. The hand briquetting equipment used is illustrated in Plate IV A and B (Appendix D)

3.7 Combustion Characteristics

After adequate drying in the sun or open shade charcoal briquettes were burned in an ordinary charcoal burner (jiko). The purpose of this test was to compare the combustion characteristics of charcoal briquettes with ordinary wood charcoal. The charcoal burner used was a type known locally as Kenya Ceramic Jiko (KCJ) No. 12 with ceramic lining on the inside walls including the perforated floor and marketed by Kenya Energy Non Governmental Organization (KENGO). The burner had side port opening into the lower chamber provided for lighting, ash removal and ventilation (Plate V A in Appendix D). The time taken to ignite (steady glowing combustion) as well as the time taken by the fire to die out were noted. Smoke emission and appearance of a flame were also observed visually. After about 15 minutes of burning the burners were taken inside a room and the door closed to reduce wind interference. The charcoal fire was used to warm up the room and the air temperature was monitored and recorded at various points. The temperature was taken at points; 30cm, 60cm, 120cm, 180cm and 240cm from the burner all at 60cm above the floor. Direct radiation was minimized by using a wooden shield between the charcoal fire and the thermometers. The purpose of this test was to compare the effectiveness of using briquettes and ordinary charcoal in warming up a room. Plate VI in Appendix D shows the experimental set up for measuring room air temperature.

3.8 Density Measurements

Dimensions of the cylindrical briquettes obtained in densification experiments were used to work out apparent density of briquettes. The diameter and length of the briquette were measured using a pair of calipers at two places each and average found and used for calculation of the volume. The weight of the individual briquette was obtained by direct weighing with a weighing balance(type oertling 21 TD). Hence density could be calculated as the ratio of weight to volume.

3.9 Moisture Content Determination

The general procedure for determining moisture content of wood using oven dry method was followed. A sample of material was taken and weighed and put in the oven at 105-110°C for 24 hours after which it was removed and weighed again. The difference in weight gave the moisture content.

3.10 Ash Content Determination

The standard method for ash content determination in wood pulp was used to evaluate the percentage ash content on dry weight basis. A specimen of the dry fuel was ground, weighed and then placed in a crucible and heated gradually in furnace at controlled temperatures to about 600°C. The sample was burned until all the carbon was consumed and the residual ash attained constant weight.

3.11 Volatile Matter Determination

To determine the volatile matter in the fuel the standard methods for wood fuels described in ASTM 872-82 (Milne, *et al.* 1990) was followed. In this method 1g of oven-dried specimen was weighed and then placed in platinum crucible with a tight-fitting lid and heated in a furnace at 930 - 970°C for about 7 minutes while occasionally stirring with a wire. After cooling in a desiccator the weight of the residue was taken. The loss in weight was then recorded as the weight of volatile matter in the sample.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Effect of Temperature on charcoal yield

The effect of pyrolysis temperature on charcoal yields from a traditional kiln was studied for temperature ranges 200-350; 350 - 450; 450-550 and 550-650°C. The Pyrolysis temperature was taken every 15 minutes and the average for the hour calculated. The temperatures were maintained at the required range by altering the air flow rate into the kiln. Examples of the temperature profile curves recorded during carbonization are given in Appendix B. The weight yields of charcoal obtained from pyrolysis at temperatures between 200°C and 650°C are presented in Table 4.1.

Air entered the system from the plenum space at bottom through the ash tray and some of the material near the entrance was burnt into ash whereas that next to the walls of the kiln was hardly charred. This was due to un-equal distribution of air within the kiln because of non-uniform pressure drop throughout the cross section of the system used. Bridging (or overhanging) of sawdust and formation of cavities was another problem encountered with this fixed bed system and contributed to poor carbonization.

Table 4.1: Charcoal yields at different temperature ranges

MAXIMUM TEMP. °C	S/D BLACK % (d.b)	S/D TORR. % (d.b)	WOOD CHAR. % (d.b)	OVERALL YIELD % (d.b)	RAW[a] SAWDUST % (d.b)	RAW WOOD % (d.b)	ASH + WASTE[b] %
200-350	16.5	11.5	15.1	20.5	24.3	16.1	4.5
350-450	14.0	6.5	17.2	18.7	18.1	7.4	3.6
450-550	22.7	8.3	26.0	28.4	0.0	0.0	2.5
550-650	16.8	8.1	20.4	22.6	0.0	0.0	2.3

a - raw means uncarbonized material recovered from the kiln
b - includes unrecoverable sawdust and fine charcoal mixed with ash
wood charcoal - charcoal from Eucalyptus tree
black s/d charcoal - fully carbonized charcoal from sawdust
Torrefied s/d - not fully converted charcoal from sawdust
s/d - sawdust

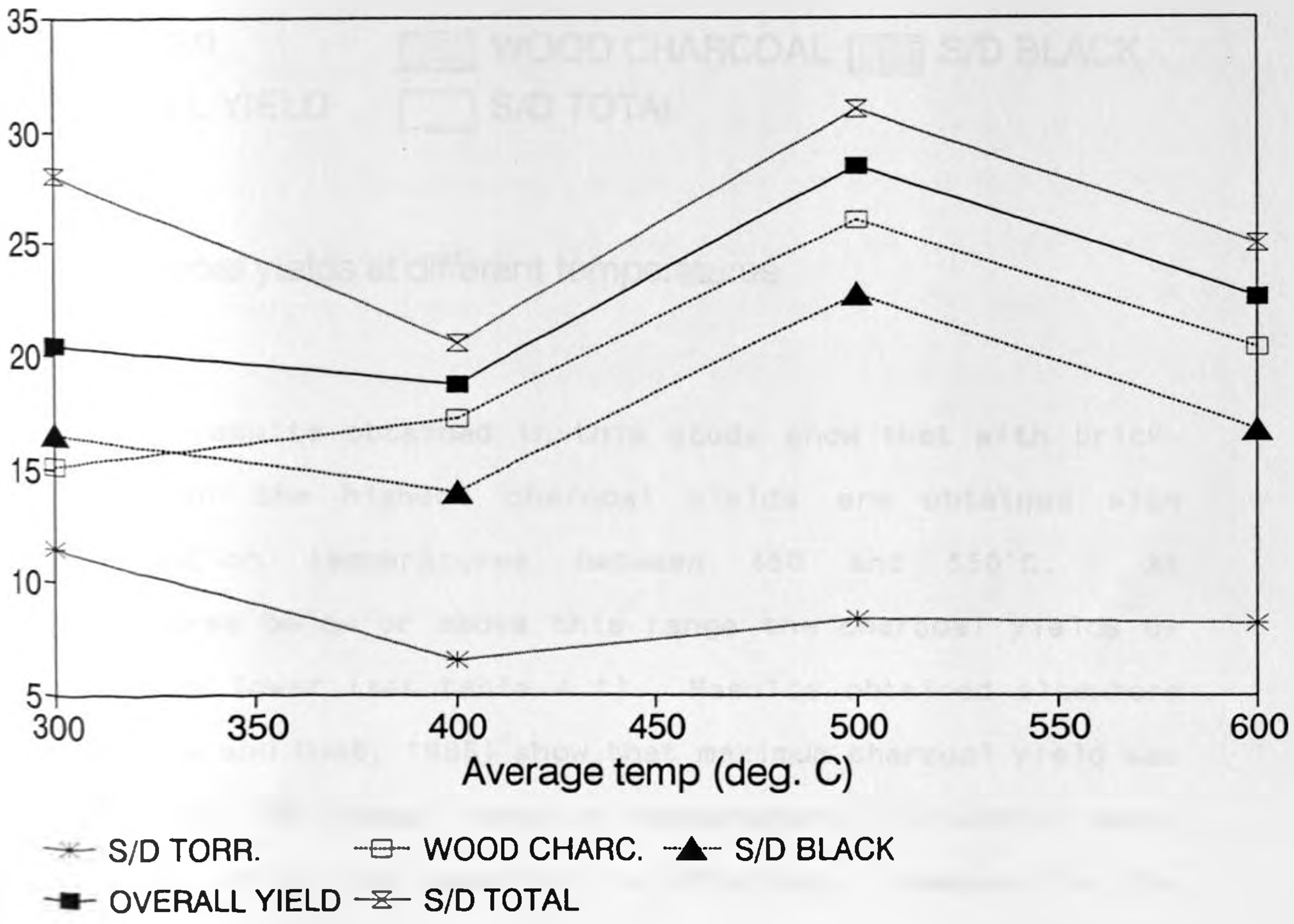
The figures give charcoal yields obtained at various pyrolysis temperatures as percentage of the original biomass charge in dry weight basis. From the table it can be deduced that charcoal yields and quality are influenced by the temperature range within which pyrolysis took place.

The columns of black sawdust charcoal and torrefied sawdust are percentage yields relative to sawdust alone and that of wood charcoal relative to wood only. The wood logs used in this case was eucalyptus tree. The overall yield represent the ratio of total dry weight of sawdust charcoal plus wood charcoal to the total dry weight of input. Uncarbonized (referred to as raw) materials were also given as percentages of their individual input but ash was treated as a fraction of total weight of feed. As can be seen from the table the solid pyrolysis end-products were divided into: black sawdust charcoal, torrefied sawdust, wood charcoal, uncarbonized material and ash. Their relative proportions depended on the carbonization temperature and moisture content. Plate VII (Appendix D) illustrate the various charcoal types obtained from the carbonization process. Black charcoal from sawdust was always more than the torrefied fraction and were separated during removal by visual judgement.

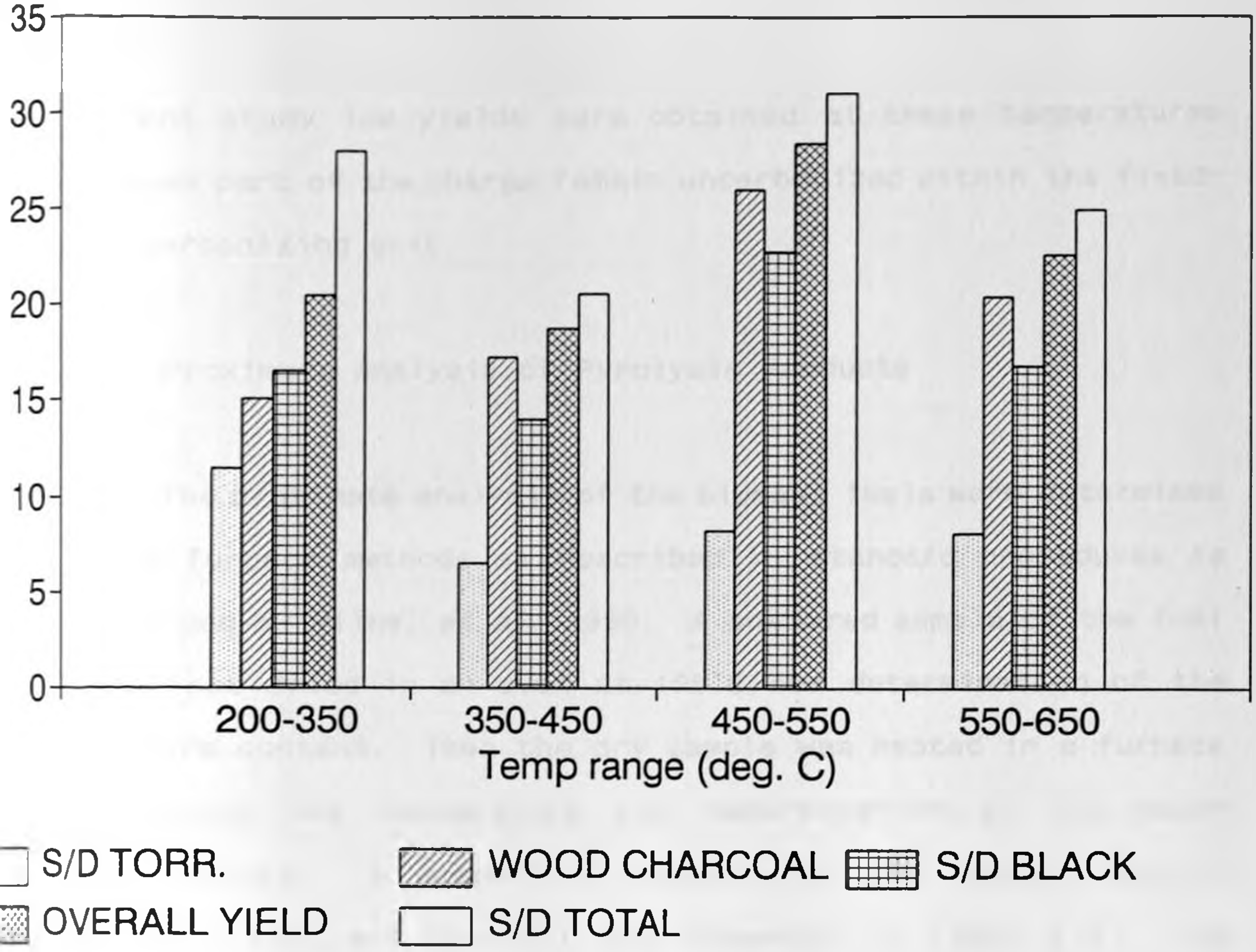
From the table it can be seen that there is a general increase in yield with temperature for all the biomass fractions upto about 500°C when it starts to decline from 28% to 23% (overall yield at 550-650°C). However more yields were realized at 450-550°C (overall yield 28%) and at 200-350°C (overall yield 26%). Lowest yields were obtained at temperature range of 350-450°C which was suspected to have been caused by excessive burning of the charge. It was expected that more charcoal yield would be obtained at low temperatures (Elders and Cutter, 1983), but this was not realized as part of the feedstock remained uncarbonized at these low temperatures, resulting in less charcoal produced from the system used. At lower temperature (200 - 350°C) some of the charge remained uncarbonized and this was attributed to the poor heat distribution centre to the walls of the kiln which resulted in incomplete conversion. At higher temperatures (450-650°C) complete conversion was achieved without uncarbonized patches in the system.

