

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND
TECHNOLOGY, KUMASI
COLLEGE OF ENGINEERING
DEPARTMENT OF AGRICULTURAL ENGINEERING**

PROJECT REPORT

ON

**DESIGN, CONSTRUCTION AND TESTING OF A BRIQUETTING
MACHINE**

**DISSERTATION SUBMITTED TO THE DEPARTMENT OF
AGRICULTURAL ENGINEERING IN PARTIAL FULFILMENT OF
THE REQUIREMENT FOR THE AWARD OF A BSc. DEGREE IN
AGRICULTURAL ENGINEERING**

BY

AMANOR, ISHMAEL NARTEY

MAY, 2014

DECLARATION

I hereby declare that this thesis has not been submitted for a degree to any other University and that it is entirely my own work and all help has been appropriately acknowledged.

AMANOR, ISHMAEL NARTEY

(STUDENT)

.....

SIGNATURE

.....

DATE

1. PROF. EBENEZER MENSAH

(SUPERVISOR)

.....

SIGNATURE

.....

DATE

2. DR. GEORGE YAW OBENG

(SUPERVISOR)

.....

SIGNATURE

.....

DATE

ABSTRACT

The demand for energy is becoming a critical challenge for the world as the population continues to grow. This calls for Sustainable energy production and supply such as renewable energy technologies. Renewable energy technologies are safe sources of energy that have a much lower environmental impact than conventional energy technologies

In Ghana biomass is the most dominant source of energy and is used significantly in the domestic sector notably charcoal and woodfuel. Despite huge amount of agricultural waste generation in the rural areas, the rural folks use charcoal and woodfuel, which leads to deforestation.

In this study, an appropriate, cost effective and easy to duplicate manually operated biomass briquetting machine suitable for use in rural communities was designed and constructed, and tested using jatropha curcas husk at different particle sizes of $\leq 2\text{mm}$, $\leq 6\text{mm}$ and original particle size. The physical properties of the briquette were determined at varying biomass-binder ratios of 100:15, 100:25, 100:35 and 100:45 using cassava starch as the binding agent. The physical properties of the briquette were significantly affected by the binder level and the particle size using 95% confidence level. The durability range of the briquette produced by the different particle sizes are higher at finer particle sizes with particle size $\leq 2\text{mm}$ having a durability range of 81.9 to 92.3% and particle size $\leq 6\text{mm}$ and original particle size ranging from 78.03 to 92.27% and 43.54 to 60.22% respectively. The best biomass-binder ratio on the basis of the briquette durability (shatter index) was attained at the 100:25 blending ratio with particle sizes $\leq 2\text{mm}$ and $\leq 6\text{mm}$ having a durability of 92.3% and 92.27% respectively, also on the basis of water resistance (weathering resistance) of the briquette, the best blend was attained at 100:25 ratio with particle size $\leq 6\text{mm}$ having a higher value of 10.7 hours. It was concluded that the strength (durability) of the briquettes at the optimum biomass-binder ratios were sufficient to withstand any mechanical handling compared to 83.26% reported by Sotsnde et al in 2010. The biomass briquetting machine had a production capacity of about 488kg/hr.

DEDICATION

I dedicate this project to God Almighty, the late John Mensah Williams, and my entire family.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

As the population of the world continues to grow, the demand for energy is becoming critical challenge for the world's energy leaders (Christoph Frei, 2012). Global energy consumption has about doubled in the last three decades of the past century. In 2004, about 77.8% of the primary energy consumption was from fossil fuels (32.8% oil, 21.1% natural gas, 24.1% coal), 5.4% from nuclear fuels, 16.5% from renewable resources, of which the main one was hydro (5.5%) whereas the remaining 11% consisted of non-commercial biomasses such as wood, hay, and other types of fodder, that in rural-economies still constitute the main resource (BP-Amoco, 2005). With improvements in energy efficiency it is expected that global energy demand doubles by 2050. This is the consequence of global population growth, global economic growth, continued urbanisation, as well as the resulting increased demand on mobility and other energy dependent services (Christoph Frei et al., 2013).

Sustainable energy production and supply are tactical objectives for developed as well as developing countries. The energy sector plays a crucial role in attaining the United Nations Millennium Development Goals (Short, 2002), and the viability of modern economics is based in part on the capacity of countries to ensure their energy supplies. Renewable energy technologies are safe sources of energy that have a much lower environmental impact than conventional energy technologies. Shell International predicts that renewable energy will supply 60% of the world's energy by 2060.

Of the various renewable energy sources, bio-residues, of which agricultural residues form a major component, can be most easily utilised to reduce the consumption of woodfuel (Hosier and Svenningson, 1987). Biomass is attracting great attention over the world as a source of renewable energy as well as an alternative to fossil fuels. Biomass resources supply over 14% of the world's energy needs (Demirbaş and Demirbaş, 2003; McKendry, 2002). The potential of biomass energy derived from forest and agricultural residues world-wide is estimated at about 30 EJ/yr., compared to an annual world-wide energy demand of over 400 EJ (McKendry, 2002).

In Ghana biomass is the most dominant source of energy and is used significantly in the domestic sector for cooking and many other heat applications. Woodfuels, in the form of forest wood, charcoal and wood processing residues are the most dominant biomass forms of energy

in use in Ghana although crop residue and other non-woody materials also find some usage. Most rural dwellers (about 70% of people in Ghana) and almost all farmers heavily depend on fuel wood for all their domestic and other commercial activities that require heat. Use of biomass in many commercial and institutional establishments all over the country is also a case in point worthy of mention. About 70% of the total national energy consumption is accounted for by biomass in either the direct or processed form (KITE, 1999). The attraction for biomass has been premised on the following: ease of its production; sustainable supply advantages; and environmental benefits (minimum environmental pollution). Several crops are being grown in energy crop farming as feedstock for first generation biofuels. *Jatropha curcas* L. (JCL) has been identified as the most suitable energy crop in tropical regions (Del Greco and Rademaker, 1998).

Biomass briquetting is the densification of loose biomass material to produce compact solid composites of different sizes with the application of pressure. Briquetting of residues takes place with the application of pressure, heat and binding agent on the loose materials to produce the briquettes. They are often used as a development intervention to replace firewood, charcoal, or other solid fuels. In the proper context biomass briquettes can save time, save money, decrease local deforestation rates, and provide income generating opportunity. Briquettes are held together by a binding agent or “binder”. This binding material can be any fibrous organic material. The material must be partially decomposed in order to release the fibers necessary to physically hold the briquette together (Boston Nyer, 2010). There are a lot of other agricultural residues in Ghana that can be used for fuel briquette. Table 1 below shows the production of some major crops and their residue in Ghana in 1990.

Table 1.1: Production of Some Major Agricultural Residues in Ghana.

Crop	Residue	Residue Production (t/t crop)	Total Crop Production ‘000 tonnes	Residue Production ‘000 tonnes
Maize	Cob	1.00	553	553
Oil Palm	Shells	0.45	429	193
Paddy Rice	Husk	0.23	81	19
Sorghum	Stalk	1.00	136	136
Millet	Stalk	2.00	75	150
Groundnut	Shell	0.5	113	56
Total			1,387	1,107

Source: Letus Power Plant, Hagan, 1997.

The worldwide experience of briquetting plants is not well known either in success or failure. There have been more failures than success throughout the world because of over optimism about the economic competitiveness of briquetting. Various technical problems have been encountered but the main difficulty has been the fact that, in many places, briquettes are too high in cost to compete with existing wood fuel (Ganiyu Tajudeen, 2007).

Attempts at briquette production are as old as attempts at cook stove technology. The Building and Road Research Institute (BRRI) has been involved in briquetting investigation of the pyrolytic by-product of char for quite some time. The char briquettes that got developed were satisfactory fuel for grilling and drying purposes. The use of the briquettes developed at the BRRI for general domestic cooking was inhibited by the fact that they were not strong enough to support large cooking pots without disintegrating. The crushing strength thus needed to be improved. The generally high price of the produced briquettes was another problem that hindered widespread use of the briquettes in the domestic sector (Hagan, 1994).

The most advanced project in Ghana in briquetting is probably the sawdust briquetting plant of 2,200 tonnes/year capacity that was established by a Taiwanese entrepreneur and a Ghanaian partner in Akim - Oda in 1984. The Plant, Chaowus Limited was producing uncarbonised sawdust briquettes from sawdust obtained at no cost from sawmills in the Akim - Oda area.

In the past 10 years, there has been renewed interest, world-wide, in biomass as an energy source. The reason for this situation is technological developments relating to the conversion, crop production, etc. promise the application of biomass at lower cost and with higher conversion efficiency than was possible previously (McKendry, 2002).

1.2 Problem statement

Solid waste management is one of the major problems in Ghana. This is not only found in the urban areas but also at the rural areas. The major waste generated at the rural areas is agricultural waste or residue (crop by-product). Despite this level of waste generation fuel for heating, cooking and other purposes is a huge problem; hence the rural folks rely on woodfuel and charcoal.

The realisation that deforestation and woodfuel shortages are likely to become serious problems in Ghana has turned attention to other types of biomass fuel. In 1992 it was estimated that about 1.5 million hectares of forest remained in Ghana, with an annual rate of deforestation of about 22,000 hectares, or 1.5% (Agyekumhene, 2001, Agyarko, 1999).

Agricultural residues are, in principle, one of the major sources. They arise in large volumes and in the rural areas which are often subject to some of the worst pressures of wood shortage. The use of briquetting for conversion of agricultural residues is comparatively recent, however, and has only been taken up in developing countries in the last few years. Main agricultural residues that are produced are paddy chaff, coconut dregs, hay, groundnut skin, jatropha husk and press cake, palm nut shell, maize cob and cotton stem. There is also bio waste as wood dust. This wood dust is produced in big scale. Beside the problem of transportation, storage and operation, open burning of this bio waste with traditional style without control can cause critical air pollution. The impact of agricultural waste on the environment depends not only on the amounts generated but also on the disposal methods used. Some of the disposal practices pollute the environment. The potential threat posed by climate change, due to high emission levels of greenhouse gases (CO₂ being the most important one), has become a major stimulus for renewable energy sources in general. When produced by sustainable means, biomass emits roughly the same amount of carbon during conversion as is taken up during plant growth. The use of biomass therefore does not contribute to a buildup of CO₂ in the atmosphere (McKendry, 2002). Hence the need at the moment in the densification of this agricultural waste in developing countries is the development of an appropriate briquetting machine suitable to the local communities. For biomass to make a significant impact as fuel for rural communities, it is imperative that an efficient, cost effective and easy to duplicate technology is developed specifically for rural communities.

1.3 Main Objectives

The main objective of this study is to design, construct and test a briquetting machine.

1.4 Specific objectives

The specific objectives were to:

- Design and construct a briquetting machine with the main feedstock being agricultural residue.
- To test the briquetting machine using different particle sizes of jatropha curcas husk at varying binder levels.
- To determine the physical properties of the jatropha curcas husk briquette.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 History of briquetting

Briquetting is the densification of loose biomass material. Fuel briquettes emerged as a significant business enterprise in the 20th century. In the 1950s, several economic methods were developed to make briquettes without a binder where multitude of factories throughout the world produced literally tens of millions of tons of usable and economic material that met the household and industrial energy needs (Lardinois and Klundert, 1993). During the two World Wars, households in many European countries made their own briquettes from soaked waste paper and other combustible domestic waste using simple lever-operated presses. Today's industrial briquetting machines, although much larger and more complex, operate on the same principle (Lardinois and Klundert, 1993). According to FAO (1990), briquetting could be categorized into five main types depending on the types of equipment used; piston presses, screw presses, roller press, pelletizing, manual presses and low pressure briquetting. Densified biomass is acquiring increasing importance because of the growing domestic and industrial applications for heating, combined heat and power (CHP) and electricity generation in many countries. In countries such as Austria, Denmark, the Netherlands and Sweden, for example, it is becoming a major industry with pellets traded internationally. In Austria, the production of pellets in 2002 was 150,000 tons but with the rapid expansion of small-scale pellets heating systems, it was expected to reach 0.9 Mt/year by 2010 (Hood, 2010). In Europe this potential has been estimated at around 200 Mt/year and is increasing continuously because advances in technology allow the densification of biomass to be more competitive, driven by high demand.

There has been briquetting projects in many African countries such as Zimbabwe, Tanzania, Uganda, Kenya, Sudan, Rwanda, Niger, Gambia, Ethiopia and Senegal, though not all of these are still functional. The raw materials most commonly briquetted in Africa are coffee husks and groundnut shells while sawdust and cotton stalks are also used to a limited extent (Hood, 2010).

The history of residue briquetting in Africa is largely one of single projects in various countries which have usually not been successful (FAO, 1990). A survey carried by FAO, (1990) showed that many briquetting plants in East Africa have been faced by outright failures while others have had their operations marred by problems. According to this survey, it was difficult to find a single agency-funded briquetting project which had been commissioned and was operating

fully satisfactorily. The reasons that seemed to explain this failure included; inappropriate or mis-specified ordering of briquetting machinery, non-availability and high cost of the briquetting machines' spare parts, poor projects' planning and implementation where free supply of raw materials was assumed, low local prices of firewood and charcoal which inhibited the marketing of briquettes and unacceptability of briquettes in the household sector due to their ignition difficulties and smoke generation which caused indoor pollution, little involvement of the private sector and early withdrawal of donor as well as lack of government financial support. The main generalization that can be made about briquetting in Africa is that it has often proved difficult to sell briquettes against the competitive price of wood or charcoal and the very high capital cost of the briquetting plants. According to Eriksson and Prior (1990), several biomass briquetting projects have been implemented in Kenya. Both direct briquetting and carbonization/ briquetting were tried on a commercial basis but due to the high cost of biomass briquettes compared with firewood, none of the plants was able to continue production. In order to produce cheap biomass briquettes for the household sector, the general trend nowadays in Africa is towards low pressure or manual briquetting. The Legacy Foundation is taking the lead in promoting the technology in Africa. Production is mainly based on women's groups to produce their family needs and excess briquettes could be sold to generate income (Eriksson and Prior, 1990).

2.2 The residual base

The potential agro-residues which do not pose any collection and drying problems, normally associated with biomass are rice husk, groundnut shells, coffee husk, palm nut shell, jatropha husk and maize cob.

There are many factors to consider before a biomass qualifies for use as feedstock for briquetting. Apart from its availability in large quantities, it should have the following characteristics:

2.2.1 Low moisture content

Moisture content should be as low as possible, generally in the range of 10-15 percent. High moisture content will pose problems in grinding and excessive energy is required for drying.

2.2.2 Ash content and composition

Biomass residues normally have much lower ash content (except for rice husk with 20% ash) but their ashes have a higher percentage of alkaline minerals, especially potash.

The ash content of some types of biomass is given in Table below.