When temperature was allowed to rise beyond 500°C the system emitted bluish white smoke. Charcoal obtained at temperatures between 500°C and 650°C was fully charred with little torrefied material and no uncarbonized patches even at the corners of the kiln. The yield at this stage was however found to be lower than that obtained at 450-550°C temperature range. This was thought to be due to greater portion of the substrate burned to achieve the high temperatures. Some of this losses could also be accounted for by devolatilization of some of the charcoal as gasification proceeds simultaneously with carbonization at temperatures above 500°C (Haggan, 1985).

The percentage charcoal yield obtained are also illustrated by a graph and a bar chart as shown in figures 4.1 and 4.2 below.



g. 4.1 Charcoal yields at various temperatures



g. 4.2 Charcoal yields at different temperatures

The results obtained in this study show that with brick-lined kiln the highest charcoal yields are obtained with carbonization temperatures between 450 and 550°C. At temperatures below or above this range the charcoal yields by weight was lower (see table 4.1). Results obtained elsewhere (Bourgeois and Doat, 1985) show that maximum charcoal yield was expected at the lowest range of temperature (200-350°C) where partially carbonized material is obtained. However in the current study low yields were obtained at these temperatures because part of the charge remain uncarbonized within the fixed-bed carbonizing unit.

4.2 Proximate Analysis of Pyrolysis Products

The proximate analysis of the biomass fuels were determined using furnace methods as described in standard procedures as described by Milne, *et al.* 1990. A powdered sample of the fuel was first dried in an oven at 105°C for determination of the moisture content. Then the dry sample was heated in a furnace at appropriate temperature for determination of its major constituents. A summary of results of the composition of sawdust, wood and charcoal are presented in Table 4.2. The table shows the percentage constituent of the sawdust and their pyrolysis products in dry weight basis. The results obtained are similar to those given in literature (Table 2.4). The proximate analysis of Kahawa coal (coffee husk briquettes) are also given in the table for comparison.

Table 4.2: Proximate analysis of wood, sawdust and their pyrolysis products.

BIOMASS FUEL	VOLATILE MATTER % (w.b)	FIXED CARBON %(d.b)	ASH CONTENT % (d.b)
Black Sawdust charcoal	38.4	56.2	5.4
Torrefied sawdust	46.2	50.2	3.6
Wood charcoal[a]	27.3	70.6	2.1
Sawdust (raw)	84.2	14.4	1.4
Kahawa coal[b]	20.0	65.0	15.0

a _ Charcoal from Eucalyptus carbonized together with sawdust as feedstock using the brick-lined kiln.

b _ Coffee husk charcoal as quoted from Laichena J.K (1992).

Complete test results of proximate analysis of the various biomass fuel and their pyrolysis products are given in Table 4.3 below. The fuels was divided into four categories : A-fully carbonized charcoal (black), B-Torrefied or partially carbonized sawdust and C - Slightly carbonized or roasted sawdust charcoal and D - for fully carbonized wood charcoal. The same analysis was performed for the briquettes obtained with different binders and the results also tabulated.

Table 4.3: Proximate analysis of biomass fuel

FUEL TYPE	MOISTURE CONTENT % w.b	ASH CONTENT % d.b	VOLATILE CONTENT % d.b	FIXED CARBON % d.b
BLACK S/D CHARCOAL	18.53	5.673	41.62	52.25
TORREFIED SAWDUST	29.87	6.133	44.41	49.91
BLACK S/D CHARCOAL	48.2	5.033	24.31	70.66
TORREFIED SAWDUST	42.68	1.855	39.4	58.75
ROASTED SAWDUST	16.54	2.93	52.71	44.36
SAWDUST	34.77	1.4	84.2	14.4
WOOD CHARCOAL	17.53	2.083	27.27	70.64
BLACK S/D CHARCOAL + 20%M	42.7	5.41	37.9	56.69
BLACK S/D CHARCOAL + 8% S	21.3	6.37	41.4	52.23
ROASTED S/D + 20%M	49.9	4.17	50.7	45.13
STARCH	12.7	0.8	99.1	0.1
MOLASSES	21.9	6.6	92.4	1

A - Black sawdust charcoal- Fully carbonized charcoal
B - Torrefied - partially carbonized sawdust
C - Roasted - slightly charred (brown) sawdust
D - Wood charcoal - charcoal from Eucalyptus tree

S/D - sawdust

M - Molasses binder

S - Starch binder

From Table 4.3 it is seen that both wood charcoal and black sawdust charcoal exhibited highest fixed carbon content of 70.6% and 56.2% respectively and the lowest volatile matter of around 27.3% and 38.4% respectively. Torrefied sawdust had intermediate values for fixed carbon and volatiles with 50% and 46.2% respectively. These results show that the fixed carbon content of biomass depends on the extent of carbonization.

Fully carbonized charcoal has a higher fixed carbon content but less volatile matter than torrefied material (Knight J.A. 1976). This means that the pyrolysis process determines the quality of charcoal obtained as indicated by the percentage fixed carbon of pyrolysis products. The quality of charcoal from the carbonization process was influenced by the maximum temperature reached and the retention time at that temperature.

There was no variation on the proximate analysis of charcoal briquettes mixed with a binder from that without a binder. Ash content for all the biomass under consideration was low (below 3.5%) except for black sawdust charcoal which had 5.4 %. This was thought to have been due to "free" ash contamination of the fully carbonized fraction from the completely burned portion of sawdust which was difficult to separate during removal from the kiln. Similarly kahawa coal has high ash content (15%) because of its method of production where the husk on the surface of production pit is burned to finish off the conversion process and no ash separation is done (Mwirigi, 1993). Molasses and Starch were found to consist of mainly volatiles which make up 92% and 99% respectively.

4.3 Energy content analysis

The energy content evaluation was done for both feed material and pyrolysis products. The energy content analysis was done using adiabatic bomb calorimeter method. The energy content was determined from the heat value and the dry weight of fuel product obtained. Table 4.4 shows the calorific value of the various input material and their pyrolysis products in dry weight basis. The table shows the energy value in MJ/kg of fuel material and the figures are similar to those found in Literature also shown in the table alongside the experimental results (Diebold & Scahill, 1985; Bourgeois and Doat, 1985). These results indicate that energy content of carbonized biomass material is influenced by extend of pyrolysis.

Table 4.4: Calorific value of wood, sawdust and pyrolysis products

Calorific value MJ/kg	Black S/D charcoal	Torrefied Sawdust	Wood charcoal	raw Sawdust	Kahawa coal
Experiment	28	23	29.5	19.3	-
Literature	30-32	24-25	30-32	20	26

Fully carbonized (black) charcoal was found to have more calorific value than both partially carbonized product and sawdust. Sawdust had energy content value of 19.3 MJ/kg oven dry basis while fully carbonized (black) charcoal exhibited higher calorific value of 28 MJ/kg and 29 MJ/kg oven dry samples for sawdust charcoal and wood charcoal respectively. Torrefied sawdust was found to have calorific value of 22-23 MJ/kg which was between that of wood and black charcoal. The torrefied fraction was divided into two categories according to the extend of carbonation:- Partially carbonized and roasted. Fully carbonized charcoal had the highest value for heat content followed by torrefied material and then uncarbonized biomass fuel. Complete results for the energy content determinations are summarized in table 4.5.

Table 4.5: Evaluation of energy content

TYPE OF FUEL	GROSS ENERGY (cal)	CORRECTED for CAPSULE + WIRE (cal)	NET ENERGY	
			kcal/kg	MJ/kg
BLACK SAWDUST CHARCOAL	1462.9	374.4	6.47	27.09
TORREFIED SAWDUST	1441.8	362.9	5.46	22.88
BLACK SAWDUST CHARCOAL	1726.0	390.8	6.94	29.11
TORREFIED SAWDUST	1341.91	326.4	5.42	22.68
ROASTED SAWDUST	1376.6	415.8	5.05	21.15
RAW SAWDUST	1168.2	365.9	4.57	19.14
WOOD CHARCOAL	2878.4	473.5	6.64	27.80
TAR RESIDUE	2689.0	444.9	6.62	27.71
BLACK S/D CHARCOAL + 30% M	2841.6	460.6	6.35	26.59
BLACK S/D CHARCOAL + 8% S	2752.1	452.3	6.49	27.16
ROASTED SAWDUST + 30% M	2483.8	470.0	4.91	20.57
STARCH	3104.7	458.3	3.98	16.67
MOLASSES	3925.6	459.4	4.36	18.26
WOOD CHARCOAL	3868.5	468.3	7.29	30.53

S/D - Sawdust

Table 4.6 shows the energy yield from the pyrolysisprocess as compared to the initial energy input. The table gives percentage energy yield of pyrolysis product in relation to the initial total energy of the raw material. These results only reflect the energy recovered as carbonized solid residue and exclude energy lost as uncarbonized residue, unrecovered char in ash or gaseous pyrolysis products. The energy yields are also shown diagrammatically in Fig. 4.3 bellow.

From these results better energy yields is obtained than the actual weight yields (Table 4.1). This is attributed to the fact that the end-products have higher calorific value than uncarbonized material and this is reflected in higher energy output in percentage basis. The above analysis excludes the energy required for transportation and briquetting.