Table 2.1: Ash content of some biomass material.

Biomass	Ash content (%)	Biomass	Ash content (%)
Corn cob	1.2	Coffee husk	4.3
Jute stick	1.2	Cotton shell	4.6
Sawdust (mixed)	1.3	Tannin waste	4.8
Pine needle	1.5	Almond shell	4.8
Soya bean stalk	1.5	Areca nut shell	5.1
Bagasse	1.8	Castor stick	5.4
Coffee spent	1.8	Groundnut shell	6.0
Coconut shell	1.9	Coir pith	6.0
Sunflower stalk	1.9	Bagasse pith	8.0
Jowar straw	3.1	Bean straw	10.2
Olive pits	3.2	Barley straw	10.3
Arhar stalk	3.4	Paddy straw	15.5
Lantana camara	3.5	Tobacco dust	19.1
Subabul leaves	3.6	Jute dust	19.9
Tea waste	3.8	Rice husk	22.4
Tamarind husk	4.2	Deoiled bran	28.2

(Source: Food and agriculture organization of the United Nations Bangkok, April 1996)

The ash content of different types of biomass is an indicator of slagging behaviour of the biomass. Generally, the greater the ash content the greater the slagging behaviour. But this does not mean that biomass with lower ash content will not show any slagging behaviour. The temperature of operation, the mineral compositions of ash and their percentage combined, determine the slagging behaviour. If conditions are favorable, then the degree of slagging will be greater. Minerals like SiO_2 , Na_2O and K_2O are more troublesome. Many authors have tried to determine the slagging temperature of ash but they have not been successful because of the complexity involved. Usually slagging takes place with biomass fuels containing more than 4% ash and non-slagging fuels with ash content less than 4%. According to the melting compositions, they can be termed as fuels with a severe or moderate degree of slagging.

2.2.3 Flow characteristics

The material should be granular and uniform so that it can flow easily in bunkers and storage silos. Some of the appropriate agro-residues are:

Jatropha curcas L. shell

Jatropha curcas L. is a non-edible perennial plant which is also known as physic nut or purging nut. It belongs to the family of Euphorbiaceae and the tribe of Joannesieae (Sirisomboon et al., 2007; De Jongh et al., 2010; Karaj & Müller, 2010). Chemical breakdown of the shells by either thermo-chemical or bio-chemical processes, produces a solid residue. This residue is ash when produced by combustion in air. The ash component forms a standard measurement parameter for solid and liquid fuels and affects both the handling and processing costs of the overall biomass energy conversion cost (McKendry, 2002). Depending on the magnitude of the ash content, the available energy of the fuel is reduced proportionately (McKendry, 2002). *Jatropha* husk ash fuses at temperatures above 750°C (Singh et al., 2008). At these high temperatures the ash reacts to form a slag, which can reduce plant throughput in combustion equipment. The shell is mechanically removed from the fruit in the first step during oil extraction. About one tonne of shell material can be obtained from one hectare and this material can be used as a source of energy. The chemical analysis of JCL shell has shown that it is made up of 34%, 10% and 12% cellulose, hemicellulose and lignin, respectively (Singh et al., 2008, Abreu, 2009). Volatile matter, ash and fixed carbon content of the shell have been shown to be 69%, 15% and 16%, respectively (Singh et al., 2008). These results show that JCL shells have very high ash content. This has an influence on the type of conversion technology that can be used to obtain energy from the shells (Jingura et al, 2010). The caloric value of JCL shells is 11.1MJ kg⁻¹ (Sotolongo et al., 2009). With this value and using a yield value of one tonne JCL shells per hectare, shells can supply 11.1GJ ha⁻¹ (Jingura et al, 2010). The chemical composition of JCL shells seems to suggest that it is a good feedstock for biological conversion and for briquetting (Singh et al., 2008).

Rice husk

When compared to sawdust, agro-residues have a higher ash content, higher potash content and have poor flow characteristics. However, rice husk is an exceptional biomass. It has good flowability, normally available with 10 percent moisture and the ash contains fewer alkaline minerals, thereby it has a high ash sintering temperature. In fact, it makes an excellent fuel although its calorific value is less than wood and other agro-residues.

Other biomass materials

- Groundnut shell: Because of low ash (2-3%) and moisture content less than 10%, it is also an excellent material for briquetting.
- Cotton sticks: This material is required to be chopped and then stored in dry form. It has a tendency to degrade during storage. Also, it has a higher content of alkaline minerals and needs to be used with caution.
- Bagasse/bagasse pith: These residues have high moisture content of 50% after milling, hence drying is energy intensive. They have low ash content and a correspondingly high heating value of the order of 4400 kcal/kg.
- Pith: is the small fibrous material which has to be removed from bagasse before bagasse is used as feedstock for making paper. Due to shortages of wood and increasing demand for paper and pulp, an ever increasing number of paper units are switching over to bagasse as feed material. The amount of pith available is almost equal to the tonnage of paper produced by a paper mill. For example, a 60 TPD mill will generate 60 TPD of bagasse pith. This material does not require milling before it is briquetted. At present, this pith is available from sugar mills at much lower costs. This is a potential material for briquetting.
- Coffee husk: An excellent material for briquetting having low ash and available with 10 percent moisture content. The material is available in the coffee growing areas.
- Mustard stalks: Like cotton sticks, it is also an appropriate material for briquetting.
- Others: Other potential biomass residues suitable for briquetting are lentil stalks, sawdust, and Lantana camara in hilly areas, tea wastes, and coir pith.

2.3 Characteristics of briquettes

Briquettes must be consistent or otherwise cracks, scratches could appear, and fine elements would separate, which is not acceptable. Briquettes with higher density have a longer burning time. The standard Ö-Norm M 7135 defines the briquette density value for the HP group (wood briquettes) and for the RP group (crust briquettes) at more than 1.12 kg/dm³ (g/cm³), and for other briquettes this value must be more than 1 kg/dm³ (g/cm³). The standard DIN 51731 defines the interval of briquette density values from 1 to 1.4 kg/dm³ (g/cm³) (Križan, 2007, Lehtikangas, 2001). The standard DIN 52182 (additional standard DIN 51731) also describes the testing method for briquette density. A piece of briquette has to be weighed and its diameter and length measured. Briquette density has to be evaluated before and after stabilization of these values according to the following ratio.

$$\rho_N = m_N / V_N \text{ (kg/dm}^3\text{)}$$

Where:

- V_N – briquette volume (dm³)
- m_N – briquette weight (kg)

Briquette strength is maximal pressure on the die, which is developed by a pressure test under predetermined conditions. In order to examine the strength in pressure for cylindrical briquettes, there are two suitable ground tests - test by cleft (pressure affecting a briquette which is in a horizontal position) and a strength test with simple pressure (pressure affecting a briquette which is in a vertical position) (Križan, 2007, Janković, 1997). It is also possible to evaluate briquette quality by means of briquette hardness. Stronger briquettes have essentially better quality. Briquette hardness and thereby briquette quality can be checked very easily by inserting the briquette into water. A quality briquette should fall to the bottom in a moment because it has a higher specific density than water. After that, when the briquette is dipped into the water, if it falls to pieces in under 5 minutes, and that usually represents very low briquette quality. When the briquette falls to pieces in under 15 minutes, it shows medium briquette quality and in less than 20 minutes, it is sign of good briquette quality. However, this method is only of an informative character (Križan, 2007).

2.4 Briquetting technology

The briquetting technologies can be divided into: high pressure compaction, medium pressure compaction assisted by a heating device and low pressure compaction with a binding agent.

Depending on the type of material, the pressure applied and the binder used, different binding methods are used. The physical properties (moisture content, bulk density, void volume and thermal properties) of the biomass are the most important factors in the binding process of biomass densification. The densification of biomass under high pressure results in mechanical interlocking and increased adhesion/cohesion (molecular forces like van der Waal's forces) of the solid particles, which form intermolecular bonds in the contact area. Additives of high viscous bonding media (binders), such as tar, molasses and other molecular weight organic liquid can form bonds very similar to solid bridges. Adhesive forces at the solid/liquid interface and cohesion forces within the solid are used for binding. Lignin of biomass/wood which is deliberated under high pressure and/or temperature can also be assumed to help binding in this way. Apart from lignin, which is gained from the feed material itself, other free atoms or molecules (e.g. moisture) can be attracted from the surrounding atmosphere to form thin adsorption layers. They also support the formation of bonds between the individual particles.

2.4.1 High and medium pressure compaction

High and medium pressure compaction normally does not use any additional binder. Normally, the briquetting process bases either on screw press or piston press technology. For the Screw Press Compress, the Biomass is extruded nonstop by the screw through a hot and taper block. For Piston Press Compress method, the hardness at the touch part like at the compress and block part is less compare with screw and block for Screw Press type. At the pass, the energy using is less compare at this time. From quality aspect, the briquetting and production procedure for Screw Press is more good compare with Piston Press type. The centre of pore that is associated with briquetting process from Screw Pressure help in achieving the perfect and flat burning. So, this briquette can be carbonized. Below is the list of the different between Piston Press and Screw Press.

Table 2.2: Different between Piston Press and Screw Press.

	Piston Press	Screw Press
The optimum of raw material Moisture Contain	10-15%	8-9%
The Hardness of between touch part	Low for compress and block case	High for screw case
Output of machine production	Level by level	Nonstop
Energy using	50 kWh/tonne	60 kWh/tonne
Briquette Density	1-1.2 gm/cm	1-1.4 gm/cm
Maintenances	High	Low
Briquette burning Performance	Not so good	Very good
Carbonization to the coal	Impossible	Produce the good coal
Appropriate of gas changing	Not appropriate	Appropriate
Homogeneity in the briquette	Non-homogeneous	Homogeneous

(Erikson, 1990)

Other briquetting technologies are less applicable in developing countries because of high investment costs and large throughputs, e.g. roller-presses to produce pellets or briquettes.

2.4.1.1 Screw press

In a screw press or screw extruder, the rotating screw takes the material from the feed port, through the barrel, and compacts it against a die which assists the build-up of a pressure gradient along the screw. Thus, the extruder features three distinct zones: feed, transport, and extrusion zones. The important forces that influence the compaction of the feed material play their role mostly in the compression zone near to the extrusion die. The frictional forces between feed material and barrel/screw, the internal friction in the material and external heating device (of the extrusion zone) cause an increase in temperature (up to 300°C), which softens the feed material. Lignin from the biomass is set free and acts as gliding and binding agent. The speed of densification, the energy consumption of the press and the quality of the briquettes produced depend on: flowability and cohesion of the feed material, particle size and distribution, surface forces and adhesiveness. Screw presses produce high quality briquettes with a homogenous structure and good combustibility, and they require only little maintenance. The main disadvantage is that the wear of the screw leads to elevated spare part costs.

The merits and demerits of this technology are:

- The output is continuous and the briquette is uniform in size.
- The outer surface of the briquette is partially carbonized facilitating easy ignition and combustion. This also protects the briquettes from ambient moisture.

- A concentric hole in the briquette helps in combustion because of sufficient circulation of air.
- The machine runs very smoothly without any shock load.
- The machine is light compared to the piston press because of the absence of reciprocating parts and flywheel.
- The machine parts and the oil used in the machine are free from dust or raw material contamination.
- The power requirement of the machine is high compared to that of piston press.

2.4.1.2 Piston press

Piston presses punch the feed material into a die with very high pressure, either mechanically by a reciprocating ram powered by a massive flywheel, or by a hydraulically driven piston. Thereby, the mass is compressed and forms a very dense briquette. Some modern (hydraulically operated) machines apply pressure not only in longitudinal but also in radial direction.

The merits and demerits of this technology are:

- There is less relative motion between the ram and the biomass hence, the wear of the ram is considerably reduced.
- It is the most cost-effective technology currently offered by the Indian market.
- Some operational experience has now been gained using different types of biomass.
- The moisture content of the raw material should be less than 12% for the best results.
- The quality of the briquettes goes down with an increase in production for the same power.
- Carbonisation of the outer layer is not possible. Briquettes are somewhat brittle.

2.4.2 Low pressure compaction

Low pressure briquetting needs a binding agent to assist the formation of bonds between the biomass particles. There are various binding agents in use which can be divided into two main groups: organic and inorganic binders. The most important binders are:

- **Organic binders**
 1. Molasses
 2. Coal tar
 3. Bitumen
 4. Starch

5. Resin

- **Inorganic binders**

1. Clay
2. Cement
3. Lime
4. Sulphite liquor

During the compaction process the briquettes are brought into shape without giving them substantial strength. Only after a subsequent curing step (drying, burning, chemical reaction, etc.) the “green” briquettes will develop the required strength and stability.

Some interesting low pressure compaction methods for briquettes from biomass are described in the following text.

2.4.2.1 Hand moulded briquettes

Hand moulds are the simplest devices to form small quantities of briquettes. Plate 2.1 shows hand moulds used in Mali for the production of briquettes from waste charcoal dust and molasses as binding agent. The briquettes reach their final strength after drying in the sun or a gentle heat treatment in a curing furnace.

A wide spread semi-mechanised method to form briquettes from mineral coal is found in China. Ground coal is mixed with water and approximately 20% of clay binder and formed into so-called honeycomb briquettes by a mechanized briquetting press (Plate 2.2). The “green” briquettes reach their final strength and stability after drying some days in a dry environment.

A method to form briquettes from biomass was found in Kenya and Benin. There, biomass of fine particle size (saw dust, rice husks, wood shavings, charcoal dust, etc.) was mixed with approximately 20% of (waste) paper pulp and formed into briquettes in a manually operated piston press (Plate 2.3).

The briquettes (Plate 2.4) were dried in the sun and gained strength due to the property of paper fibre in building up hydrogen bonds among themselves and the biomass (Vest, 2003).



Plate 2.1: Hand moulds for charcoal dust and molasses binder in Mali (Senegra, 00223/202507)



Plate 2.2: Chinese semi-mechanised briquetting press (Beijing, 0086/10/677 812 07)



Plate 2.3: Manual briquetting press for biomass and waste paper in Benin (DCAM, 00229/321129)



Plate 2.4: Manually produced briquettes from biomass and waste paper in Benin (DCAM, 00229/321129)

2.5 TECHNOLOGICAL PARAMETERS OF THE BRIQUETTING PROCESS

2.5.1 Material humidity

If the production of briquettes with standard defined quality is required, it is necessary to know the impact of the material humidity on the quality. For a growing tree water has a very positive effect, because it is a necessary prerequisite for every vegetal organism to exist. For a cut tree, water is unacceptable. Material humidity depends on the type of material. Every material has its own specific nature. However, it is difficult to determine the optimal value of humidity for briquetting. After analysis, the optimal value of material humidity for briquetting is from 10 % to 18 %, which can be calculated according to type of material. If the humidity of the pressing material is very low or very high (beyond the 10-18% interval) material elements are not

consistent and a briquette falls to pieces. Material humidity has an impact on lignin plastification. The lignin softening temperature depends on the type of material and lignin isolation method. The relations between material humidity, compacting pressure and pressing temperature are very interesting. Pressing the material where temperature, pressure and material humidity values are not in optimal interval results in a briquette that is not compact and which can fall to pieces. It is possible to combine temperature effects on lignin plastification with pressure briquetting. Nevertheless, when the material humidity is very high it causes the excess water to turn into steam that tears a briquette to pieces. When the material humidity is very low (lower than 10%), for a quality briquette very high pressure is required and it is very expensive and uneconomic. Finding the optimal value of material humidity will be one part of this experiment (Križan, 2007, Janković, 1997).

2.5.2 Compacting pressure

This factor is the most important factor with the main influence on briquette strength. Briquette strength is higher when there is higher pressure. Briquette strength increases to the strength limit of the compacting material. Briquette strength has an impact on briquette durability because when the strength increases, the absorption of atmospheric humidity decreases. Compacting pressure, seen from the viewpoint of complex analysis or research, is a very interesting and very complicated parameter. Various parameters have an impact on compacting pressure e.g. type of pressing material, temperature in the pressing chamber, pressing material temperature and of course also the length, diameter and shape of the pressing chamber and the manner of briquetting. The manner of briquetting has an impact on layer distribution in briquettes and so on briquette strength. When warmed material is pressed, the briquettes have a better density and better quality at lower pressure. Material warming during the briquetting process reduces the needed pressure for briquetting of briquettes for the required quality. The briquettes then have consistent shape and volume without cracks and scratches (Križan, 2007).

2.5.3 Pressing temperature

Pressing temperature has an expressive impact on briquette quality and strength. This parameter determines the segregation of lignin from the cellular structure of the wood. Lignin is very important in the briquetting process because its function in material pressing is to join the fibres. In addition, lignin acts as a stabilization factor for the cellulose molecules in the cell wall. The more lignin is included in the material the more the material can release it and then the briquette quality is higher because lignin causes higher material strength. Lignin is released

only at specific pressing temperatures that have to be provided during the briquetting process. The optimal value for pressing temperature for lignin plastification is approximately 120°C, but optimal temperature depends on the type of pressing material. It is not important to increase the pressing temperature. When the temperature is out of optimal value range the briquette is unstable, it has low strength that causes faster decay in burning, and the briquette burns for a shorter time. Lower temperatures do not lead to high quality briquettes. Higher temperatures cause the occurrence of highly volatile elements or pressing material to burn. With an increase in the pressing temperature by constant compacting pressure, briquette strength is also increased, but only to a specific value (Križan, 2007).

2.5.4 Fraction largeness

Fraction largeness has a very high impact on the briquetting process. The bigger the fraction is, the more power is needed for briquetting. A briquette has lower homogeneity and stability. An increase in fraction size results in the decrease of binding forces which lead to faster decay in burning (the briquette burns faster and that is not an advantage). Increase of the fraction size results in the increase of needed compacting pressure and a decrease of briquette quality (Križan, 2007).

CHAPTER THREE

3.0 MATERIALS AND METHODS

For the purpose of this study, mild steel was used for the construction of the machine. Mild steel plates and rods were bought from a local mild steel market at Kumasi-Suame magazine in Ghana. The machine was fabricated at the Agricultural Engineering workshop in the Kwame Nkrumah University of Science and Technology-Kumasi (KNUST). The machine was fabricated using electric arc welding machine.

3.1 Conceptual designs

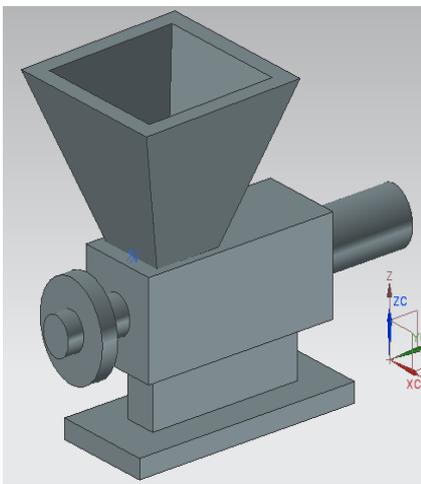


Figure 3.1: Conceptual design 1

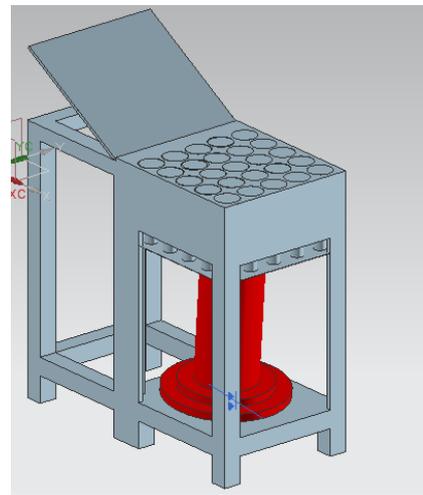


Figure 3.2: Conceptual design 2

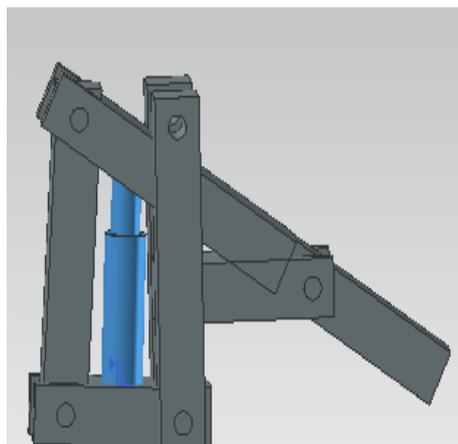


Figure 3.3: Conceptual design 3

Conceptual design one operated with the aid of an electric motor. The compaction of biomass material was as a result of a screw auger, pressing the material against a die at high pressure (high pressure system).

The second conceptual design employed a hydraulic car jack for the compaction work. It operated by a set of pistons pressing the biomass material against a closed lid (cover).

The third conceptual design was a manually operated lever arm press. It works by pressing the biomass material in a cylindrical mould and it is one press at a time.

Conceptual design two was selected, based on the fact that it produces more briquettes at a time unlike conceptual design type which produces one at a time.

3.2 Description of the machine

A manually operated biomass briquetting machine was designed and constructed (Figure 4). The briquetting machine consist of 25 moulds each with an internal diameter of 70mm and a depth of 190.5mm welded to a 6mm flat mild steel plate at the top and bottom and positioned vertically over equal number of pistons. The pistons were made such that there was a clearance of about 2mm between the piston head and the mould walls to allow the escape of water during compaction. The opposite ends of the rods were welded on a flat metal plate of 12mm thickness which rests on a 20 ton capacity hydraulic jack. The jack drives the pistons in and out of the moulds during operation.

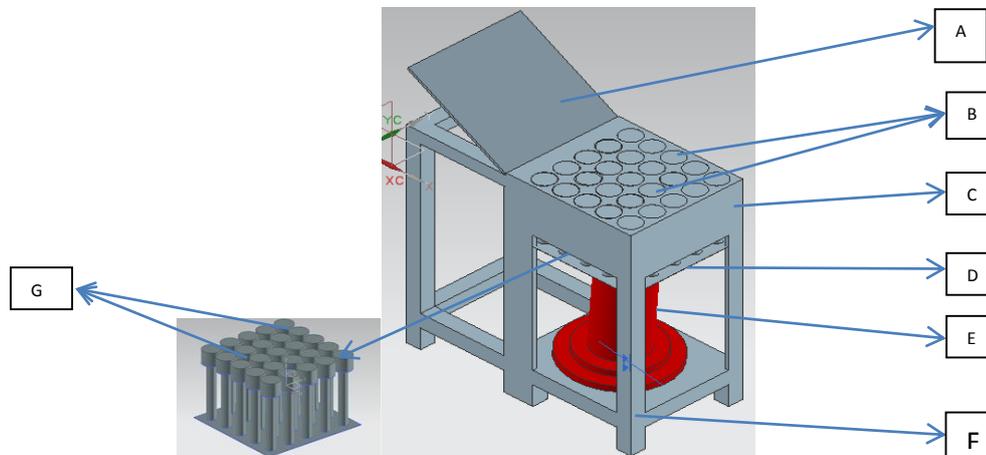


Figure 3.4: The biomass briquetting machine

A- mould cover, B- moulds, C- mould box, D- under plate, E- car jack (20 ton), F- body frame and G- pistons.

A flat metal plate (A), 12mm thick, was hinged to the mould box to cover the open ends of the moulds during compaction and opened during ejection of the briquettes. The vertical motion of the pistons in the moulds and the ejection of compressed briquettes from the moulds was by manual operation of the hydraulic jack (E). The hydraulic jack rests on angle bars welded to

the frame (F) of the machine. By this arrangement, the force from the hydraulic jack was centrally applied to the metal plate bearing the pistons. The machine was fabricated using mild steel and angle bars. Below is an orthographic view of the machine.

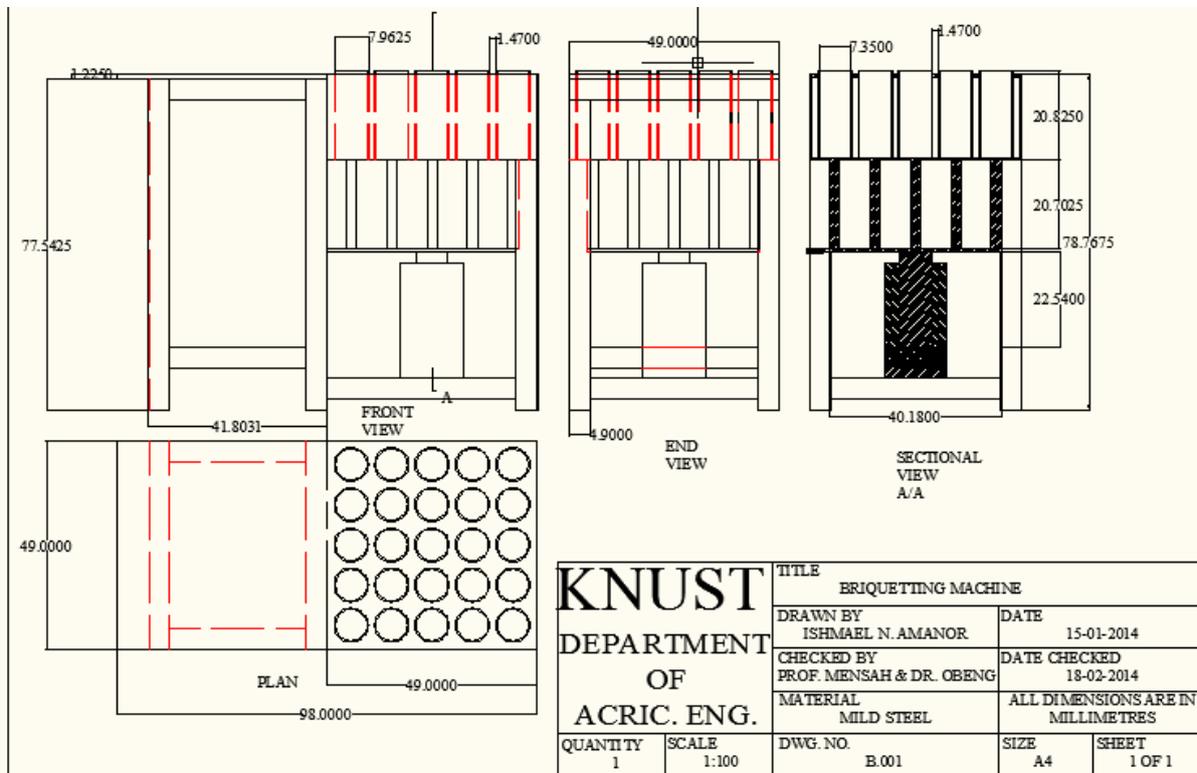


Figure 3.5: Design of the briquetting machine

3.3 Design of machine element and material selection

Properties of mild steel

- Ultimate strength = 400MPa
- Yield strength (σ_y) a. tensional = 250MPa
b. shear = 145MPa
- Modulus of elasticity (E) = 200GPa
- Modulus of rigidity = 77.2GPa

Density (ρ) = 7860kg/m³

Coefficient of thermal expansion = 11.7GPa

(Source: Mechanics of Materials, sixth edition by Ferdinand P. Beer, et al., 2012.)

3.3.1 Mould (cylinder)

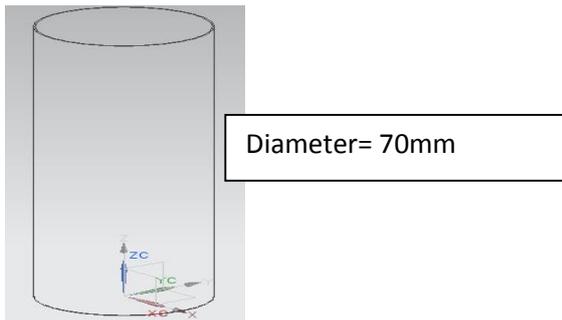


Figure 3.6: briquette mould

Briquette cross-sectional area (A_{b1})

$$A_{b1} = \pi r^2, \text{ where } r = 3.4925\text{cm} \quad A_{b1} = \pi (3.4925 \times 10^{-2})^2 = 3.832 \times 10^{-3} \text{m}^2$$

$$\text{Total area } A_{bT} = 3.832 \times 10^{-3} \text{m}^2 \times 25 = 0.0958 \text{m}^2$$

$$\text{Design pressure } (P_{CT}) = 17.5 \text{ KN/m}^2$$

$$\text{Force applied } (F_{CT}) = P_{CT} \times A_{bT} = 17.5 \text{ KN/m}^2 \times 0.0958 \text{m}^2$$

$$F_{CT} = 1.6765 \text{KN}$$

$$\sigma_z = \left(\frac{d_2^2 - d^2}{d_2^2 - d_1^2} \right) \frac{d_1^2}{d^2} p_1$$

$$\sigma_h = \left(\frac{d_2^2 + d^2}{d_2^2 - d_1^2} \right) \frac{d_1^2}{d^2} p_1$$

$$\frac{2}{3} \sigma_y = \frac{1}{3} \sqrt{(\sigma_h - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_h)^2}$$

σ_z = axial stress

σ_h = hoop stress

σ_r = radial stress = 0

σ_y = design yield stress

$d = d_1$ = internal diameter = 6.985cm

$d_2 = d_1$ = external diameter = 7.62cm

$$P = \frac{17.5}{25} = 0.7 \text{ KPa}$$

$$\sigma_z = 0.7 \text{ KPa}$$

$$\sigma_h = 7.9761 \text{KPa}$$

$$\sigma_y = 5.409 \text{KPa}$$

$$\sigma_y < 250 \text{MPa}$$

3.3.2 Mould cover

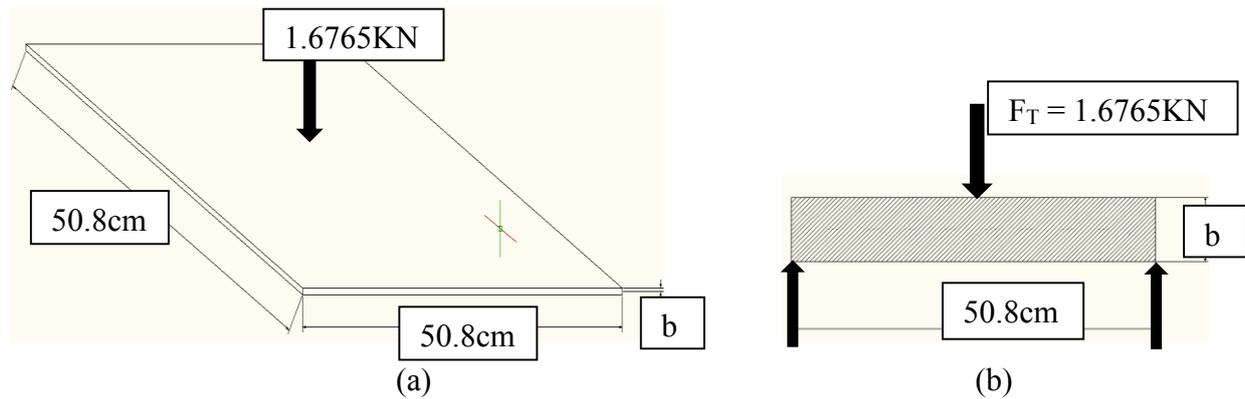


Figure 3.7: (a) mould cover, (b) cross-sectional area of (a)

- Function: a. Resist bending (deflection)
b. Resist shearing
- Constraint: a. Required length (L) = 20”
b. Force (F) = 1.6765 kN.