Table 4.6: Energy yield of Pyrolysis products

	Energy Yield (% of initial input d.b)				
Temp. °C	sawdust torrefied charcoal	wood charcoal	black sawdust charcoal	Overall yield	sawdust total yield
200-350	14.0	23.1	24.9	29.435	38.9
350-450	7.9	26.3	21.1	27.49	29
450-550	10.1	39.6	34.2	41.84	44.3
550-650	9.9	31.1	25.3	33.015	35.2

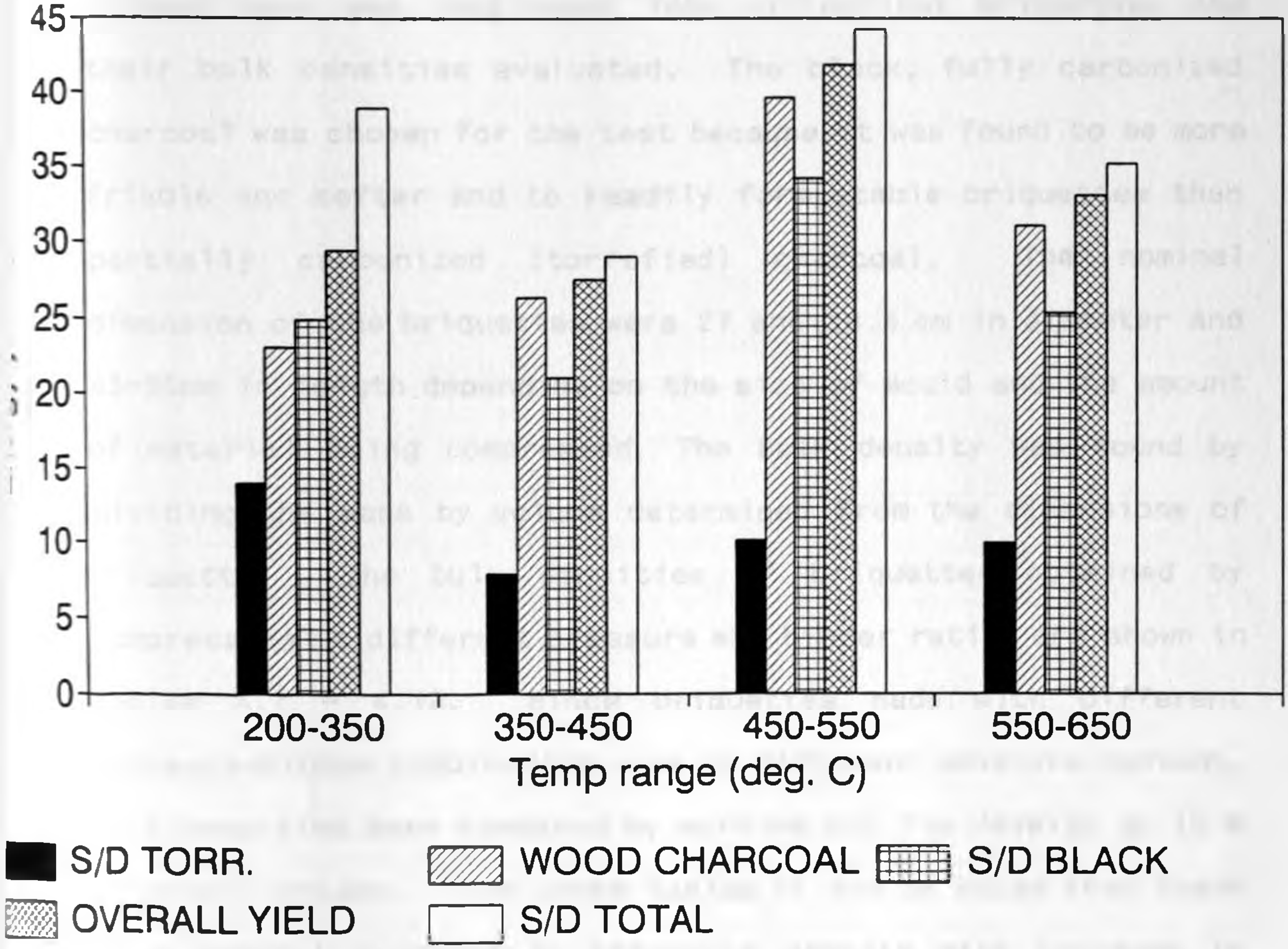


Fig. 4.3 Energy yields at different temperatures

4.4 Bulk Density of Charcoal Briquettes

Loose black sawdust charcoal obtained from sawdust from cypress wood was compressed into cylindrical briquettes and their bulk densities evaluated. The black, fully carbonized charcoal was chosen for the test because it was found to be more friable and softer and to readily form stable briquettes than partially carbonized (torrefied) charcoal. The nominal dimension of the briquettes were 27 and 28.5 mm in diameter and 45-55mm in length depending on the size of mould and the amount of material being compressed. The bulk density was found by dividing the mass by volume determined from the dimensions of briquette. The bulk densities of briquettes obtained by compressing at different pressure and binder ratios are shown in Tables 4.7 - 4.13. Since briquettes made with different pressure-binder combination were at different moisture content, bulk densities were compared by working out the density at 10 % moisture content. From these tables it can be noted that there is a general increase in briquette density with increase in compression pressure and binder ratio.

4.4.1 Effect of Compression Pressure on Briquette Bulk Density

The effects of compression pressure on stability and density of briquettes mixed alternatively with 5% molasses and 3% starch as binders were determined. The ratio of binders used was chosen because the intention was to achieve stable briquettes with a little binder as possible so as to minimize the cost. The results obtained from a hand-operated hydraulic press machine are summarized in tables 4.7 and 4.8. Detailed results of bulk densities are shown in Tables 4.9 and 4.10

Table 4.7: Bulk density for 5% molasses-bound briquettes

COMPRESSION FORCE		DENSITY AS REC. kg/m^3	DENSITY AT 10% M.C kg/m^3
FORCE (KN)	PRESSURE (N/cm^2)		
0	0	162.8	158.5
1	175	435.4	428.2
2	350	493	489.7
3	525	536.3	529.8
4	700	519.2	520.3
5	875	537.3	540.2

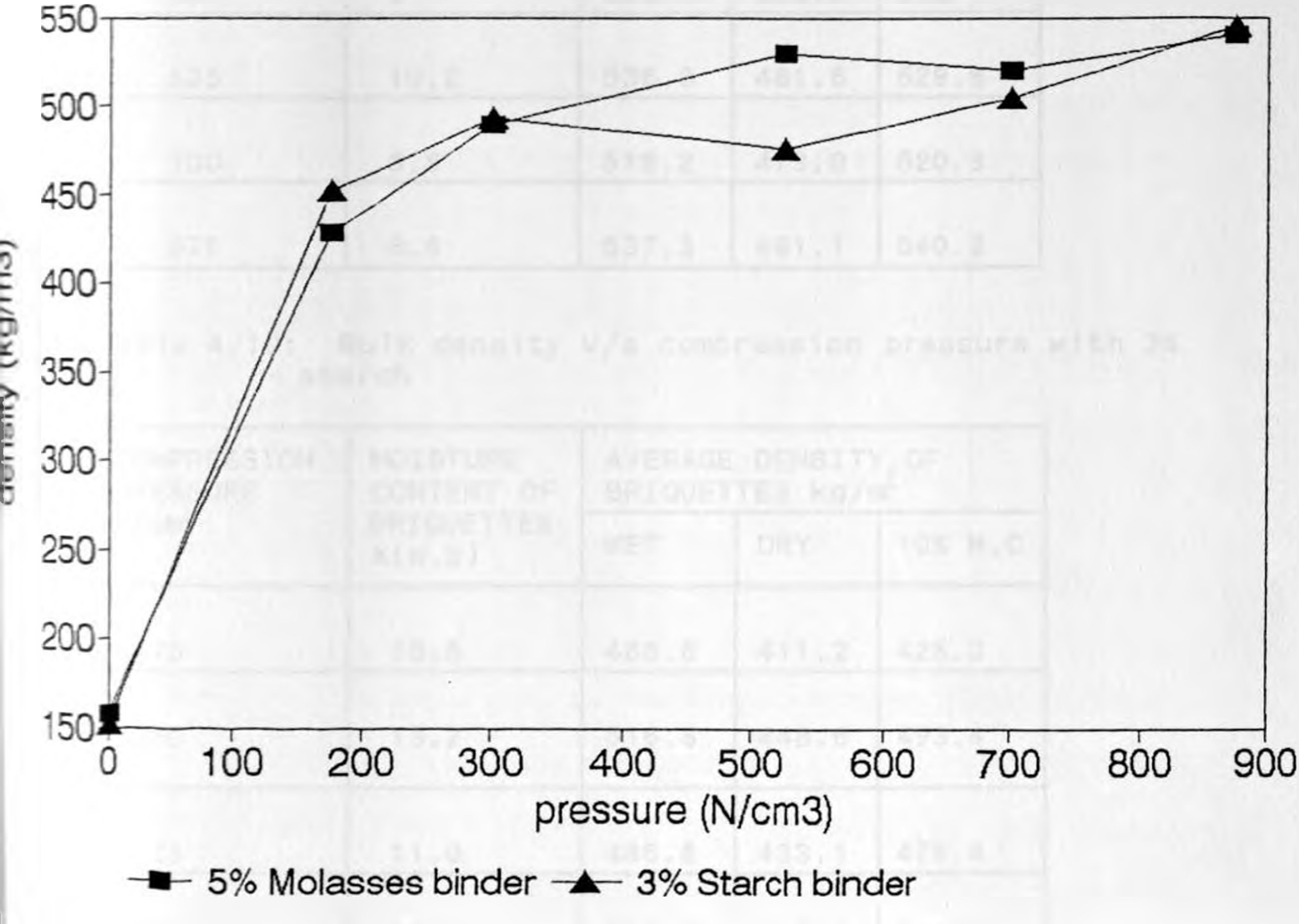
Table 4.8: Bulk density for 3% starch-bound briquettes

COMPRESSION FORCE		DENSITY AS REC. kg/m^3	DENSITY AT 10% M.C kg/m^3
FORCE (KN)	PRESSURE (N/cm^2)		
0	0	165.3	151.8
1	175	486.0	452.3
2	350	516.8	493.4
3	525	486.7	476.4
4	700	519	505.3
5	875	554	544.8

DENSITY AS REC. - density recorded at a different moisture which is the compared at 10 % moisture content

The bulk density of the loose carbonized material was found to be between 160 and 180kg/m^3 but this could be increased to a maximum of 500kg/m^3 by compressing, depending on densification pressure and binder ratio. The retention time used for the densification force varied between 1 and 2 minutes and was found to be insufficient to reduce porosity. With greater compression pressure higher bulk densities could be achieved but frictional forces between the briquette and internal walls of the mould increased as reflected by the increased tendency of briquette to disintegrate on removal from the mould. This was observed during the extrusion of briquette from the mould as more effort was required to force it out. With increased compression pressures there was a greater tendency of briquette to expand after release of the force.

The characteristics of bulk density-compression pressure curves were similar for both starch and molasses bound briquettes, although starch seems to be more effective at lower densification pressure (0-500 N/cm^2). At lower compression force starch appears to be more efficient than molasses and gives higher density briquettes although at higher densification force the difference is not significant. As shown in figure 4.4, lower density was observed for starch binder at 525 N/cm^2 and was attributed to experimental errors. There was no much difference between the two binders used at compression pressures above 700 N/cm^2. This is evident on close observation of figure 4.4. During compression it was observed that briquettes bounced back or lengthened on release of the compression rod. This implied that more retention time should be allowed to enable sawdust particles to consolidate and coalesce to form a stable briquette than the one minute used. This reduced the final density attainable with an increased loading using the briquetting system employed.



4.4 Bulk density verses compression pressure

Table 4.9: Bulk density v/s compression pressure with 5% molasses

COMPRESSION PRESSURE N/cm^2	MOISTURE CONTENT OF BRIQUETTES . % w.b	AVERAGE DENS. OF BRIQ. kg/m^3		
		WET	DRY	10% M.C
175	10.6	435.4	389.2	428.2
350	9.7	493.0	445.2	489.7
525	10.2	536.3	481.6	529.8
700	8.9	519.2	473.0	520.3
875	8.6	537.3	491.1	540.2

Table 4.10: Bulk density v/s compression pressure with 3% starch

COMPRESSION PRESSURE N/cm^2	MOISTURE CONTENT OF BRIQUETTES %(w.b)	AVERAGE DENSITY OF BRIQUETTES kg/m^3		
		WET	DRY	10% M.C
175	15.5	486.6	411.2	425.3
350	13.2	516.8	448.6	493.4
525	11.0	486.6	433.1	476.4
700	10.5	519.0	464.5	511.0
875	10.6	554.4	495.6	544.8

4.4.2 Effect of binder ratio on bulk density

Table 4.11 shows the variation of bulk density with different binder ratios when compression pressure of 300 N/cm^2 was used. For good comparison the density was evaluated at 10% moisture content. The density at 10% moisture content was evaluated by working out the dry mass density and adding the weight moisture equal to 10% of dry weight.

Table 4.11: Briquette bulk densities verses binder ratios

MOLASSES RATIO	DENSITY kg/m^3	DENSITY 10% M.C	STARCH RATIO	DENSITY kg/m^3	DENSITY 10% M.C
0	332.4	329.0	0	332.4	329.0
5	407.1	400.3	2	398	391.8
10	431.8	424.1	3	422	415.9
15	450.2	436.8	5	435.4	430.1
20	468.8	450.7	8	436.8	428.6

The density was found by working out the ratio of mass to volume at the prevailing moisture content of individual briquettes and then evaluating the density at 10% moisture content. A detailed evaluation of densities of individual briquettes are shown in Tables 4.12 and 4.13 and in fig. 4.6. A compression pressure of 300 N/cm^2 was applied during densification test. Within the range of this study, there is a general increase in bulk density with percentage ratio of binder but it was upto a limit for starch binder. The bulk density achieved using 8% starch-binder ratio by weight approached an asymptote at about 430kg/m^3. The bulk density of briquettes bound with molasses appeared greater than that of briquettes bound with starch. These trends are also illustrated in figs 4.5 and 4.6

Table 4.12: Bulk Density v/s Starch Binder Ratio

STARCH RATIO % WT	MOISTURE CONTENT % w.b	AVERAGE DENSITY kg/m^3		
		WET	DRY	10% M.C
0	9.15	329.3	299.2	329.1
2	10.6	398.0	356.2	391.8
3	10.7	422.0	378.1	415.9
5	10.2	435.4	391	430.1
8	10.8	436.8	389.6	428.6

Table 4.13: Bulk density v/s molasses binder ratio

MOLASSES RATIO % WT	MOISTURE CONTENT % w.b	AVERAGE DENSITY kg/m^3		
		WET	DRY	10% M.C
0	9.15	329.3	299.2	329.1
5	10.6	407.1	364.0	400.4
10	10.7	431.7	385.5	424.1
15	11.8	450.2	397.1	436.8
20	12.6	468.8	409.7	450.7

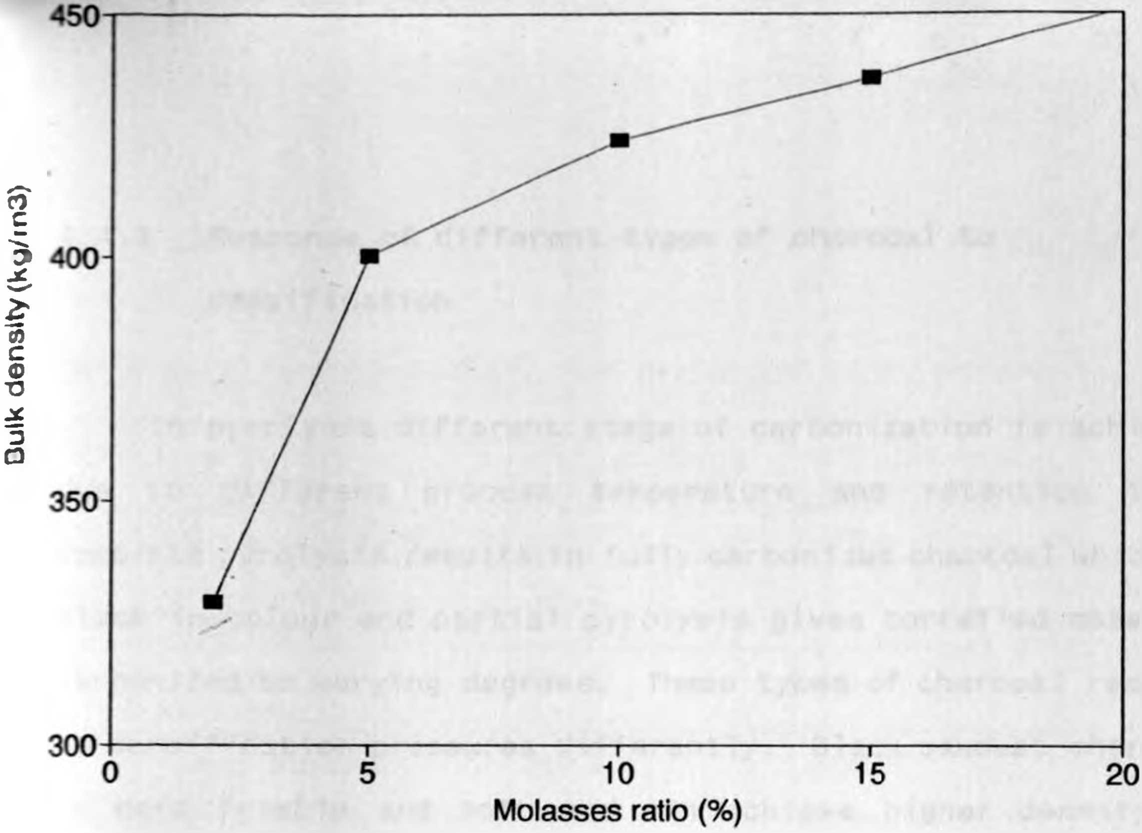


Fig. 4.5 Bulk density verses molasses ratios

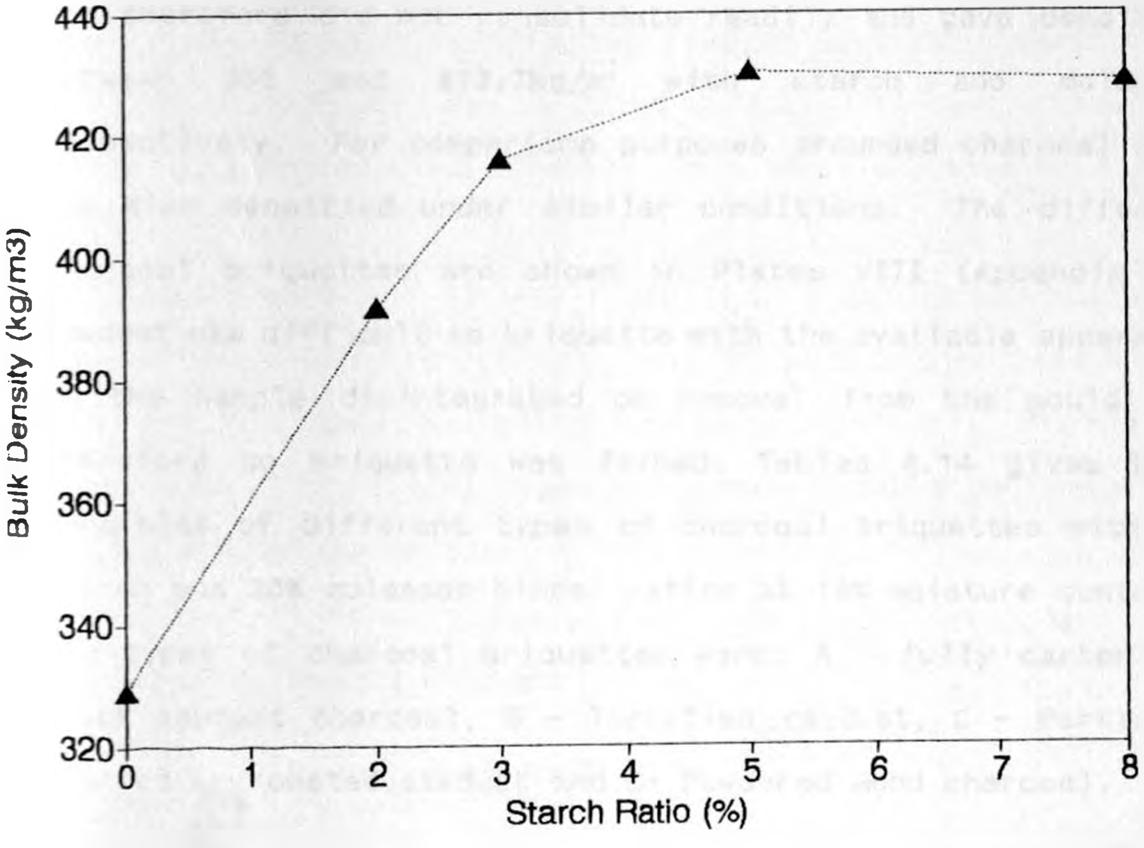


Fig 4.6 Bulk Density verses Starch Ratio

4.4.3 Response of different types of charcoal to densification

In pyrolysis different stage of carbonization is achieved due to different process temperature and retention time. Complete pyrolysis results in fully carbonized charcoal which is black in colour and partial pyrolysis gives torrefied material carbonized to varying degrees. These types of charcoal respond to densification pressures differently. Black sawdust charcoal is more friable and soft and can achieve higher density on densification than partially carbonized material which is course and does not readily consolidate.

In this study torrefied sawdust was partially carbonized and therefore did not consolidate readily and gave densities between 395 and 413.7kg/m^3 with starch and molasses respectively. For comparison purposes grounded charcoal dust was also densified under similar conditions. The different charcoal briquettes are shown in Plates VIII (Appendix D). Sawdust was difficult to briquette with the available apparatus as the sample disintegrated on removal from the mould and therefore no briquette was formed. Tables 4.14 gives bulk densities of different types of charcoal briquettes with 3% starch and 20% molasses binder ratios at 10% moisture content. The types of charcoal briquettes were: A - fully carbonized black sawdust charcoal, B - Torrefied sawdust, C - Partially charred or roasted sawdust and D- Powdered wood charcoal. The variation in density is also graphically shown in fig. 4.7.

Table 4.14: Bulk density for different types of charcoal

TYPE	CATEGORY OF BRIQUETTE	with 3% Starch and 300 N/cm^2	with 20% Mol. and $300N/cm^2$
A	Black s/d charcoal	448.7	479.6
B	Torrefied s/d charcoal	380.2	413.7
C	Roasted s/d charcoal	331.5	394.9
D	wood charcoal dust	668.6	688.0

The bulk density of ground charcoal dust after briquetting was 688 kg/m^3. This was followed by black sawdust charcoal with density of 480 kg/m^3. Torrefied sawdust gave the lowest bulk density of $395kg/m^3$ and $413.7kg/m^3$ for different types of torrefied material respectively. This is illustrated on figure 4.7.

From figure 4.7 it was found that consolidated charcoal dust achieved the highest bulk density with either binder and this was followed by black sawdust charcoal. Partially carbonized (torrefied) sawdust was non friable and gave low density briquettes because it had a tendency to rebounce after compression. Thus the stage of pyrolysis process determined the quality of briquettes formed.