Under shearing

$$\frac{F}{A_m} < \sigma_y \quad \text{where, } A_m = 50.8\text{cm} \times b, F = 1.6765\text{KN and } \sigma_y = 145\text{MPa}$$

$$A_m = \frac{F}{\sigma_y}$$

$$0.508 \times b = \frac{F}{\sigma_y} \quad b = \frac{F}{0.508\sigma_y} = 2.276 \times 10^{-5}\text{m} \quad b \geq 0.02276\text{mm}$$

Under bending

Allowable bending stress (σ_b) = 0.55 × yield strength

$$\sigma_b = 0.55 \times 250 = 137.5\text{MPa}$$

Assuming the force will be distributed uniformly over the area;

$$BM_{\max} = \frac{WL^2}{8} \text{ (Maximum bending moment)}$$

$$w = \frac{F_{CT}}{L_m} = \frac{1.6765}{0.508} = 3.300\text{KN/m}$$

$$BM_{\max} = \frac{(3.3)(0.508)^2}{8} \quad BM_{\max} = 0.1065\text{KNm}$$

Sectional modulus of the cover is:

$$z = \frac{L_m b^2}{6} = \frac{0.508 \times b^2}{6}, \quad \text{but } z = \frac{BM_{\max}}{\sigma_b} \rightarrow \frac{0.508 \times b^2}{6} = \frac{BM_{\max}}{\sigma_b}$$

$$b^2 = 11.811 \times \frac{BM_{\max}}{\sigma_b} \quad \rightarrow \quad b \geq \sqrt{11.811 \times \frac{BM_{\max}}{\sigma_b}} \quad \rightarrow \quad b = \sqrt{11.811 \times \frac{0.1065}{137.5 \times 10^3}} \geq 3.2989 \times 10^{-3} \text{m} \quad b \geq 3.3 \text{mm}$$

3.3.3 Moulds cover back hinges and front lock

Force acting on the mould cover will be distributed between the back hinge and the locking device.

$$\text{Total force } (F_T) = 1.6765 \text{KN} \quad \frac{1.6765}{2} = 0.8383 \text{KN}$$

$$\text{Force in hinges } (hf) = 0.8383 \text{KN}$$

$$\text{Number of hinges} = 2$$

$$\text{Force per hinge } (Fh) = \frac{hf}{2} = \frac{0.8383}{2} \quad \rightarrow \quad Fh = 0.41515 \text{KN}$$

Function: Resist shearing and bending

Under shearing

$$\tau = \frac{1.5Q_{\max}}{A} \quad \text{where; } \tau = 145 \text{MPa, } A = \pi r_i^2 \quad \text{and } Q = Fh = 0.41515 \text{KN}$$

$$r_i^2 = \frac{1.5 \times 0.41515}{\pi(145 \times 10^3)} = 1.3670 \times 10^{-6} \quad \rightarrow \quad r_i \geq 1.1692 \times 10^{-3} \text{m} \geq 1.1692 \text{mm}$$

$$d \geq 2.3384 \text{mm}$$

Under bending

$$r^3 \geq \frac{WL^2}{2\pi\sigma_b} \quad r \geq \sqrt[3]{\frac{FhL}{2\pi\sigma_b}} \quad w = \frac{Fh}{L}$$

$$L = 8 \text{cm} = 0.08 \text{m}$$

$$\sigma_b = 0.55 \times 250 = 137.5 \text{MPa}$$

$$r \geq \sqrt[3]{\frac{0.41515 \times 0.08}{2\pi \times 137.5 \times 10^3}} \quad r_h \geq 3.375 \times 10^{-3} \text{m} = 3.375 \text{mm, } d \geq 6.75 \text{mm}$$

$$\text{Force on locker } (Lf) = 0.8383 \text{KN}$$

Function: Resist shearing and bending

Under shearing

$$\tau = \frac{1.5Q_{\max}}{A} \quad \text{where; } \tau = 145 \text{MPa, } A = \pi r_i^2 \quad \text{and } Q = hf = 0.41515 \text{KN}$$

$$r_i^2 = \frac{1.5 \times 0.8383}{\pi(145 \times 10^3)} = 2.7604 \times 10^{-6} \quad \rightarrow \quad r_i \geq 1.6614 \times 10^{-3} \text{m} \geq 1.6614 \text{mm}$$

$$d \geq 3.3228 \text{mm}$$

Under bending

$$r^3 \geq \frac{WL^2}{2\sigma_b} \quad r \geq \sqrt[3]{\frac{WL^2}{2\pi\sigma_b}} \quad w = \frac{hf}{L}$$

$$L = 27\text{cm} = 0.27\text{m}$$

$$w = \frac{0.8383}{0.27} = 3.1048\text{KN/m}$$

$$\sigma_b = 0.55 \times 250 = 137.5\text{MPa}$$

$$r \geq \sqrt[3]{\frac{(3.1048) \times 0.27^2}{2\pi \times 137.5 \times 10^3}}$$

$$r_h \geq 1.9486 \times 10^{-4}\text{m} = 1.9486\text{mm}, \quad d \geq 3.8973\text{mm}$$

3.3.4 Piston rods

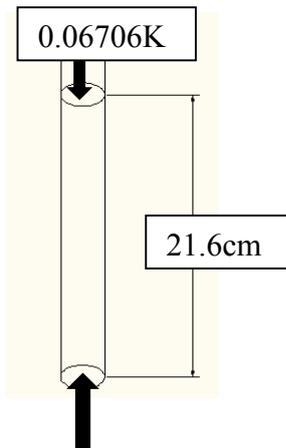


Figure 3.8: piston rod

Number of rods = 25

$$\text{Force per rod} = \frac{1.6765}{25} = 0.06706\text{KN}$$

$$\text{Using Euler's equation; } P_{cr} = \frac{\pi^2 EI}{L^2} \rightarrow P_{cr} = 0.06706\text{KN}, \quad L = 0.2159\text{m}$$

$$I = \frac{\pi r^4}{4} \rightarrow P_{cr} = \frac{\pi^2 E (\pi r^4)}{4L^2} \rightarrow r^4 \geq \frac{4L^2 P_{cr}}{\pi^3 E}$$

$$r^4 \geq \frac{4(0.06706)(21.59 \times 10^{-2})^2}{\pi^3 (200 \times 10^6)} = 2.0163 \times 10^{-12} = \sqrt[4]{(1.1916 \times 10^{-12})}$$

$$r \geq 1.1916 \times 10^{-3}\text{m} \approx 1.2\text{mm} \quad d \geq 2.4\text{mm}$$

3.3.5 Under plate (piston plate)

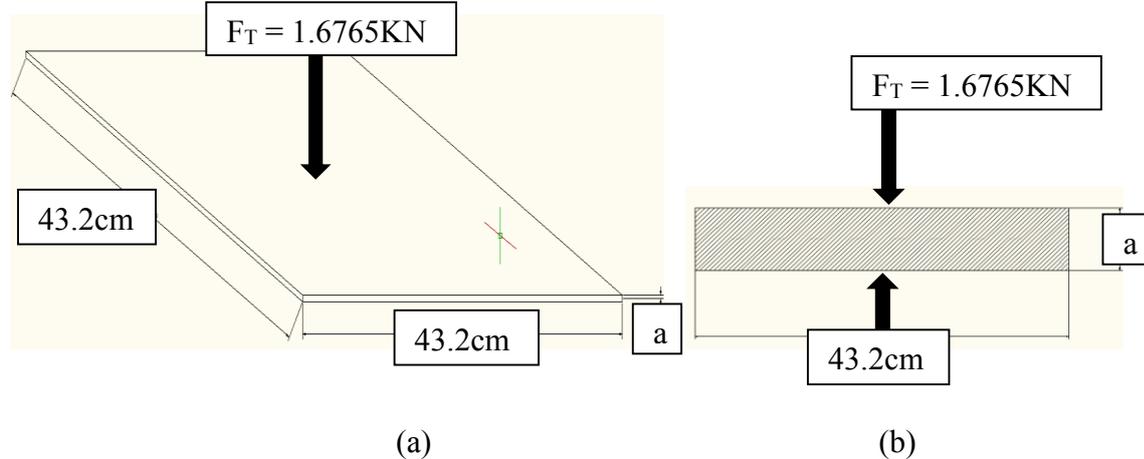


Figure 3.9: (a) under plate, (b) cross-sectional area of (a)

Function: a. Support bending load

b. Support shearing load

Constraint: a. Required length (L) = 17'' = 0.432m

b. Force (F) = 1.6765kN

Under bending

Assuming the force is distributed uniformly over the area;

$$BM_{\max} = \frac{WL^2}{8}, \text{ where; } W = \frac{1.6765}{0.432} = 3.8808 \text{ kN/m}$$

$$BM_{\max} = \frac{(3.8808) \times (43.2 \times 10^{-2})^2}{8} = 0.091 \text{ kNm}$$

$$\sigma_b = 137.5 \text{ MPa}$$

$$z = \frac{L \times a^2}{6} \rightarrow z = \frac{BM_{\max}}{\sigma_b} \rightarrow a^2 = \frac{6(BM_{\max})}{L \times \sigma_b} \rightarrow a^2 = \sqrt{\frac{6(BM_{\max})}{L \times \sigma_b}} \rightarrow$$

$$a \geq \sqrt{\frac{6(0.091)}{0.432 \times (137.5 \times 10^3)}}$$

$$a \geq 3.0318 \times 10^{-3} \text{ m} \quad a \geq 3.03 \text{ mm}$$

Under shearing

The maximum shear will occur at the middle;

$$\tau = \frac{1.5Q_{\max}}{A}, \quad \text{where; } A = 0.432 \times a \quad \text{and } \tau = 145 \text{ MPa}$$

$$\tau = \frac{1.5 \times 1.6765}{0.508a} \rightarrow a = \frac{1.5 \times 1.6765}{(145 \times 10^3) \times 0.432} \geq 4.0146 \times 10^{-5} \text{ m} \approx 0.04 \text{ mm}$$

Table 3.1: component selection

component	Design consideration	Calculated parameter	Selected size
Mould cover	a. Shearing b. Bending	a. $b \geq 0.023\text{mm}$ b. $b \geq 3.3\text{mm}$	$b = 12\text{mm}$
moulds	shearing	$\sigma_y = 5.409\text{MPa}$	$t = 3\text{mm}$
pistons	Buckling	$d \geq 2.4\text{mm}$	$d = 25\text{mm}$
Piston plate	a. Shearing b. Bending	a. $b = 0.04\text{mm}$ b. $b \geq 3.03\text{mm}$	$b = 12\text{mm}$
Hinges /Locker	c. Shearing d. Bending	a. $d \geq 6.75\text{mm}$ / $d \geq 3.8973\text{mm}$	$d = 25\text{mm}$

3.4 Construction of the machine

3.4.1 Construction of mould and mould box

The machine contains 25 moulds, each of 203mm length and a 76mm external diameter galvanized pipe. The moulds were cut with a cutting disc and ground to ensure a uniform and level height. The mould box is made up of the moulds and two 6mm mild steel plate and was constructed by first cutting two 508×508mm size out of the 6mm plate. 25 circles of the same size as the moulds with 15mm spacing between them was marked on the two plates and cut using a gas welding touch. All the 25 moulds was carefully set straight between the two plates with the aid of a spirit level and a try square and welded, this was done one after the other.



Plate 3.1: mould box under construction

3.4.2 Construction of piston and under plate

The machine requires equal number of pistons as the number of moulds to produce all the 25 briquettes required. The pistons are made up of 216mm long, 25mm rod and a 6mm round plate with a diameter of 58mm. The pistons were constructed by positioning each rod and welded at the center of the round plate. Each piston was put in a lathe machine and the round plate was carefully turned to the required diameter. A plate, 12mm thick and 432mm × 432mm size was cut and 25 holes of 1 inch diameter with a clearance of about 1mm was centered in accordance with the centers of the moulds and drilled using a drilling machine in a three step drilling process. The pistons were inserted in the holes drilled on the base plate and welded upright to ensure easy and free movement of pistons in the moulds during operation.



Plate 3.2: Piston under fabrication



Plate 3.3: Piston being machined in a lathe machine

3.4.3 Construction of frame and mould cover

The frame, which is the member that supports the mould box, the jack, mould cover and the pistons with the base plate was constructed with a 51mm angle bars. The frame was made up of six 762mm long vertical stands which support the weight of the mould box, mould cover and the pistons with the base plate and also support the dynamic load that the jack would exert during compaction of the biomass material. The six vertical bars were held in position with the aid of eight 432mm long angle bars, welded horizontally between the vertical bars at

the top and down of the pressure side and also held with six 356mm angle bars at the side which would support the mould cover when opened. Four 432mm long bars was welded at 216mm from the top, which serves as a support for the mould box, it also have another two angle bars welded at distance of 432mm from the top which serves as a seat for the under plate. The mould cover, 12mm thick plate of size 508×508mm was hinged to the frame with the aid of two hinges which were welded to the frame.