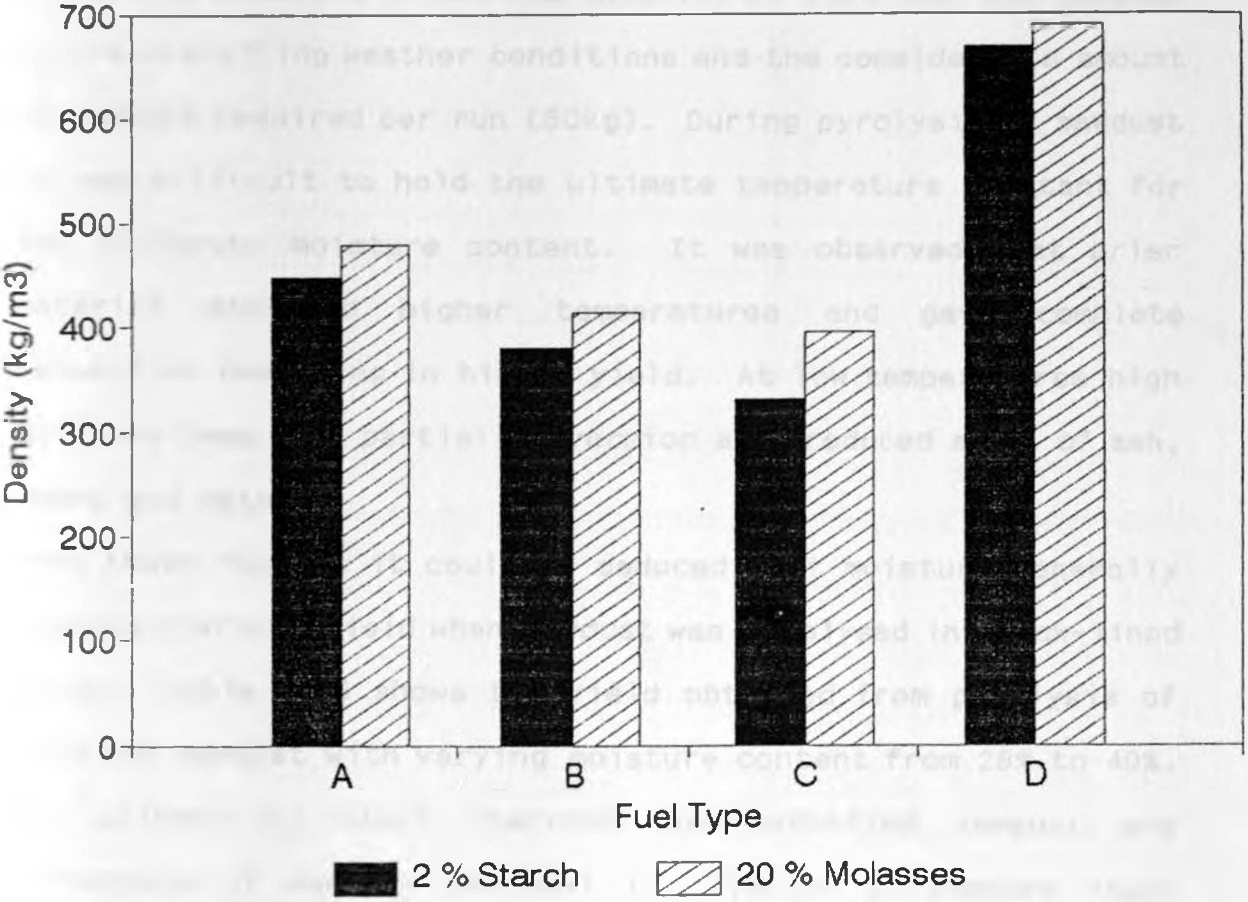


Fig. 4.7 Bulk density of different types of charcoal

A - Fully carbonized (black) charcoal
B - Torrefied, partially carbonized (dark-brown) sawdust
C - Roasted, slightly carbonized (brown) sawdust
D - Ordinary wood charcoal

4.5 Effects of Moisture Content on Charcoal Yield

Sawdust was sun-dried and its moisture content determined by sampling and oven-drying method before putting in the kiln. It was not possible to dry the material to less than 28% because of the prevailing weather conditions and the considerable amount of sawdust required per run (50kg). During pyrolysis of sawdust it was difficult to hold the ultimate temperature constant for the different moisture content. It was observed that drier material attained higher temperatures and gave complete conversion resulting in higher yield. At low temperatures high moisture feed gave partial conversion and produced a lot of ash, smoke and water.

From these results it could be deduced that moisture generally reduced charcoal yield when sawdust was pyrolysed in brick-lined kilns. Table 4.15 shows the yield obtained from pyrolysis of wood and sawdust with varying moisture content from 28% to 40%. The columns on black charcoal and torrefied sawdust are percentage of sawdust charcoal in relation to sawdust input whereas wood charcoal was the ratio of wood charcoal to initial wood used in percent dry weight basis. The overall yields give the ratio of combined weight of end-products to the initial total weight of input. The uncarbonized material referred to as raw was the fraction of uncharred residue to their individual input on dry weight basis. The ash content was the percent weight of ash to the total weight of sawdust and wood.

Table 4.15: Charcoal yield at various input moisture contents.

MOISTURE CONTENT % w.b		Pyrolysis Products yield for different moisture content of input						
SAWDUST	WOOD	SAWDUST BLACK. %(d.b)	SAWDUST TORREFIED % d.b	WOOD CHARCOAL % d.b	OVERALL YIELD % (d.b)	RAW SAWDUST % d.b	RAW WOOD % d.b	ASH + WASTE % d.b
40	35	17.6	11.92	14.1	19.8	35.4	16.4	4.31
38.5	27	13.0	4.59	13.7	15.5	25.3	10.0	4.18
34	29	16.0	9.48	18.9	22.1	9.2	7.9	3.64
36	24	15.0	8.48	20.7	22.0	10.6	4.8	3.03
30	26	22.7	8.32	26.0	28.4	0.0	0.0	2.51
28	24	16.96	8.41	19.13	22.16	0.0	0.0	1.92

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The moisture content of the biomass influenced proportion of charcoal produced. Yields obtained varied from about 16.93% to 28.4% (overall) when moisture content of sawdust was reduced from 40% to 28% and wood from 35% to 24% as shown in table 4.15. It was also noted that for higher m.c feedstock more ash and unrecoverable char fines were produced. With moisture content of 40% ash and waste char fine was about 4.3% and the uncarbonized fraction was 35% and 16% for sawdust and wood respectively. The low charcoal yield obtained at moisture content of 28% (sawdust) and 24% (fuelwood) was probably due to extended complete combustion of part of the charge resulting in less charcoal production. From these results it appears that the optimal moisture content for pyrolysis of wood and sawdust lies between 25 and 35% for both biomass.

4.6 Air Flow Rate

Air flow was measured in the air inlet duct of diameter 58mm with a pitot-static tube. The air flows encountered for the system was quite low which gave the velocity head between 0.25mm and 1mm of water and therefore the sensitivity of the instrument used was achieved by using the lowest scale. The velocity head read in the manometer was used to work out the air velocity. The air flow was varied occasionally by moving a shutter at the entrance of the duct to control the temperatures in the kiln. The velocity head read in the manometer ranged from 0 to 1.25mm of water. The values for velocity pressure in head of water (m) was converted to volumetric flow rate as the product of cross-sectional area of the duct and the air velocity. Since the temperatures were controlled by the rate of combustion of part of the charge it meant that it was also influenced by the air flow rate.

The velocity of a fluid moving in a pipe is given by

$$v=\sqrt{(2gh\frac{\rho_w}{\rho_a})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where ρ_w = density of water in the manometer (kg/m^3)

ρ_a = density of ambient air at (kg/m^3)

g = acceleration due to gravity (9.81 m/s^2)

h = the velocity head read as the differential head in manometer (m of water).

It was found that flow rates of 0.75 m^3/min was only possible when assisted by a gust of wind blowing directly on the inlet pipe. The common flow rates used for appropriate temperatures was between 0.336 and 0.58 m^3/min. The low air flow recorded through the duct was suspected to be due to lack of air tight conditions as air might have entered the system through jointed corners and doors of the kiln. Temperatures were controlled better by also varying the opening of a throttle valve inside the smoke outlet pipe. Temperatures in the kiln were more sensitive to variation of this valve than varying air inlet through the duct.

4.7 Combustion Characteristics

4.7.1 Ignition Time

About 500g of wood charcoal and charcoal briquettes were burned in a charcoal burner (JIKO) and the time taken for each fuel to ignite was recorded (see App. D Plates V A, B & C). Lighting was done using wood chips and pieces of paper and a little paraffin sprinkled on the floor of the cooker. The Ignition time was the time taken from the moment of lighting to the time that a steady glowing fire was observed. Table 4.14 gives time of Ignition in minutes for both ordinary charcoal and briquetted charcoal.

Table 4.16: Comparison of ignition time (mins)

Test	1	2	3	4	5	6
Ordinary charcoal	10	10	9	10	13	10
Charcoal Briquettes	8	9	7	10	10	8

Since time taken to light (when a steady burning combustion takes place) depended on visual judgement, both types of charcoal were ignited at the same time in two similar "jikos". The lighting time was therefore a comparison of how fast the charcoal achieve steady burning. The results showed that charcoal briquettes took shorter time to ignite than ordinary lump charcoal, but both took between 7 and 10 minutes to light. The difference in ignition time for the charcoal briquettes and lump wood charcoal was attributed to volatile content of the fuels. Charcoal briquettes had lower bulk density and more volatiles hence burned faster than ordinary lump charcoal. Charcoal briquettes was found to produce a flame for a few minutes after igniting which went off immediately thereafter. Production of smoke was assessed by visual observation and no smoke screen was used. Briquettes made with molasses as a binder produced a less smoke than with the other types of charcoal. This was thought to have been emitted by the burning molasses in the briquette. No significant smoke was emitted from either lump charcoal or starch-bound charcoal briquettes. The lighting time for both charcoal briquettes and lump charcoal was range from 7 to 13 minutes. Statistical analysis using General Linear Model (analysis of variance - Two- way anova method) showed that there was significant difference between the lighting time for ordinary charcoal and charcoal briquette at 5% level. But there was no significant differences between the lighting time for the two types of fuel at 1% level. The statistical results for the ANOVA method are presented in Appendix A Table AIV

4.7.2 Room Air Temperature

The charcoal burner was ignited and left for 15 minutes outside to achieve a good steady fire after which it was taken into a room to warm its air. Air temperature was taken every 5 minutes at various points along a line from the burner and 60 cm above the floor. Direct radiation was reduced using a wooden shield placed between the thermometer and the "Jiko". Plate VI in Appendix D shows the measurement of room temperature. Equal amount of the different types of charcoal were used alternatively to heat the air in a room from initial temperature of 17°C. Table 4.17 gives the air temperature at a point 30 cm from the "JIKO" taken every 10 minutes for one and a half hours. The results were also plotted in a graph form and are shown in Fig. 4.8 below. Temperatures taken at the other points showed similar trend but reduces with the distance from the charcoal burner.

Table 4.17 Rise in room air temperature over Time

Room Air Temperature (°C)										
Time (mins)	0	10	20	30	40	50	60	70	80	90
Ordinary Charcoal	17	27	32	35	35	35	33	30	27	25
Sawdust Charcoal	17	29	33	34	34	31	29	27	25	24
Kahawa Coal	17	26	27	28	27	26	25	24	23	23
Charcoal dust	17	26	30	31	31	30	27	26	25	24

Table 4.17 and Fig. 4.8 reveal that combustion characteristics for all types of charcoal make air temperature rise and fall over time. Ordinary wood charcoal exhibited a fairly faster rate of temperature rise and a stable peak which is longer than for the other charcoal types. The ordinary lump charcoal exhibited a better heat intensity for a longer period than briquetted charcoal as reflected by the broader crest of the graph. Sawdust charcoal produce a sharp temperature rise which peaked at 34.5°C. However the heating intensity goes down faster as the glowing briquette embers become covered with ash. Kahawa coal and consolidated charcoal dust have a lower heated effect as evidenced by the small air temperature rise. For all types of charcoal the greatest heating intensity occurred 30 to 40 minutes after putting the stove in the room, that is 40 to 50 minutes after lighting.

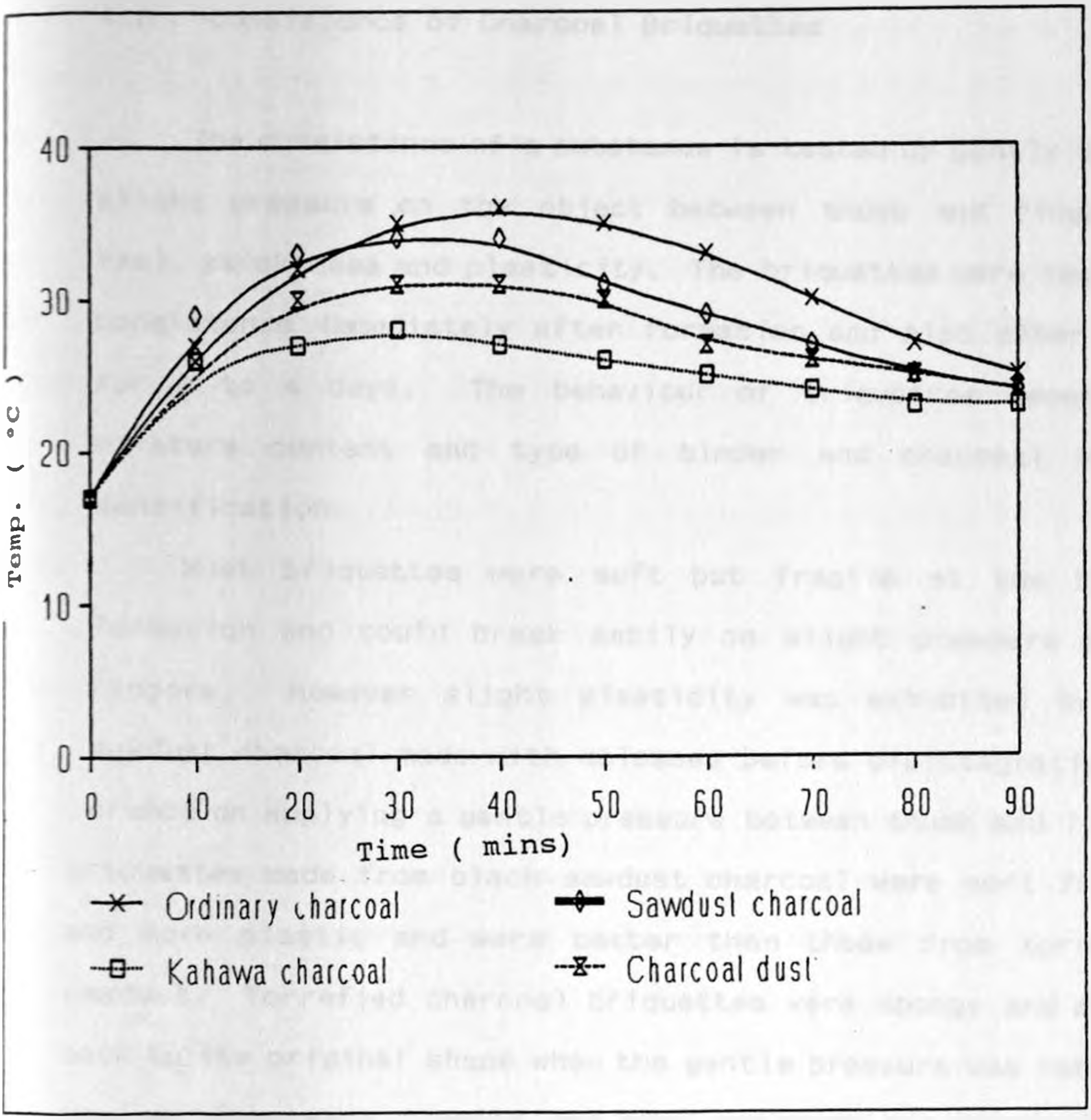

Fig. 4.8 Changes in room air temperature with time

4.8 Consistence of Charcoal Briquettes

The consistence of a substance is tested by gently applying slight pressure on the object between thumb and fingers for feel, stickiness and plasticity. The briquettes were tested for consistence immediately after formation and also after drying for 3 to 4 days. The behaviour of briquettes depended on moisture content and type of binder and charcoal used in densification.

Most briquettes were soft but fragile at the time of formation and could break easily on slight pressure between fingers. However slight plasticity was exhibited by black sawdust charcoal made with molasses before disintegrating into crumbs on applying a gentle pressure between thumb and fingers. Briquettes made from black sawdust charcoal were soft friable and more plastic and were better than those from torrefied sawdust. Torrefied charcoal briquettes were spongy and sprang back to its original shape when the gentle pressure was removed. However they were fragile and when pressure was increased it disintegrated readily into particles.

There was no sticky consistence exhibited by any of the charcoal briquette except that moist molasses-bound briquettes were slightly sticky. This was attributed to the characteristics of the molasses itself which is sticky.

The moisture content of briquettes dropped to between 10 and 20% after drying for 3-4 days. Consistence analysis proved that these briquettes were tougher but still fragile and had a tendency to break easily. Only molasses-bound black charcoal briquettes were found to have more moisture content (14-20%) which were slightly plastic. Briquettes made from black charcoal and starch were more brittle and did not shrink easily and particles flake off readily. These briquettes were however friable and broke into crumbs or powder when pressure was increased depending on the moisture content. Dry torrefied briquettes were soft, tough but not friable and on pressing more particles broke off the surface.

There was no significant plasticity in briquettes from both types of sawdust charcoal after drying. In comparison wood charcoal dust were dense, tough and resistant to slight pressure but still friable. On the other hand Kahawa coal which is pelleted mechanically is very dense and does not break easily by pressing between fingers though they are also friable.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

The foregoing studies have shown that charcoal briquettes for domestic use can be obtained from sawdust by pyrolysis followed by densification. The following conclusions were made within the range of the studies done.

i) Charcoal yields of about 28% (overall) on dry weight basis were obtained on pyrolysis of wood and sawdust at temperatures between 450 and 550°C in brick-lined kiln.

ii) Highest energy yield of 42% (overall) was recovered as solid residue at pyrolysis temperature range of 450-550°C

iii) Density of briquettes obtained was 540kg/m^3 with a compression pressure of 900N/cm^2 in combination with a binder from about 160kg/m3 of loose material.

iv) The stability of briquette can be greatly improved by use of a binder in conjunction with pressure of 300N/cm^2. The higher the binder ratio the better the briquette quality. Using molasses ratio of 20% increased the bulk density from 329 kg/m^3 to 470kg/m^3. Similarly with 8% starch binder ratio the bulk density was 437 kg/m^3 . There was no major differences between the two binders except that starch-bound briquettes gave more consistent briquettes.

v) Moisture content of 40% and 35% for sawdust and wood respectively gave an overall yield of 19.75% but moisture content of 30% (sawdust) and 26% (fuelwood) gave an overall yield of 28%.

vi) Different types of charcoal responded differently to densification treatments. With a combination of $350N/cm^2$ pressure and molasses ratio of 20% black, sawdust charcoal was more friable and attained higher bulk density ($480kg/m^3$) than torrefied sawdust ($414kg/m^3$). For a pressure of $350N/cm^2$ and starch ratio of 3% bulk density for black sawdust charcoal and torrefied sawdust was 480 kg/m^3 and 380 kg/m^3 respectively. In comparison densified charcoal dust (from wood lump charcoal) gave a bulk density of 688kg/m3 and 668kg/m3 with a combination of 300N/cm2 pressure with 20% molasses ratio and 8% starch respectively.

vii) Sawdust did not form any stable briquette with the available manual equipment for any compression force and binder ratio under the prevailing conditions.

viii) Combustion characteristics of charcoal fuels revealed that black sawdust charcoal ignites more readily but is consumed faster than ordinary wood charcoal. Sawdust charcoal briquettes generate maximum heat intensity 35 minutes compared to 45 minutes for ordinary charcoal after lighting. Thus sawdust charcoal briquettes may be recommended for cooking short-time meals like breakfast for a few people.

ix) Sawdust charcoal made with molasses and torrefied sawdust burn with a flame and produce a little smoke during lighting time.

5.2 Recommendation for Further Research

i) In the preceding studies, gaseous products were not collected nor quantified. It is here suggested that a well designed carbonization unit is needed that enable better control of temperature distribution and recovery of gaseous products.

ii) A small Laboratory scale apparatus should be used to study effect of moisture content and temperature on pyrolysis of sawdust in a controllable environment.

iii) The sawdust used in this study was not graded before being carbonized. It is suggested that the effect of particle size on pyrolysis of sawdust should be studied. A method of carbonizing sawdust without the use of wood and sticks should be sought.

iv) Densification Pressure-Retention time

There is a need to establish optimum retention time of briquettes during densification with regards to pressure and binder ratio for stable briquettes.

v) It is the suggestion of the author that the compressive strength of briquettes as a function of compression pressure-binder ratio combination be studied by evaluating either unconfined compressive strength or by triaxial test.

5.3 Future Prospects of Briquetting Technology

Briquetting technology is attractive but commercial application is upset by the high production cost. Appropriate densification system is necessary that produce a fuel at a cost that is affordable to the user. Carbonized sawdust briquettes are excellent substitute for wood charcoal if they can be produced at competitive prices. The establishment of inexpensive but labour-intensive briquetting techniques that employs mechanical or hydraulic type hand-operated ram presses to create job opportunities for the rural communities (Mathews, 1987). The main component costs of a densification system are initial equipment (capital) cost, energy requirement during process, maintenance cost, labour and actual production costs. In briquetting, high pressures are employed resulting in high energy consumption and increased wear of the equipment which further escalates the operating costs. Actual production cost include cost of the feedstock, collection and preparation cost, energy consumption of the compacting process and labour cost. These costs and other associated overheads will depend on the type of equipment used and the level of equipment utilization. Conversion of sawdust into charcoal briquettes for use in domestic cookers is feasible but needs large-scale production to take advantage of economies of scales. Future adaptation of briquetting technology will depend on the reduction of briquetting cost and a significant increase in the current prices of alternative fuels. Establishing an intermediate small-scale briquetting technology would create employment at low capital investment and provide domestic energy for rural communities.

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7. APPENDICES

Appendix A

Table I. Amount of residue produced in different Mills, oven dry tons per m³ of product*

Plant or product	Softwood	Dense hardwood	Low-density hardwood
Planning Mill	0.15	0.13	0.12
Sawmill	0.60	0.74	0.48
Hardwood flooring	-	0.42	-
Handle blanks	-	1.50	-
Furniture Frames	0.48	0.47	0.32
Pallets and Skids	0.20	0.23	0.16

* Source: W. Resch, (1982)

Table II. Comparison of Energy Sources*

Sources	KJ/kg	Btu/lb
Petroleum	48846	21000
Coal	31401	13500
Douglas-fir bark	22097	9500
Bagasse	21260	9140
Wood (oven dry)	20934	9000
Raw sewage	16468	7080
Rice straw	15212	6540
Spent Pulp Liquor	12444	5350

* Source: Moslemi, (1982).

Appendix A

Table I Amount of residue produced in different mills, oven dry tons per m^3 of product*

Plant or product	Softwood	Dense Hardwood	Low-density Hardwood
Planning Mill	0.18	0.17	0.12
Sawmill	0.60	0.74	0.48
Hardwood flooring	-	0.42	-
Hardle blanks	-	1.10	-
Furniture Frames	0.48	0.47	0.32
Pallets and Skids	0.20	0.23	0.16

* Source: Resch, (1982)

Table II Comparison of Energy Content*

Sources	KJ/kg	Btu/lb
Petroleum	48846	21000
Coal	31401	13500
douglas-fir bark	22097	9500
Bagasse	21260	9140
Wood (oven dry)	20934	9000
Raw sewage	16468	7080
Rice straw	15212	6540
Spend Pulp Liquor	12444	5350

* source: Moslemi, (1982).

Table III Proximate analysis of some biomass species[*]

Species	Total ash	Solvent soluble	Water soluble	Lignin	Hemi-Cellulose	Cellulose
Softwood	0.4%	2.0%	-	27.8%	24.0%	41.0%
Hardwood	0.3%	3.1%	-	19.5%	35.0%	39.0%
Wheat straw	6.6%	3.7%	7.4%	16.7%	28.2%	39.9%
Rice straw	16.1%	4.6%	13.3%	11.9%	24.5%	30.2%
Bagasse	2.3%	8.4%	10.0%	18.5%	29.0%	33.6%

* Source: Shafizadeh, (1983).