Plate 3.4: Frame under construction



Plate 3.5: Frame after construction

3.5 Testing of the machine

For the purpose of this study, jatropha husk was used for the testing of the machine. The jatropha husk sample was collected from a jatropha seed oil extraction plant at Yeji, Brong-Ahafo region, Ghana. Cassava starch was prepared with cassava bought from a local market and used as a binding agent mainly to overcome the major problem of material compaction and post compaction recovery, which represents enormous waste in energy input (Faborode, 1998).

3.5.1 Biomass-binder Mixture

Jatropha husk sample in three different particle sizes (original particle size, particle size less than or equal to 6mm and particle size less than or equal to 2mm) was mixed with an already prepared cassava starch in proportions of 100:15, 100:25, 100:35 and 100:45 by weight respectively. The starch and the biomass sample was well mixed without forming a mixture with high moisture content because the formation of a mixture with higher moisture content due to excess addition of water reduces both the durability and density of the briquette

(Mohamed, 2004). The biomass-binder mixture was hand fed into the moulds and compacted to form the briquettes after which they were sun dried to constant weight.



Plate 3.6: Briquette of raw char (original particle size) at different binder level after drying

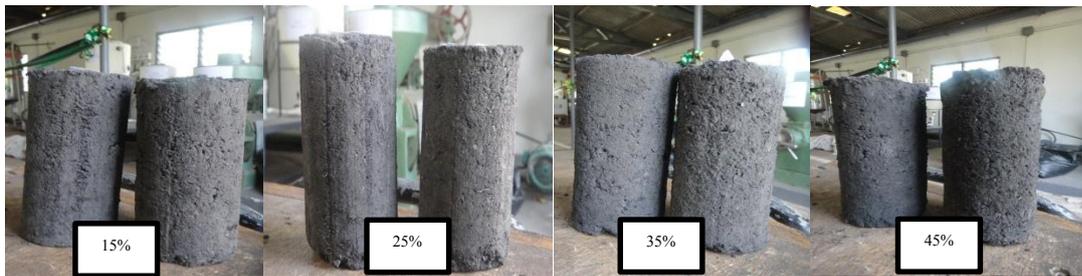


Plate 3.7: Briquette of particle size less than or equal to 6mm at different binder level after drying

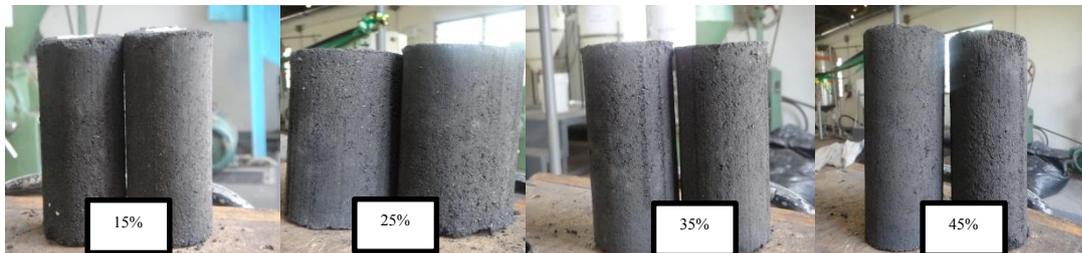


Plate 3.8: Briquette of particle size less than or equal to 2mm at different binder level after drying

3.5.2 Performance evaluation

For the performance evaluation, five briquette samples were randomly selected from the jatropha husk briquette for evaluation. During the densification process, the following statistic: time for loading biomass into moulds, T1 in seconds, time for compressing the biomass, T2, in seconds, and time for ejecting the biomass briquettes, T3, in seconds, were observed and recorded in line with work of Adekoya, 1998. The production capacity of the machine in kg/hr was recorded. On ejection of the briquettes from the moulds, the mass and the dimensions of the briquettes were taken to determine the density in g/cm^3 using an electronic weighing

balance and a caliper. The compressed density, relaxed density, relaxation ratio and dimensional stability of the jatropha husk briquette were determined in accordance with the methods described by Olorunnisola, 2007.



Plate 3.9: Biomass loading stage



Plate 3.10: Biomass compression stage



Plate 3.11: Briquette ejection stage



plate 3.12: Pistons at top dead center after briquette ejection

3.5.3 Physical Properties Determination

The bulk density of the loose biomass sample was determined by weighing an empty cylindrical container of known volume and mass, and then carefully filled with the biomass sample. After filling every one-quarter portion of the container with the sample, it was tapped on a table for some number of times to allow the material to settle down. After completely filling the container, excess material at the top was removed by moving a straight edge over

the container. The mass of the containing sample was determined. The compressed density (density immediately after compression) of the briquette was determined immediately after ejection from the moulds as the ratio of measured weight to the calculated volume. The relaxed density (density determined when dried) and relaxation ratio (ratio of compressed density to relaxed density) of the briquette were determined in the dry condition of the briquette after 8 days of sun drying to a constant weight at an ambient temperature. The relaxed density was calculated as the ratio of the briquette weight (g) to the new volume (cm³). This gives an indication of the relative stability of the briquette after compression. The compaction ratio was obtained from the ratio of the maximum density and the initial density of the jatropha husk sample (Oladeji1, 2012). Briquette stability was measured in terms of its dimensional changes when exposed to the atmosphere. The dimensional stability of the briquette was determined by measuring the height at an interval of 0, 30, 60, 1440, 2880, 4320, 5760, 7200, 8640 and 10,080 minutes (Sotannde, 2010). Durability represents the measure of shear and impact forces a briquette could withstand during handling, storage and transportation processes (Adapa, 2009). The durability of the briquette was determined in accordance with the chartered index described by (Suparin, 2008) after sun drying to a constant weight. The briquette was dropped repeatedly from a height of 1.5m onto a metal base. The fraction of the briquette that remained unshattered was used as an index of briquette durability (Sah, 1980), (Khankari, 1989). The durability rating of the briquette was expressed as a percentage of the initial mass of the material remaining on the metal plate and this gave an indication of the ability of the briquette to withstand mechanical handling. Water resistance of the briquette was tested by immersing the briquette in a container filled with cold tap water and measuring the time required for the onset of dissolving in water. The higher the water resistance time, the more stable the briquette is in terms of weathering resistance (Richards, 1990).

3.5.4 Data analysis

The experiment was set up with 5 replications. The data obtained from the test were analysed for One-way single-factor analysis of Variance (ANOVA) at 95% confidence level using SPSS software (version 16.0) and where significant differences were identified. The difference between the mean values of the properties tested for were determined using the Fisher's Least Significant Difference (FLSD) at 5% level of significance.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Machine capacity

The mean biomass loading time, t1, mean biomass compaction time, t2, and the mean briquette ejection time, t3 as well as their percentages of the total production time and the corresponding mean mass of biomass-binder mixture (briquette) produced were recorded as shown in Table 4.1.

Table 4.1: Production time components of the briquetting machine

MEAN PRODUCTION TIME COMPONENTS	TIME (SEC)	% OF TOTAL PRODUCTION TIME
Biomass loading time (t1)	38	30.65
Biomass compaction time (t2)	53	42.74
Biomass ejection time (t3)	33	26.61
TOTAL	124	100

Mean mass of briquette produced = 16.83kg

The machine produces averagely 16.83kg of briquette in about 124 second's time frame. From table 1 above the mean biomass loading time of 38 seconds, mean biomass compaction time of 53 seconds and mean biomass ejection time of 33 seconds were recorded respectively. The production capacity of the machine was about 488kg/hr (tested with jatropha husk) as compared to a machine capacity (tested with saw dust) of 43kg/hr reported by Obi in 2013. The efficiency of the machine in terms of capacity is more by 10 times greater than what Obi reported. The pie chart below shows the time of the various stages of the production as a percentage of the total production time.

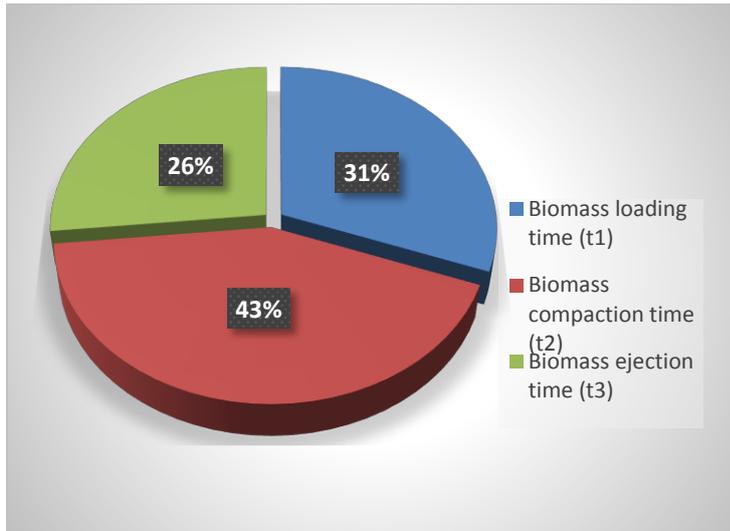


Figure 4.1: Mean percentage production time of the three stages of jatropha husk briquette

4.2 Physical Properties of Jatropha husk Briquette

The physical properties of the jatropha husk briquette are shown in Table 4.3. The influence of binder level and particle size was significant on the physical properties of the briquette ($P < 0.05$). The compressed density of the raw char (RC) ranged from 1.11 to 1.46g/cm³ on the addition of 15 to 45% cassava starch. The compressed density of the particle size less than or equal to 6mm ($\leq 6\text{mm}$) ranged from 1.098 to 1.14 g/cm³ on the addition of 15 to 45% cassava starch. The compressed density of the particle size less than or equal to 2mm ($\leq 2\text{mm}$) ranged from 1.048 to 1.153g/cm³ on the addition of 15 to 45% cassava starch.

4.2.1 Effect of the various binder levels on briquette produced from original particle size

The briquette produced from the raw char (original particle size) exhibited an unpredictable behaviour during the test. The compressed densities of binder level 25%, 35% and 45% shows no significant difference although 45% had a slightly higher value, with 15% binder recording the least value. However there is no significant variation between the various binder levels in terms of relaxed density, relaxation ratio and compaction ratio, although 45% binder level had a slightly higher value in all. The durability of all the briquette was inversely proportional to the compressed density and compaction ratio with 15% binder level showing a different characteristic (having 1.11g/cm³ compressed density and 2.6:1 compaction ratio) and a higher value of 60.22% recorded at binder level 35%. The durability of the briquette is attributed to the strength of the briquette immediately and after some few days of compaction (initial

strength of the briquette) which affect or disturbs the bonds between the particles hence reducing the durability of the briquette after drying. The various characteristics are presented in table 4.3.

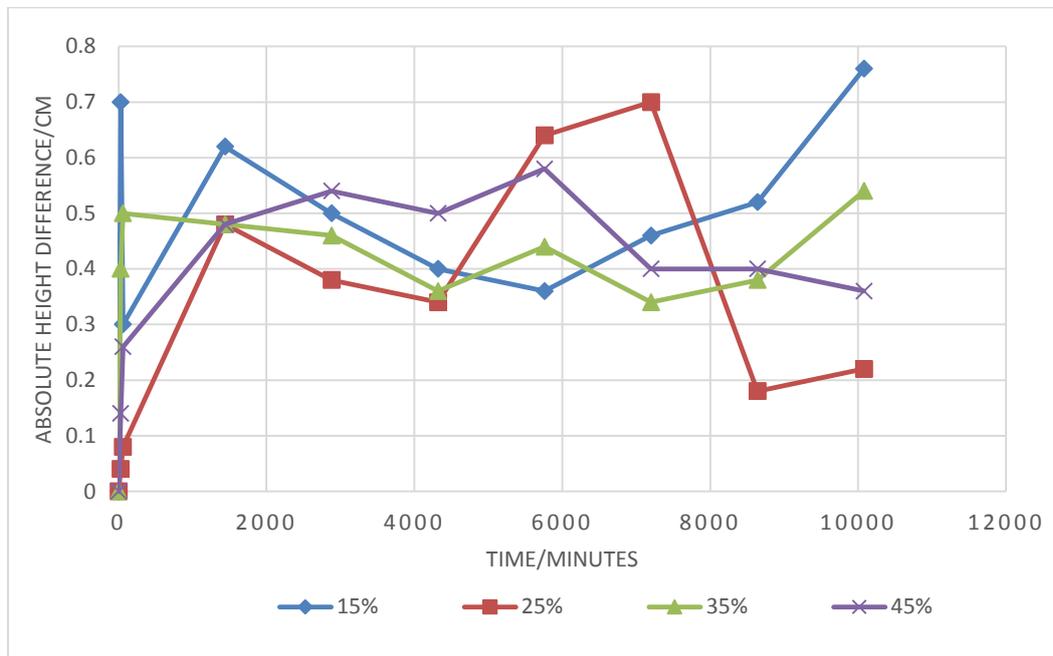


Figure 4.2: Height stability of jatropa husk briquette (raw char)

The height stability of the briquette which was measured in terms of its changes in height when exposed to atmosphere is shown in Figure 4.2 above. From the figure, none of the briquette was stable but the briquette with 25% binder had a least final difference in height (0.22cm) and a water resistance time of 1.02 hours with 15% binder having the highest final difference in height and a water resistance time of 0.56 hours. This implies that the final difference in height of original particle size of (raw char) jatropa husk briquette is directly proportional to its water resistance (weathering resistance) strength (with reference to figure 4.2).