Table IV Charcoal Composition in relation to Carbonization Temperature[*]

Temperature °C	Element Composition %			Yield (%) Charcoal/ Wood	Volatile Matter %	Low Calorific value MJ/Kg
	C	H	O			
200	53.2	6.3	41.3	91.8	-	15.2
300	73.2	4.9	21.9	51.4	31	28.0
400	82.9	3.8	13.5	37.8	-	31.1
500	82.9	3.1	6.7	31.0	13	33.7
600	92.2	2.0	5.2	29.1	-	33.8
700	92.8	2.4	4.8	27.8	7	-
800	95.7	1.0	3.3	26.7	-	33.4
900	96.1	0.7	3.2	26.6	-	-
1000	96.6	0.5	3.6	26.1	-	32.8

*Derived from Oliveira, Gomer & Mendez

Source Caceres, A. (1985)

ble B1 Statistical ANOVA Table for Lighting time

rep	treat	minutes
1	1	10
1	2	8
2	1	10
2	2	9
3	1	9
3	2	7
	1	10
	2	10
	1	13
	2	10
	1	10
	2	8

Analysis of Variance

APPENDIX B

jects Factors

	N
	2
	2
	2
	2
	2
	2
	6
	6

Treat 1 Ordinary charcoal Ignition time

Treat 2 Charcoal Briquettes ignition time

Tests of Between-Subjects Effects

e MINUTES

Sum of Squares	df	Mean Square	F	Sig.
5.333a	7	157.905	296.071	.000
4.000	5	2.800	5.250	.048
8.333	1	8.333	15.625	.011
2.667	5	.533		
08.000	12			

= .998 (Adjusted R Squared = .994)

ble B1 Statistical ANOVA Table for Lighting time

rep	treat	minutes
1	1	10
1	2	8
2	1	10
2	2	9
3	1	9
3	2	7
4	1	10
4	2	10
5	1	13
5	2	10
6	1	10
6	2	8

te Analysis of Variance

Subjects Factors

	N
1	2
2	2
3	2
4	2
5	2
6	2
1	6
2	6

Treat 1 Ordinary charcoal Ignition time

Treat 2 Charcoal Briquettes ignition time

Tests of Between-Subjects Effects

Variable: MINUTES

Type III Sum of Squares	df	Mean Square	F	Sig.
1105.333[a]	7	157.905	296.071	.000
14.000	5	2.800	5.250	.048
8.333	1	8.333	15.625	.011
2.667	5	.533		
1108.000	12			

ared = .998 (Adjusted R Squared = .994)

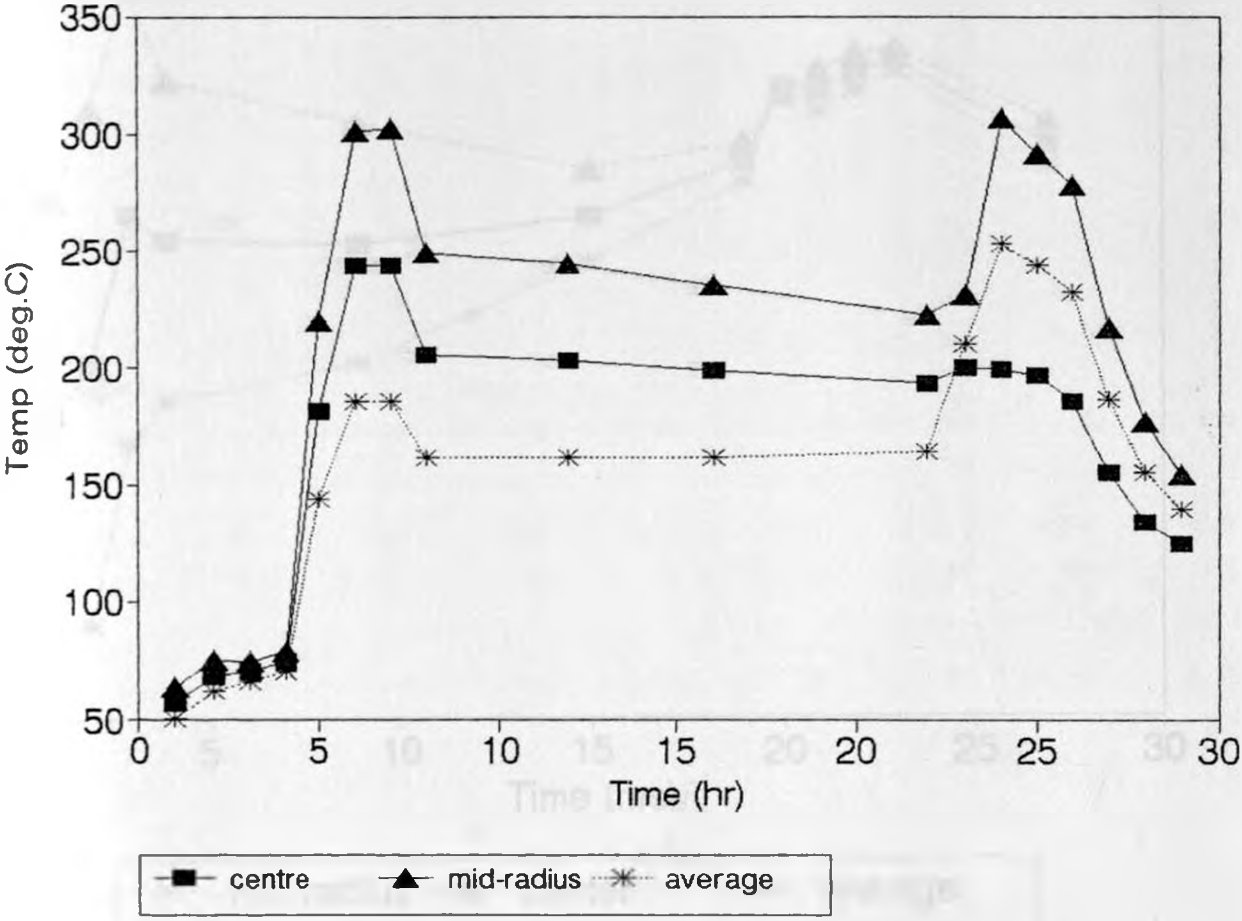
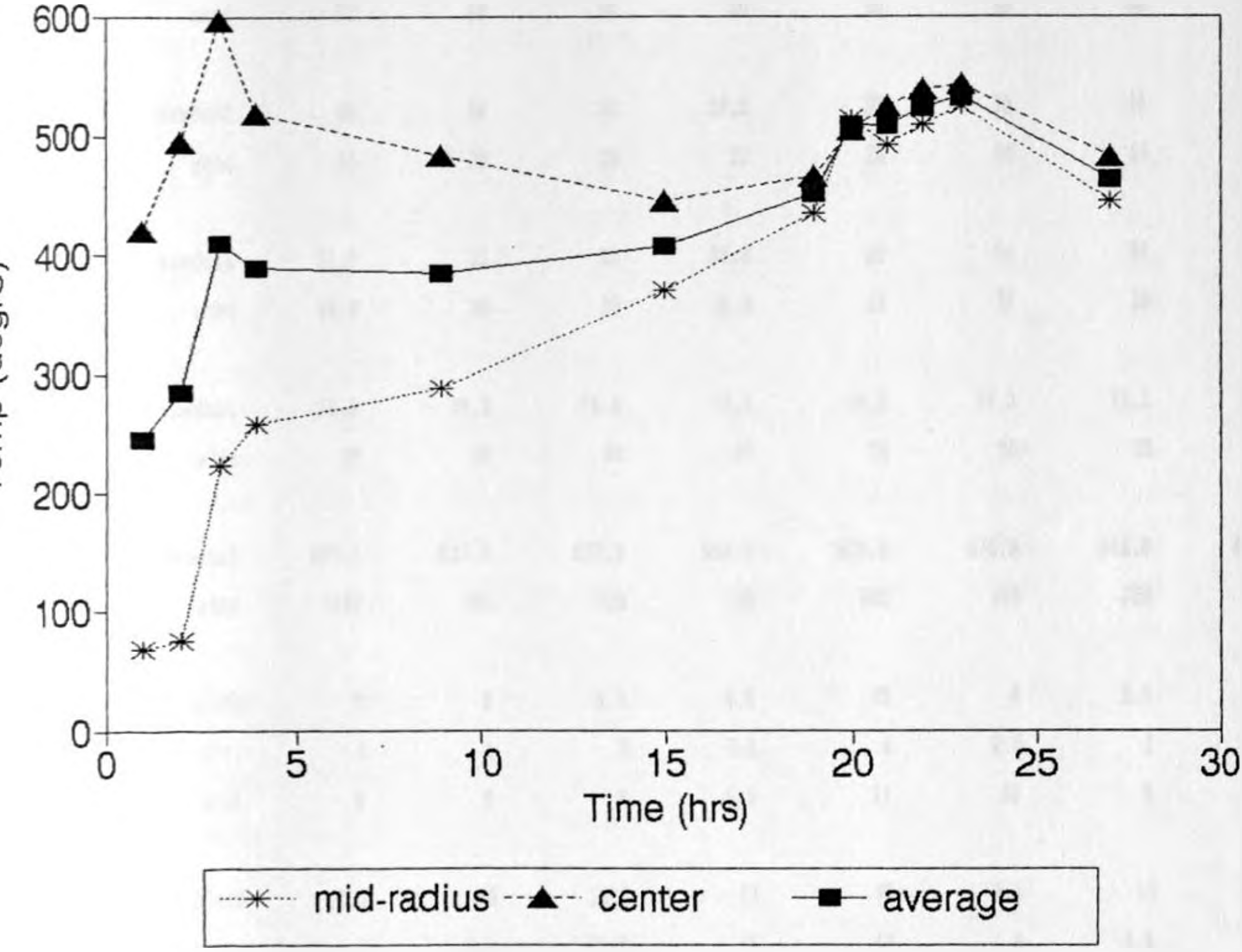


Fig. B1 Second test run - Temperature Profile



g. B2 Sixth test run - Temperature Profile

APPENDIX C

CARBONIZATION EXPERIMENTAL TESTS

Exp.	Run No.	1	2	3	4	5	6	7	8
Operating Temp.		200-350	200-350	550-650	350-450	450-550	450-550	350-450	550-650
Wet wt of input	sawdust	52	50	50	50	50	50	50	50
	wood	84	50	50	50	50	50	50	50
M.C of Input	sawdust	40	34	34	38.5	30	30	36	28
	wood	35	30	28	27	26	26	24	24
Dry wt of input	sawdust	31.2	33	33	30.8	35	35	32	36
	wood	54.6	35	36	36.5	37	37	38	38
Cal.value of input	sawdust	19.3	19.3	19.3	19.3	19.3	19.3	19.3	19.3
	wood	20	20	20	20	20	20	20	20
G.H.V of input	sawdust	603.1	637.9	637.9	594.4	676.6	676.6	618.6	695.9
	wood	1092	700	720	730	740	740	760	760
Wet wt of Charcoal	s/d black	6	6	6.5	4.5	10	8	5.5	7
	s/d torr.	4	4	3	1.5	4	2.5	3	3.5
	wood	8	6	9	5.5	11	10	9	8.5
M.C(%w.b) Charcoal	s/d black	8.3	15	15.6	11	16	6.5	13	12.8
	s/d torr.	7	8.5	13.4	6	12	8	9.5	13.5
	wood	3.5	6	13.6	9	10.8	5.8	12.5	14.5
Dry wts Charcoal	s/d black	5.5	5.1	5.5	4.0	8.4	7.6	4.8	6.1
	s/d torr.	3.7	3.7	2.6	1.4	3.5	2.3	2.7	3.0
	Wood	7.7	5.6	7.8	5.0	9.8	9.4	7.9	7.3

Cal. value	s/d black	29.1	29.1	29.1	29.1	29.1	29.1	29.1	29.1
Charcoal	s/d torr.	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
	wood	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5
G.H.V	s/d black	160.1	148.4	159.6	116.5	244.4	217.7	139.2	177.6
Charcoal	s/d torr.	87.4	86.0	61.1	33.1	82.7	54.1	63.8	71.2
	wood	235.5	172.0	237.2	152.7	299.3	287.3	240.2	221.7
Char yield	s/d black	17.6	15.5	16.6	13.0	24	21.4	15.0	17.0
(% d.w.b)	s/d torr.	11.9	11.1	7.9	4.6	10.1	6.6	8. 5	8.4
	s/d total	29.6	26.5	24.5	17.6	34.1	27.9	23.4	25.4
	wood	14.1	16.1	21.6	13.7	26.5	25.5	20.7	19.1
	overall	19.8	21.2	23.0	15.5	30.2	26.7	22.0	22.2
Energy	s/d black	26.6	23.3	25.0	19.61	36.1	32.2	22.5	25.5
yield (% input)	s/d torr.	14.5	13.5	9.6	5.57	12.2	8.0	10.3	10.2
	s/d total	41.1	36.8	34.6	25.2	48.4	40.2	32.8	35.8
	wood	21.6	24.6	32.9	20.9	40.4	38.8	31.6	29.2
	Overall	28.5	30.4	33.7	22.8	44.2	39.5	32.2	32.3
residual material	raw wood	10	6	0	4	0	0	2	0
(in kg)	raw s/d	13	5	2	9	0	0	4	0
	ash+waste	4	3.5	2	3	2	2	2.3	1.5
M.C	raw wood	15.5	7.5		9			8	
residual material	raw s/d	23	13.5	11.5	13.5			14.7	
	ash+waste	7.5	9.5	10	6.5	8.2	10	7.9	5.6
Dry Residual material	raw s/d	10.0	4.3	1.8	7.8	0	0	3.4	0

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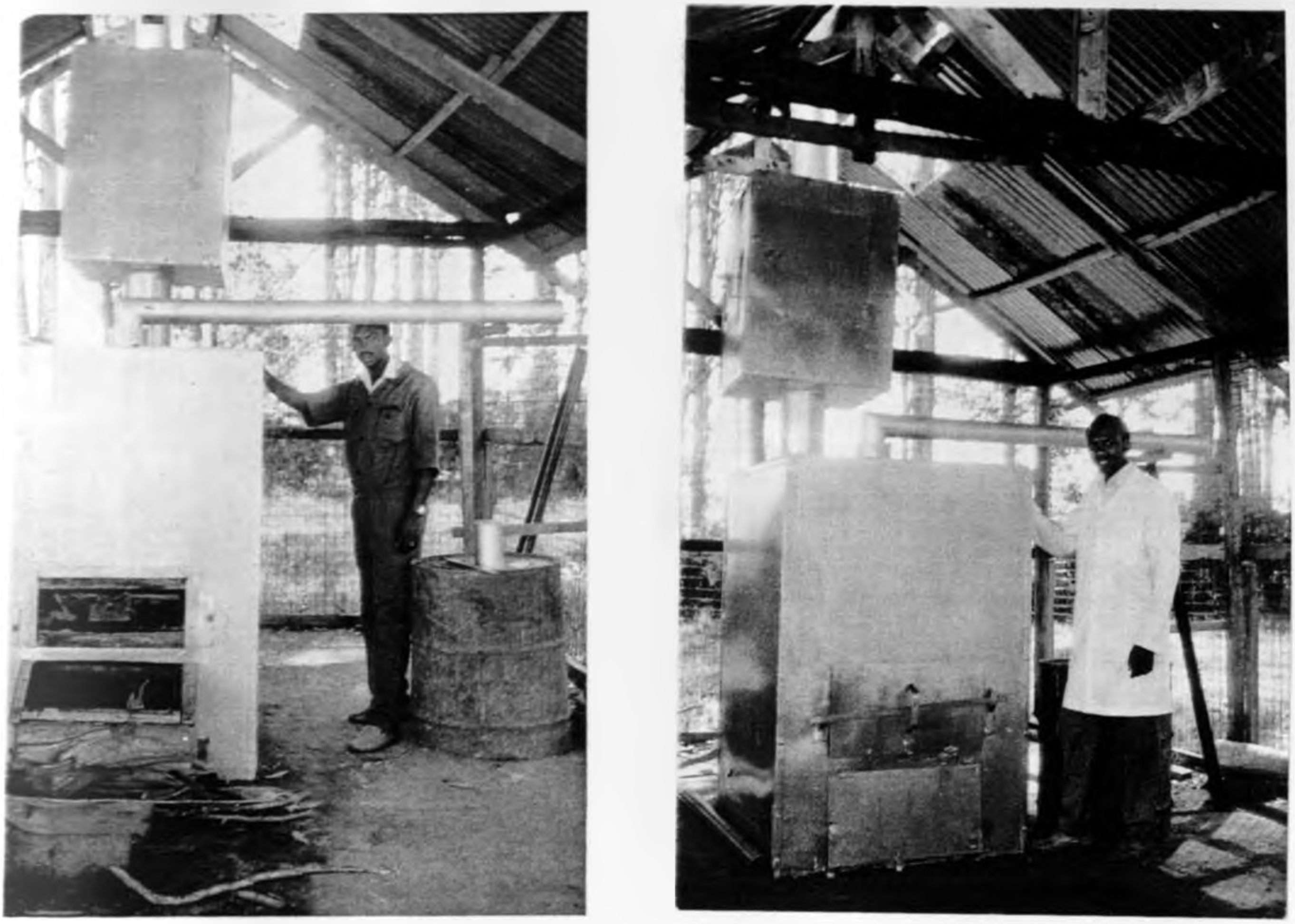
(in kg)	raw wood	8.5	5.6	0	3.6	0	0	1.8	0
	ash+waste	3.7	3.2	1.8	2.8	1.8	1.8	2.1	1.4
	Dry matter% (initial wt).	45.6	40.4	28.2	36.7	32.7	29.2	32.5	24.1
Residual material	raw s/d	32.1	13.1	5.4	25.3	0	0	10.7	0
(% d.w.b)	raw wood	15.5	15.9	0	10.0	0	0	4.8	0
	ash+waste	4.3	4.7	2.6	4.2	2.6	2.5	3.0	1.9



A

B

PLATE I

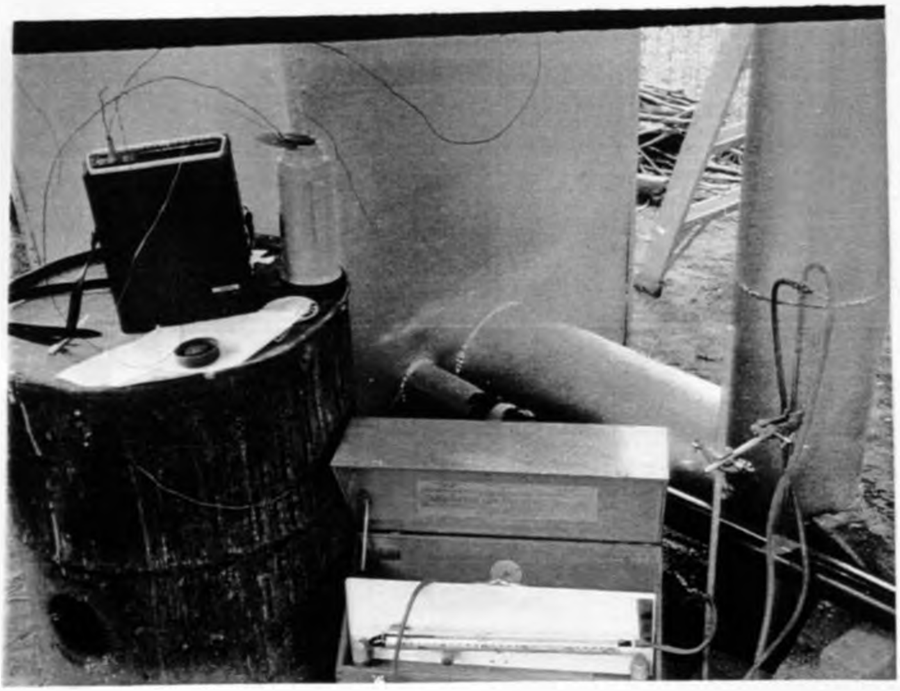


PLATE II

PLATE III

PLATE IV A

PLATE IV B

PLATE V A

PLATE V.B

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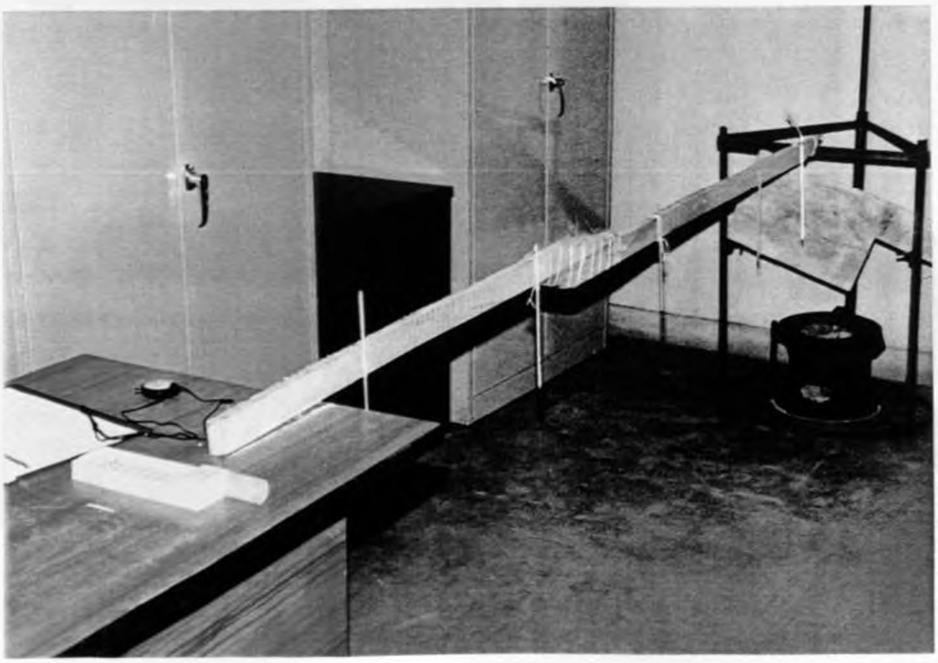
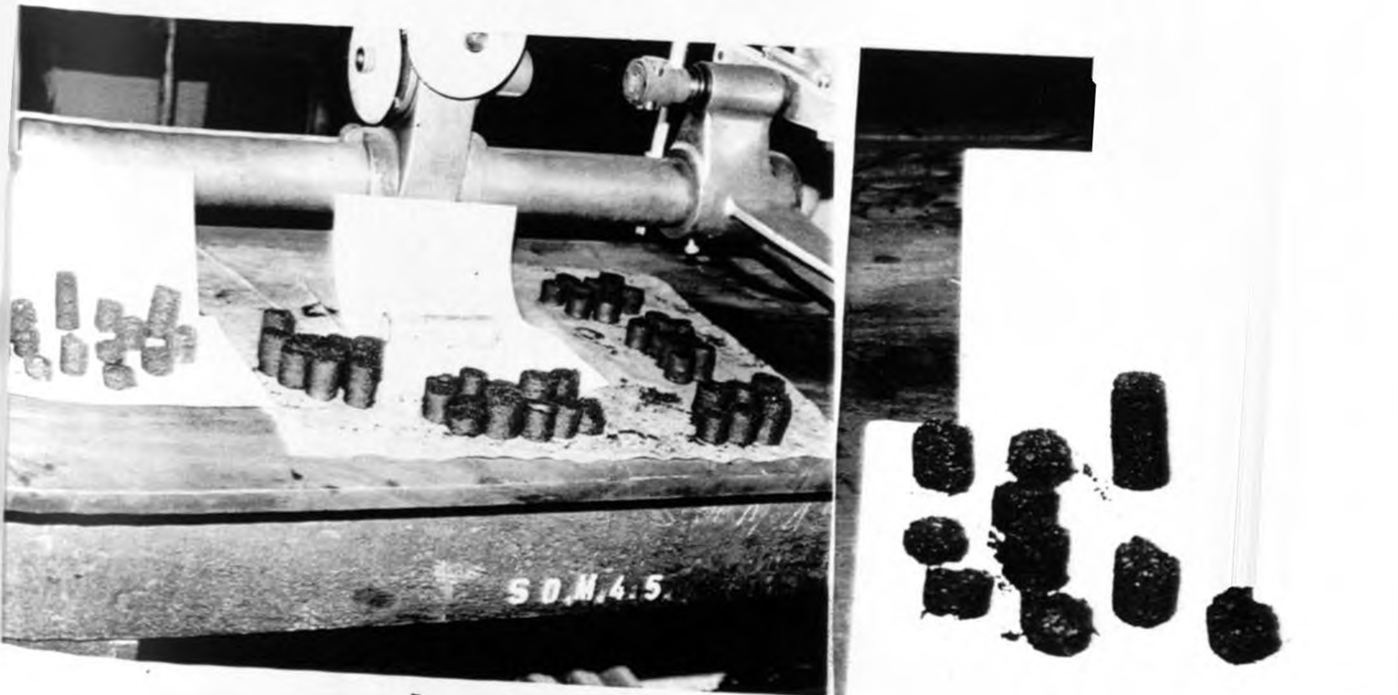


PLATE VI

A

B

PLATE VII



A

B

PLATE VIII