Table 4.2: Physical properties of jatropha husk briquette

Particle size (% binder)	Compressed density ($\rho_c = \frac{m_i}{v_i}$) g/cm ³	Relaxed density ($\rho_r = \frac{m_f}{v_f}$) g/cm ³	Relaxation ratio ($\frac{\rho_c}{\rho_r}$)	Compaction ratio ($(\frac{\rho_c}{\rho_b})$)	Durability %	Water resistance Hours
RC (15)	1.1070 ^B	.2435 ^A	4.5344 ^A	2.6307 ^A	53.528 ^G	.5600 ^D
RC (25)	1.3693 ^A	.2922 ^A	4.7033 ^A	3.2541 ^A	51.260 ^I	1.0198 ^E
RC (35)	1.2911 ^A	.2634 ^A	4.9601 ^A	3.0682 ^A	60.216 ^A	.8718 ^A
RC (45)	1.4558 ^A	.2930 ^A	5.0420 ^A	3.4596 ^A	43.540 ^E	.9368 ^A
≤ 6mm (15)	1.1386 ^B	.6201 ^D	1.8371 ^C	2.7059 ^A	90.638 ^D	9.2590 ^I
≤ 6mm (25)	1.0980 ^B	.6465 ^C	1.6998 ^C	2.6093 ^A	92.270 ^C	10.6988 ^J
≤ 6mm (35)	1.1223 ^B	.4078 ^B	2.8478 ^B	2.6671 ^A	80.950 ^B	1.0568 ^B
≤ 6mm (45)	1.1391 ^B	.4032 ^B	2.8489 ^B	2.7070 ^A	78.026 ^B	1.0716 ^B
≤ 2mm (15)	1.0482 ^B	.5691 ^H	2.1208 ^C	5.0400 ^B	90.440 ^D	.2134 ^C
≤ 2mm (25)	1.1127 ^B	.6715 ^C	1.6571 ^C	2.6444 ^A	92.296 ^C	.1632 ^C
≤ 2mm (35)	1.1526 ^B	.7165 ^E	1.6086 ^C	2.7391 ^A	81.936 ^B	.3599 ^G
≤ 2mm (45)	1.1121 ^B	.5316 ^G	2.0932 ^C	2.6427 ^A	84.182 ^H	.7767 ^H
Significance level	0.00	0.000	0.000	0.001	0.000	0.000

Bulk density
 $\rho_b =$
0.421kg/cm

3

Mean values with the same alphabet in each column are not significantly different ($P < 0.05$) using Fisher' least significance difference (FLSD).

Table 4.3: Physical behaviour (characteristic) of jatropha husk briquette

Particle size	% binder	Mean initial mass g	Mean initial height cm	Initial handling property after production	Mean final mass g	Mean final height cm	Final handling property After drying
Raw char	15	669.62	13.78	Break easily the first two days	139.9	13.38	Moderately strong
Raw char	25	758.72	13.76	Break easily the first 24 hours	162.58	13.78	Strong and easy to handle
Raw char	35	833.52	14.66	Bit stronger after 1 hour	167.12	15.2	Strong and easy to handle
Raw char	45	862.62	14.86	Break easily even after 3 days	173.98	15.22	Moderately strong
≤6mm	15	579.02	12.58	A little difficult to handle	318.94	13.06	Very strong and easy to handle
≤6mm	25	678.5	14.46	Easy to handle	363.26	14.2	Very strong and easy to handle
≤6mm	35	681.34	15	Difficult to handle	244.8	14.56	Very strong and easy to handle
≤6mm	45	745.62	15.76	Very difficult to handle	243.76	15.1	Very strong and easy to handle
≤2mm	15	565.22	13.4	Very easy to handle	334.28	13.48	Very strong and easy to handle
≤2mm	25	582.56	13.32	Very easy to handle	350.12	13.32	Very strong and easy to handle
≤2mm	35	622.96	13.52	Very easy to handle	383.22	13.66	Very strong and easy to handle
≤2mm	45	627.26	14.66	Very easy to handle	302	14.6	Very strong and easy to handle

4.2.2 Effect of the various binder levels on briquette produced from particle size less than or equal to 6mm ($\leq 6\text{mm}$)

Briquette produced from particle size less than or equal to 6mm shows no significant variation in the compressed density likewise for the compaction ratio for the various binder levels, although 45% binder recorded the highest value of 1.14g/cm^3 and 2.707:1 respectively. The 25% binder recorded the highest relaxed density of 0.65g/cm^3 with 15, 35 and 45% binders recording 0.62g/cm^3 , 0.41g/cm^3 and 0.40g/cm^3 respectively. From table 4.3 above, it was observed that the durability of the briquette produced by particle size less than or equal to 6mm is directly proportional to the relaxed density with the higher value of 92.27% and a low value of 78.026% recorded at 25 and 45% binder levels respectively. It was also observed that the relaxed density is inversely proportional to the relaxation ratio, which means that the greater the relaxed density the lower the relaxation ratio of the briquette. Therefore the greater the weight lost and increase in height during drying, the lower the relaxed density which causes higher relaxation ratio that decreases the durability of the briquette. Once again the initial strength (easiness to handle) has a great influence on the durability of the briquette (refer to table 4.3 above). The water resistance of the briquette was observed to be directly proportional to the durability and relaxed density, with 25% binder recording approximately 10.7 hours and 15, 35 and 45% recording 9.3, 1.1 and 1.1 hours respectively.

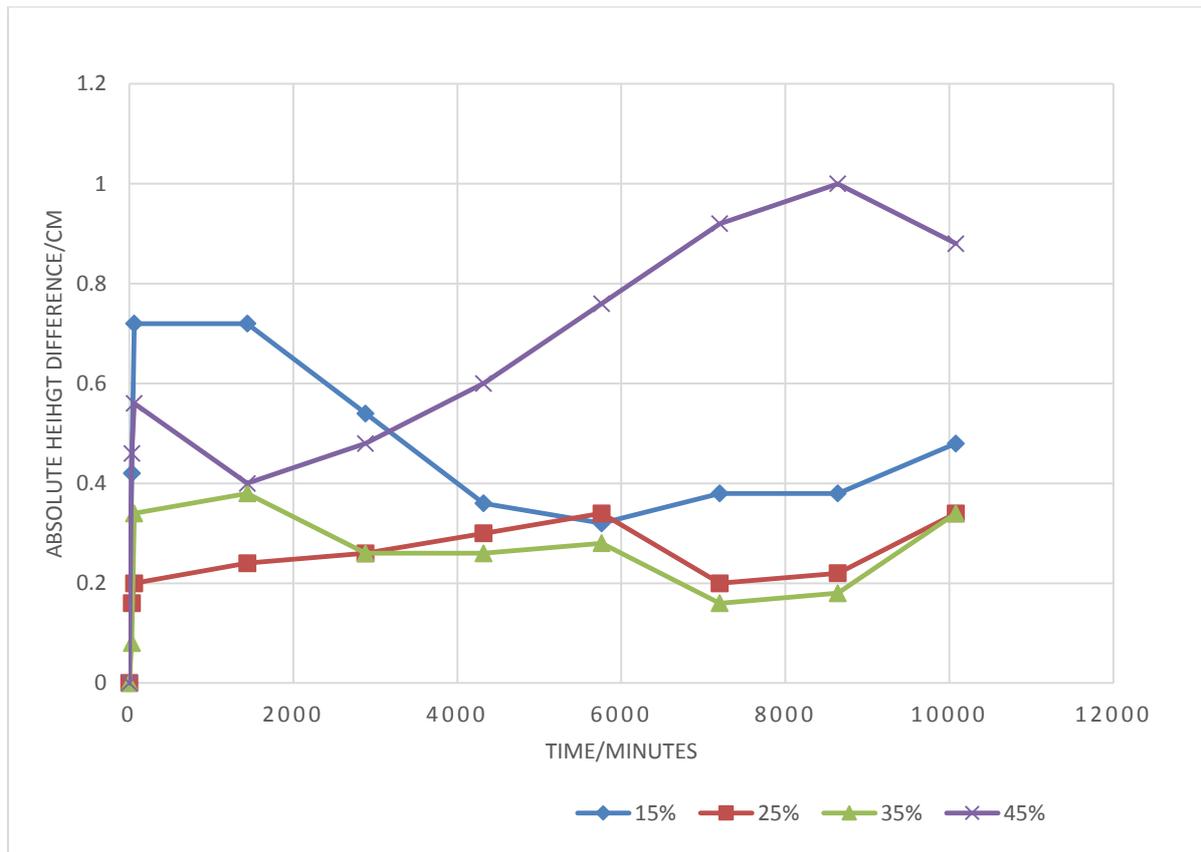


Figure 4.3: Height stability of jatropha husk briquette with particle size less than or equal to 6mm

The height stability of the briquette produced from particle size less than or equal to 6mm which was measured in terms of its changes in height when exposed to atmosphere is shown in Figure 4.3. From the figure, briquette produced with 35% binder appeared to be most stable between the 3rd and 5th day, but 25% binder had the least maximum change in height, hence it can be concluded that the two binder levels were the most stable briquettes when exposed to the atmosphere compared to briquettes at other binder levels.

4.2.3 Effect of the various binder levels on briquette produced from particle size less than or equal to 2mm ($\leq 2\text{mm}$)

The briquette produced by particle size less than or equal to 2mm was observed to have approximately constant characteristic with all four binder level in terms of compressed density, relaxation ratio and compaction ratio. From table 4.2 it was observed that only 15% binder had a higher compaction ratio of 5:1 with the rest recording a value of nearly 3:1. From table 4.3 the initial strength of briquette produced from particle size less than or equal to 2mm is very high and very easy to handle, therefore the final durability of the briquette is only dependent

on the relaxed density which also depend on the strength of the bond or the cohesion between the biomass particles forming the briquette. The strength of the bond was also observed to depend on the height stability, which is shown on the figure 4.4 below.

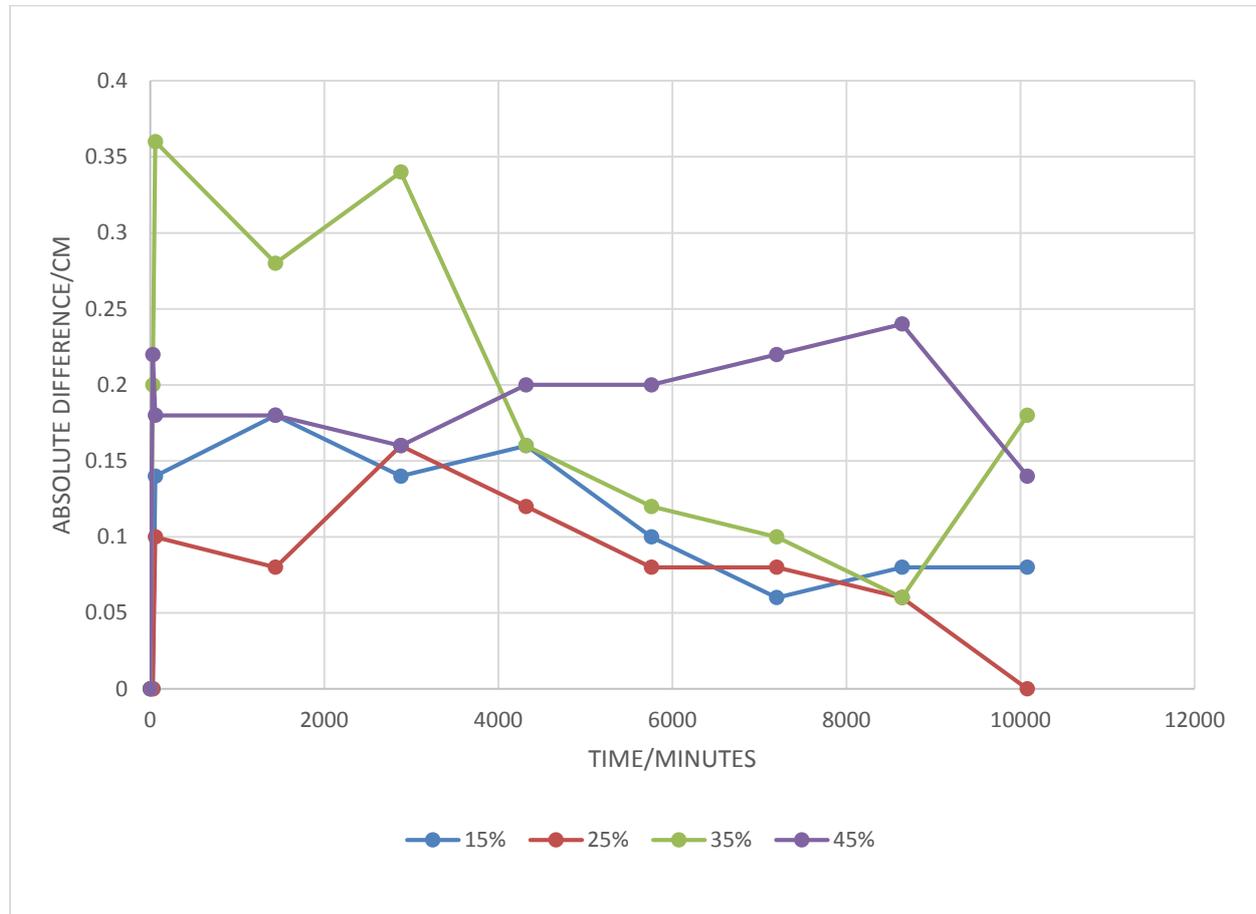


Figure 4.4: Height stability of jatropha husk briquette with particle size less than or equal to 2mm

From the figure above 25% binder recorded zero (0) change in final height and a corresponding 92.3% durability and 35% binder having 0.18 change in height and a durability of 81.94%, with 15% and 45% recording 0.08 and 0.14 change in height and 90.44% and 84.18% respectively. Based on this observation a relationship can be established that the durability of briquette produced from carbonized jatropha husk with particle size less than or equal to 2mm is directly proportional to the height stability of the briquette after drying to an equilibrium weight.

The water resistance capacity of the briquette with particle size less than or equal to 2mm from table 4.2, increases with increasing binder level. Although 15% binder recorded a slightly

higher duration of 0.21 hours than 25% which had duration of 0.16 hours, they showed no significant difference.

4.3 Best particle size of jatropha husk and binder blend

The best blend of biomass-binder ratio was assessed on the basis of the briquette initial strength and final durability of the briquette since these two parameters are a measure of the compressed density of the major indices for assessing the combustion, handling characteristics and ignition behaviour of briquettes as reported by Sotannde in 2010. From table 4.2 above, the compressed densities of briquettes produced from particle size less than or equal to 6mm and particle size less than or equal to 2mm do not have any significant variation the durability of the briquette depends on the relaxed density, which is the final density of the briquette after sun drying to an equilibrium weight. It was also observed that the relaxed density is dependent to some extent on the initial strength of the briquette and the height stability of the briquette.

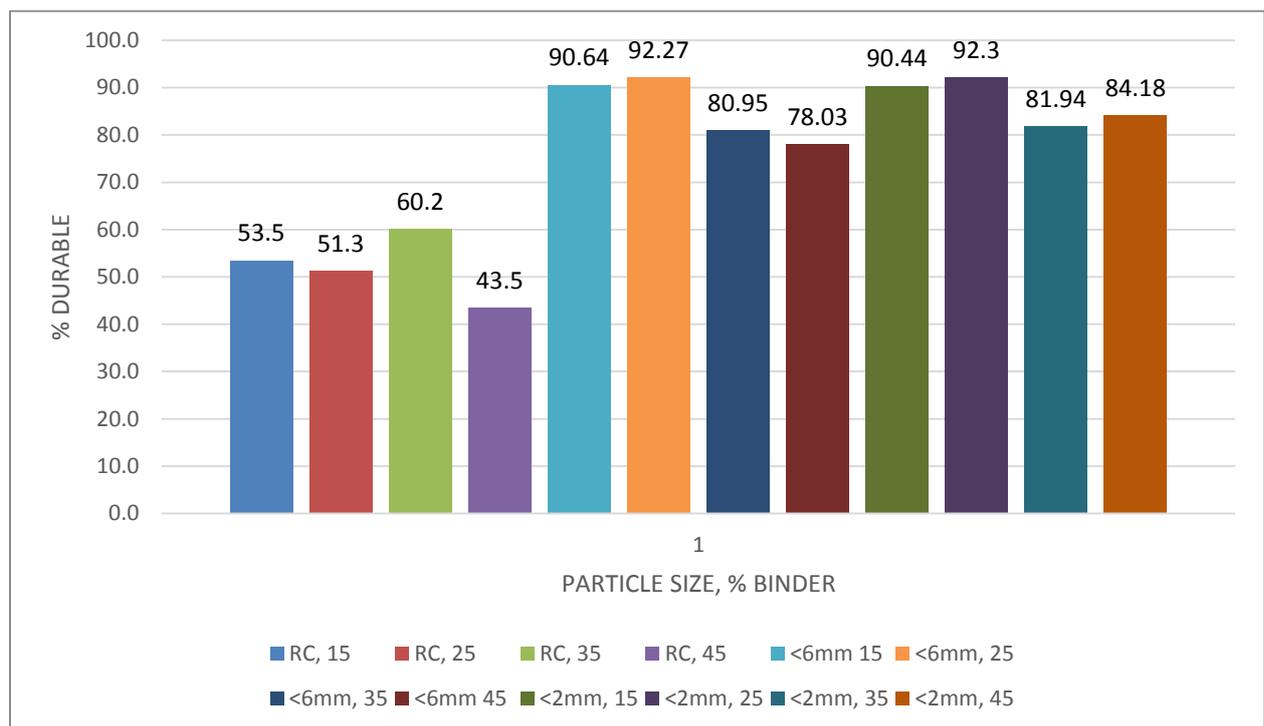


Figure 4.5: Durability of jatropha husk briquette

From figure 4.5 above, it was observed that the durability of particle size less than or equal to 2mm with 25% binder had a higher value of 92.3% and particle size less than or equal to 6mm with 25% binder had the second high value of 92.27%. This two blends produced briquette

which are more durable than what was reported by other researchers using different biomass with starch as binder Sotannde et al. (2010) and Obi (2013) reported 83.26% and 91.43% respectively.

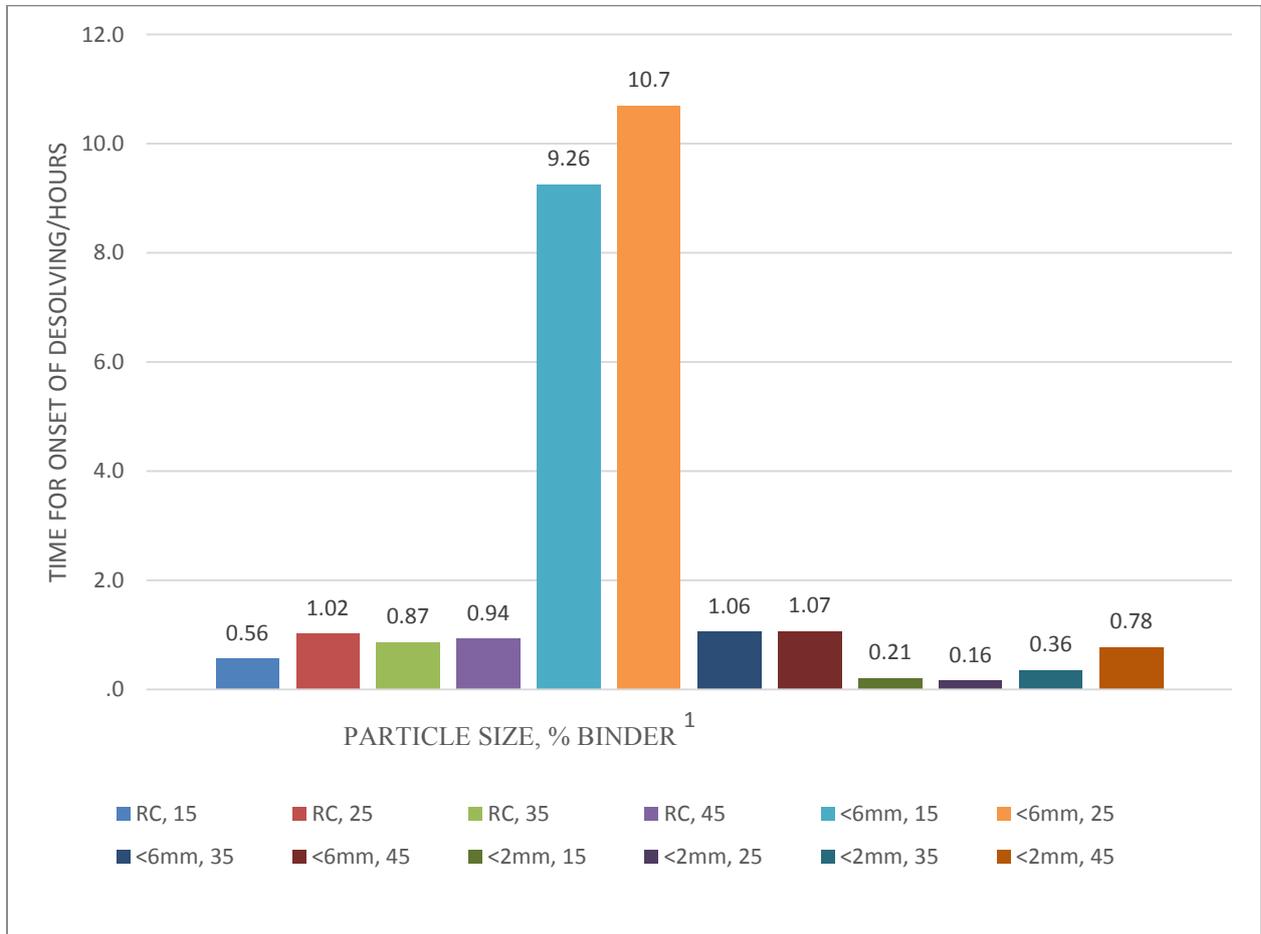


Figure 4.6: Water resistance of jatropha husk briquette

From figure 4.6, comparing the particle size at different binder levels it was observed that particle size less than or equal to 6mm with 15% and 25% binder had the highest water resistance (weathering resistance) with values of 9.26 hours and 10.7 hours respectively. From the water resistance test it was also observed that the finer particle size dissolve easily in water although it had the highest range of durability.

In terms of quality jatropha husk briquette production using the manual briquetting machine it is recommended that particle size less than or equal to 2mm or 6mm with starch as a binder in the ratio of 100:25 is used for durable briquette.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

In this study the following conclusions were arrived at:

1. A manual biomass briquetting machine suitable for the production of biomass briquettes on a small scale with a production capacity of 488kg/hr was designed and constructed and used in the production of biomass briquette using carbonized jatropha husk.
2. The physical properties of the jatropha husk briquette were found to be significantly affected by the particle size and binder level.
3. Briquette with higher durability was produced using the constructed briquetting machine. Though for best jatropha husk briquette quality on the basis of relaxed density, initial handling strength and durability, particle size less than or equal to 2mm and 6mm with a binder blending ratio of 100:25 should be used.

Further studies are recommended in the following areas:

1. Determination of capacity of the machine using different biomass at varying particle size and binder level.
2. Determine the heating value and combustion properties of the briquette produced by the machine.
3. Introduction of electrically controlled pistons to perform the compaction instead of using manually operated hydraulic car jack.

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APPENDIX

1.0 **DENSITY (ρ)** = $\frac{\text{mass}}{\text{volume}}$

Bulk density $\rho_b = \frac{\text{mass of loose biomass}}{\text{volume of container}} = \frac{933}{2217.16} = 0.4208\text{g/cm}^3$

2.0 PHYSICAL PARAMETERS

2.1 Original particle size (15% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	681.3	131.9	7.2	7	13.3	13.6
s2	710.5	153.8	7.3	7.5	13.4	14
s3	695.4	152.3	7.4	7.3	13.8	13
s4	569.7	114.6	7.8	7.5	14.6	13.1
s5	691.2	146.9	7.9	7.7	13.8	13.2

2.2 Original particle size (25% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	751.3	160.4	7	7	13.8	13.5
s2	726.2	159.1	7	7	13.5	13.4
s3	723.7	158.8	7.1	7.2	13.6	13.5
s4	810.5	174.1	7.4	7.2	13.9	14.3
s5	781.9	160.5	7.3	7.5	14	14.2

2.3 Original particle size (35% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	826.9	178.3	7.2	7.5	14.5	15
s2	867.2	180.3	7.8	7.2	15	15.3
s3	857.5	176	7.8	7.3	14.7	15.7
s4	802.4	129.2	7.1	7	14.7	15.2
s5	813.6	171.8	7.6	7.4	14.4	14.8

2.4 Original particle size (45% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	823.1	153.5	7	7.3	13.6	15
s2	845.7	154.2	7.2	7	15.5	15.5
s3	883.6	195	7	7	15	15
s4	890.9	196.2	7	7	15.2	15.4
s5	869.8	171	7.5	7	15	15.2

2.5 Particle size less than or equal to 6mm (15% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	589.6	333.7	7.2	7.1	12.7	13.3
s2	576.6	307	7	7	12.5	12.7
s3	591.5	323.1	7.2	7.1	12.8	13.3
s4	561.3	301.6	7	7	12.4	13
s5	576.1	329.3	7.5	7.2	12.5	13

2.6 Particle size less than or equal to 6mm (25% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	670	371.2	7.3	7.1	14.5	14.4
s2	669.4	364.2	7.4	7	14.2	14
s3	671.8	357.2	7.2	7.1	14.2	14.3
s4	689.2	358.5	7.6	7.2	14.6	14.2
s5	692.1	365.2	7.4	7.1	14.8	14.1

2.7 Particle size less than or equal to 6mm (35% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	674.4	267.5	7.1	7.1	14.5	14.6
s2	680	284.2	7	7	15.5	15.3
s3	670	257.8	7.5	7.5	14.5	14.6
s4	691.8	246.3	7.3	7.3	15.5	14
s5	690.5	168.2	7.4	7.4	15	14.3

2.8 Particle size less than or equal to 6mm (45% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	720	222	7.1	7	15.9	15.8
s2	718.1	282.7	7.5	7.2	15.5	15
s3	749.3	243.5	7.5	7.2	15.8	15
s4	787.9	234.2	7.1	7.2	15.8	14.5
s5	752.8	236.4	7.2	7.1	15.8	15.2

2.9 Particle size less than or equal to 2mm (15% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	546.5	321.7	7	7.1	13	13.1
s2	555.1	325.3	7.2	7	13	13.1
s3	580.5	349.2	7.2	7	13.5	13.5
s4	564	330.4	7.2	7	13.5	13.7
s5	580	344.8	7.2	7	14	14

2.10 Particle size less than or equal to 2mm (25% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	568	337.5	7	7.1	13	13
s2	569.6	339.2	7	7	13.2	13.2
s3	588.7	356.8	7	7.1	13.3	13.3
s4	589.5	355.1	7.4	7.1	13.6	13.6
s5	597	362	7	7	13.5	13.5

2.11 Particle size less than or equal to 2mm (35% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	615.8	373.6	7.4	7	13.5	13.5
s2	603	362.5	7.2	7.1	13.3	13.2
s3	641.7	399.9	7.1	7.1	13.8	14
s4	626.5	388.4	7	7	13.5	13.8
s5	627.8	391.7	7	7.1	13.5	13.8

2.12 Particle size less than or equal to 2mm (45% binder level)

Sample No.	Mass/(g)		Diameter/(cm)		Height /(cm)	
	Initial (Mi)	Final (Mf)	Initial (di)	Final (df)	Initial (hi)	Final (hf)
s1	630.9	297.2	7	7.1	15	14.7
s2	622	297.4	7	7	14.5	14.6
s3	633.3	302.6	7	7.1	15	14.8
s4	606.6	293.6	7	7	14	14
s5	643.5	319.2	7	7	14.8	14.9

3.0 PHYSICAL PROPERTIES

3.1 Original particle size (15% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.2581	0.252	4.9925	2.9898
s2	1.2668	0.2487	5.0937	3.0105
s3	1.1717	0.2799	4.1861	2.7845
s4	0.8166	0.198	4.1242	1.9406
s5	1.0218	0.239	4.2753	2.4282
Mean	1.107	0.24352	4.53436	2.63072

3.2 Original particle size (25% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.4146	0.3087	4.5824	3.3617
s2	1.3978	0.3085	4.531	3.3218
s3	1.344	0.2889	4.6521	3.1939
s4	1.3558	0.299	4.5344	3.222
s5	1.3344	0.2558	5.2166	3.1711
Mean	1.36932	0.29218	4.7033	3.2541

3.3 Original particle size (35% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.4007	0.2691	5.2051	3.3287
s2	1.2099	0.2894	4.1807	2.8752
s3	1.2208	0.2678	4.5586	2.9011
s4	1.3787	0.2209	6.2412	3.2764
s5	1.2455	0.2699	4.6147	2.9598
mean	1.29112	0.26342	4.96006	3.06824

3.4 Original particle size (45% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.5726	0.2456	6.4031	3.7372
s2	1.3401	0.2585	5.1841	3.1846
s3	1.5307	0.3378	4.5314	3.6376
s4	1.523	0.331	4.6012	3.6193
s5	1.3125	0.2923	4.4902	3.1191
Mean	1.45578	0.29304	5.042	3.45956

3.5 Particle size less than or equal to 6mm (15% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.1402	0.6337	1.7993	2.7096
s2	1.1986	0.6281	1.9083	2.8484
s3	1.135	0.6136	1.8497	2.6972
s4	1.1762	0.6028	1.9512	2.7952
s5	1.0432	0.6221	1.6769	2.4791
Mean	1.13864	0.62006	1.83708	2.7059

3.6 Particle size less than or equal to 6mm (25% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.104	0.6511	1.6956	2.6236
s2	1.0961	0.676	1.6214	2.6048
s3	1.162	0.6309	1.8418	2.7614
s4	1.0406	0.6201	1.6781	2.4729
s5	1.0873	0.6542	1.662	2.5839
Mean	1.098	0.64646	1.69978	2.60932

3.7 Particle size less than or equal to 6mm (35% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.1747	0.4628	2.5382	2.7916
s2	1.14	0.4827	2.3617	2.7091
s3	1.0459	0.3997	2.6167	2.4855
s4	1.1806	0.4203	2.8089	2.8056
s5	1.0703	0.2735	3.9133	2.5435
Mean	1.1223	0.4078	2.84776	2.66706

3.8 Particle size less than or equal to 6mm (45% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.1437	0.3651	3.1326	2.7179
s2	1.0487	0.4629	2.2655	2.4922
s3	1.0735	0.3987	2.6925	2.5511
s4	1.2595	0.3967	3.1749	2.9931
s5	1.1702	0.3928	2.9791	2.7809
Mean	1.13912	0.40324	2.84892	2.70704

3.9 Particle size less than or equal to 2mm (15% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.0923	0.2613	4.1803	9.9342
s2	1.0488	0.6452	1.6255	3.8629
s3	1.0561	0.6721	1.5713	3.7341
s4	1.0261	0.6267	1.6373	3.891
s5	1.0175	0.64	1.5898	3.778
Mean	1.04816	0.56906	2.12084	5.04004

3.10 Particle size less than or equal to 2mm (25% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.1353	0.6557	1.7314	2.698
s2	1.1213	0.6677	1.6793	2.6647
s3	1.1502	0.6776	1.6975	2.7334
s4	1.0078	0.6595	1.5281	2.395
s5	1.1491	0.6968	1.6491	2.7308
Mean	1.11274	0.67146	1.65708	2.64438

3.11 Particle size less than or equal to 2mm (35% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.0606	0.7191	1.4749	2.5204
s2	1.1136	0.6936	1.6055	2.6464
s3	1.1745	0.7215	1.6279	2.7911
s4	1.2059	0.7313	1.649	2.8657
s5	1.2084	0.7169	1.6856	2.8717
Mean	1.1526	0.71648	1.60858	2.73906

3.12 Particle size less than or equal to 2mm (45% binder level)

Sample No.	Density, (m/v)/ (g/cm)		relaxation ratio	compaction ratio
	Compressed ($\rho_c = M_i/V_i$)	Relaxed ($\rho_r = M_f/V_f$)	ρ_c/ρ_r	ρ_c/ρ_b
s1	1.0929	0.5107	2.14	2.5972
s2	1.1146	0.5293	2.1058	2.6488
s3	1.0971	0.5164	2.1245	2.6072
s4	1.1259	0.5449	2.0663	2.6756
s5	1.1298	0.5567	2.0295	2.6849
Mean	1.11206	0.5316	2.09322	2.64274

4.0 STRENGTH PROPERTIES

$$\text{Shatter index} = \text{durability} = \frac{\text{total mass} - \text{mass shattered}}{\text{total mass}} \times 100$$

4.1 Original particle size (15% binder level)

Replicate	Shatter index				Water resistance
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	hours
S1	131.9	61.5	46.63	53.37	0.533
S2	153.8	62.2	40.44	59.56	0.5
S3	152.3	60.4	39.66	60.34	0.534
S4	114.6	67.3	58.73	41.27	0.7
S5	146.9	68.9	46.90	53.1	0.533

4.2 Original particle size (25% binder level)

Replicate	Shatter index				Water resistance
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	hours
S1	160.4	82.9	51.68	48.32	0.966
S2	159.1	76.7	48.21	51.79	1.167
S3	158.8	78.5	49.43	50.57	0.833
S4	174.1	83.4	47.90	52.1	0.966
S5	160.5	74.6	46.48	53.52	1.167

4.3 Original particle size (35% binder level)

Replicate	Shatter index				Water resistance
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	hours
S1	178.3	67.0	37.58	62.42	0.783
S2	180.3	66.0	36.61	63.39	1.05
S3	176	69.1	39.26	60.74	0.683
S4	129.2	60.2	46.59	53.41	0.783
S5	171.8	66.8	38.88	61.12	1.06

4.4 Original particle size (45% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	153.5	80.9	52.70	47.3	0.917
S2	154.2	89.3	44.94	55.06	0.833
S3	195.0	130.6	66.97	33.03	1.05
S4	196.2	135.1	68.86	31.14	0.917
S5	171.0	83.5	48.83	51.17	0.967

4.5 Particle size less than or equal to 6mm (15% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	333.7	20.5	13.93	87	9.25
S2	307	21.8	7.10	92.9	9.245
S3	323.1	25.1	7.77	92.23	9.25
S4	301.6	30.2	10.01	89.99	9.5
S5	329.3	29.4	8.93	91.07	9.05

4.6 Particle size less than or equal to 6mm (25% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	371.2	36.3	9.78	90.22	10.75
S2	364.2	16.5	4.53	95.47	10.743
S3	357.2	31.5	8.82	91.18	10.751
S4	358.5	15.6	4.35	95.65	10.75
S5	365.2	40.8	11.17	88.83	10.5

4.7 Particle size less than or equal to 6mm (35% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	267.5	28.9	10.80	89.2	0.867
S2	284.2	60.00	21.11	78.89	1
S3	257.8	62.1	24.09	75.91	1.5
S4	246.3	30.2	12.26	87.74	0.867
S5	168.2	45.4	26.99	73.01	1.05

4.8 Particle size less than or equal to 6mm (45% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	222	45.6	20.54	79.46	0.933
S2	282.7	54.5	19.28	80.72	0.917
S3	243.6	59.7	24.51	75.49	1.1
S4	234.2	56.9	24.3	75.7	1.475
S5	236.4	50.2	21.24	78.76	0.933

4.9 Particle size less than or equal to 2mm (15% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	321.7	42.3	13.15	86.85	0.1
S2	325.3	25.6	7.87	92.13	0.5
S3	349.2	31.8	9.11	90.89	0.167
S4	330.4	36.9	11.17	88.83	0.2
S5	344.8	22.4	6.50	93.5	0.1

4.10 Particle size less than or equal to 2mm (25% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	337.5	36.2	10.73	89.27	0.133
S2	339.2	18.8	5.54	94.46	0.1833
S3	356.8	16.9	4.74	95.26	0.1167
S4	355.1	40.2	11.32	88.68	0.133
S5	362.0	22.4	6.19	93.81	0.25

4.11 Particle size less than or equal to 2mm (35% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	373.6	48.3	12.93	87.07	0.35
S2	362.5	94.5	26.07	73.93	0.4833
S3	399.9	96.6	24.16	75.84	0.2833
S4	388.4	30.2	7.78	92.22	0.35
S5	391.7	75.9	19.38	80.62	0.333

4.12 Particle size less than or equal to 2mm (45% binder level)

Replicate	Shatter index				Water resistance hours
	Mass (g)	Mass shattered (g)	% shattered	Durability (%)	
S1	297.2	39.6	13.32	86.68	0.5667
S2	297.4	60.5	20.34	79.66	0.7
S3	302.6	66.9	22.11	77.89	0.8333
S4	293.6	30.2	10.29	89.71	1.3333
S5	319.2	41.6	13.03	86.97	0.45

5.0 HIEGHT STABILITY OF THE BRIQUETTE

5.1.1 ORIGINAL PARTICLE SIZE

Biomass-binder blend of 100:15

	height/cm									
No./Time	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13.3	13.6	13.8	13.5	13.6	13.5	13.5	14.2	13.5	13.6
s2	13.4	13.5	13.6	13	13.2	13.3	13.5	13.2	13	14
s3	13.8	14	14.1	13	13.3	13.3	13.3	13.8	13.6	13
s4	14.6	14.2	14.2	13.2	13.4	13.5	13.7	14.1	13	13.1
s5	13.8	13.7	13.9	13.5	13.5	13.7	13.7	14.5	14	13.2
mean difference	0	0.7	0.3	0.62	0.5	0.4	0.36	0.46	0.52	0.76

5.1.2 Biomass-binder blend of 100:25

	height/cm									
No/Time	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13.8	13.6	13.8	13.6	13.9	14	14.6	13.1	14	13.5
s2	13.5	13.5	13.5	13	13.5	14.2	14.7	13.2	13.8	13.4
s3	13.6	13.6	13.6	12.5	12.6	13	13.4	12.6	13.5	13.5
s4	13.9	13.9	13.6	14	14.2	13.8	13.5	13.2	13.8	14.3
s5	14	14	14.1	14.5	14.5	13.9	13.4	13.2	13.8	14.2
mean difference	0	0.04	0.08	0.48	0.38	0.34	0.64	0.7	0.18	0.22

5.1.3 Biomass-binder blend of 100:35

No/Time	height/cm									
	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
1	14.5	15.5	15.6	15.4	15.3	14.9	14.6	14.9	15	15
2	15	15	15.1	14.5	14.7	15	15.5	15	15.2	15.3
3	14.7	15.4	15.6	15.5	15.2	15.1	15	14.7	15	15.7
4	14.7	15	15.1	14.8	14.2	13.9	13.5	13.5	14	15.2
5	14.4	14.4	14.4	14.5	14.6	14.6	14.5	14.5	14.6	14.8
mean difference	0	0.4	0.5	0.48	0.46	0.36	0.44	0.34	0.38	0.54

5.1.4 Biomass-binder blend of 100:45

No/Time	height/cm									
	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13.6	13.7	13.8	14	14.3	14.8	15	14	15	15
s2	15.5	15.6	15.8	14.9	15.1	15.5	15.9	14.5	15.2	15.5
s3	15	15.1	15.3	14.5	14.4	14.7	14.8	14.8	14.8	15
s4	15.2	15.5	15.6	14.8	14.5	14.5	14.5	14.9	15.3	15.4
s5	15	15.1	15.1	14.5	14.6	14.7	14.8	15.1	15	15.2
mean difference	0	0.14	0.26	0.48	0.54	0.5	0.58	0.4	0.4	0.36

5.2 PARTICLE SIZE LESS THAN OR EQUAL TO 6MM (<6MM)

5.2.1 Biomass-binder blend of 100:15

No./Time	height/cm									
	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	12.7	13.2	13.3	13.3	13.1	13.1	13.1	13.2	13.2	13.3
s2	12.5	12.8	13.1	13	13.1	12.7	12.5	12.6	12.6	12.7
s3	12.8	13	13.4	13.3	13.2	13	13	13.4	12.7	13.3
s4	12.4	13.1	13.2	13.4	13	12.8	12.8	12.9	13.1	13
s5	12.5	12.9	13.5	13.5	13.2	13.1	13.1	12.7	13	13
mean difference	0	0.42	0.72	0.72	0.54	0.36	0.32	0.38	0.38	0.48

5.2.2 Biomass-binder blend of 100:25

No/Time	height/cm									
	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	14.5	14.7	14.7	14.3	14.3	14.4	14.5	14	14.5	14.4
s2	14.2	14.3	14.3	14	14	13.9	13.9	14.2	14.1	14
s3	14.2	14.4	14.4	14.1	14.2	14.3	14.5	14.3	14.2	14.3
s4	14.6	14.8	15	14.1	14	13.9	13.9	14.5	14.3	14.2
s5	14.8	14.9	14.9	14.6	14.5	14.5	14.4	14.5	14.1	14.1
mean difference	0	0.16	0.2	0.24	0.26	0.3	0.34	0.2	0.22	0.34

5.2.3 Biomass-binder blend of 100:35

	height/cm									
No./Time	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	14.5	14.7	14.8	14.9	14.7	14.6	14.5	14.5	14.5	14.6
s2	15.5	15.5	15	15.1	15.2	15.1	15.1	15.5	15.5	15.3
s3	14.5	14.7	14.8	14.7	14.7	14.8	14.8	14.5	14.6	14.6
s4	15.5	15.5	15.2	15.1	15.1	15	15	15.2	15.3	14.9
s5	15	15	15.3	15.1	15.2	15	14.8	14.5	14.4	14.3
mean difference	0	0.08	0.34	0.38	0.26	0.26	0.28	0.16	0.18	0.34

5.2.4 Biomass-binder blend of 100:45

	height/cm									
No./Time	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	17	16.2	16.1	16.1	16.1	16	16	15.7	15.8	15.8
s2	15.5	16	16.4	15.6	15.3	15.2	14.9	15	14.9	15
s3	15.8	15.5	15.5	16	16	16.1	16.1	15	14.9	15
s4	15.8	16.2	16.2	15.8	15.5	15.2	15	15	14.8	14.5
s5	15.8	15.5	15.5	15	15	14.9	14.7	14.6	14.5	15.2
mean difference	0	0.46	0.56	0.4	0.48	0.6	0.76	0.92	1	0.88

5.3 PARTICLE SIZE LESS THAN OR EQUAL TO 2MM (<2MM)

5.3.1 Biomass-binder blend of 100:15

	height/cm									
No	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13	13	13.2	13	13.2	13.1	13.1	13	13.1	13.1
s2	13	13	13	13.2	13.3	13.1	13.1	13	13	13.1
s3	13.5	13.5	13.5	13.2	13.5	13.4	13.3	13.3	13.4	13.5
s4	13.5	13.5	14	13.4	13.5	13.4	13.5	13.6	13.7	13.7
s5	14	14	14	13.7	13.8	13.6	13.9	14	14	14
mean difference	0	0	0.14	0.18	0.14	0.16	0.1	0.06	0.08	0.08

5.3.2 Biomass-binder blend of 100:25

	height/cm									
No	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13	13	13	13	13	13	13	13	13	13
s2	13.2	13.2	13.5	13.1	13	13	13	13	13.1	13.2
s3	13.3	13.3	13.4	13.2	13.2	13.1	13.2	13.2	13.3	13.3
s4	13.6	13.6	13.5	13.5	13.2	13.5	13.5	13.5	13.5	13.6
s5	13.5	13.5	13.5	13.6	13.6	13.4	13.5	13.5	13.6	13.5
mean difference	0	0	0.1	0.08	0.16	0.12	0.08	0.08	0.06	0

5.3.3 Biomass-binder blend of 100:35

	height/cm									
No.	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	13.5	13.5	13.7	13.2	13.1	13.2	13.4	13.5	13.5	13.5
s2	13.3	13.5	13.6	13.6	13.6	13.3	13.3	13.3	13.2	13.2
s3	13.8	14	14.3	14	14	14	14	14	13.8	14
s4	13.5	13.8	14	14	14	13.8	13.8	13.7	13.7	13.8
s5	13.5	13.8	13.8	13.6	13.8	13.5	13.5	13.4	13.5	13.8
mean difference	0	0.2	0.36	0.28	0.34	0.16	0.12	0.1	0.06	0.18

5.3.4 Biomass-binder blend of 100:45

	height/cm									
No.	0min	30min	60min	1440min	2880min	4320min	5760min	7200min	8640min	10080min
s1	15	14.7	14.8	14.8	14.6	14.7	14.6	14.6	14.5	14.7
s2	14.5	14.6	14.5	14.5	14.6	14.6	14.5	14.6	14.5	14.6
s3	15	14.7	14.7	14.7	14.7	14.5	14.5	14.5	14.5	14.8
s4	14	14.2	14.2	14.1	14	14	14	14	14.1	14
s5	14.8	15	15	15	14.8	14.9	14.9	14.9	14.9	14.9
mean difference	0	0.22	0.18	0.18	0.16	0.2	0.2	0.22	0.24	0.14