BRIQUETTING OF BIOMASS RESIDUES AND THEIR CHARACTERIZATION

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

CHEMICAL ENGINEERING

(With Specialization in Industrial Pollution Abatement)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this dissertation work titled "**Briquetting of Biomass Residues and Their Characterization**", in partial fulfillment of the requirements for the award of the degree of Master of technology in Chemical Engineering with specialization in "Industrial Pollution Abatement", and submitted to the Department of Chemical Engineering, Indian Institute of Technology, Roorkee, is an authentic record of the work carried out by me during the period June 2007 to June 2008, under the guidance of **Dr. B. Prasad,** Assistant Professor, Department of Chemical Engg., IITR, Roorkee. The matter embodied in this work has not been submitted for the award of any other degree.

Date: 26th June 08

Place: IIT, Roorkee

(Varun Panwar)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Biomass densification refers to the process whereby biomass in the form of small particles, like straw, sawdust or chips, is concentrated by machines into small pellets or briquettes.

Depending on the particular machine used, this process increases the bulk density of the biomass by about 10 to 12 times of its original bulk density. The moisture content of the compacted biomass generally should be between 7% and 14%. If it is higher, the biomass will not compact easily, if lower it will not bind together as well.

Densification is an important strategy for the biomass market because it improves the convenience and accessibility of biomass: densification reduces the bulkiness of biomass products and therefore increases their transportability (an important selling point for biomass use, as the farms and forests biomass is harvested from are often far away from its consumers). Currently, the challenge the biomass industry faces is developing a cost effective way to produce biomass fuel pellets.

Densification of loose biomass (viz., agricultural and agro-industrial wastes) is called biomass briquetting. It facilitates easy transportation, better handling and storage besides being efficient in use as an alternative fuel to coal and firewood. The high temperature developed during the high-pressure densification process assists the inherent lignin present in the biomass to bind the biomass and form a densified fuel called briquettes

In India, briquettes are mostly manufactured from groundnut shell, saw dust, coffee husk, bagasse, mustard stalk, cotton stalk and press mud.

Briquettes find applications in process industries of any scale using either coal or firewood and in commercial and domestic sectors. In addition, briquettes are widely used in brick kilns in the northern region. Recently, briquettes have also been successfully tried in steel rolling mills and for gasification for power generation.

Experimental Programme

Biomass Collection and Preparation

The biomass materials were obtained from nearby Roorkee Town. Initial moisture was quiet high (about 25-37%), so biomass residues were dried by normal floor drying. Four types of woody materials –mango leaves, eucalyptus leaves, wheat straw, and mango sawdust were studied. The materials were obtained from sawmills and farms, and were tested while they were fresh, i.e., stored for less than three months. The sawdust was sieved to remove particles larger than 1.2mm before use. Different moisture contents for the compaction tests were achieved by air drying - spreading the materials on the floor in the laboratory under room temperature and natural venting. It is found that in three days (with normal humidity conditions) moisture come down to 8 to 9%.

Physico-Chemical and Thermo-Chemical Properties of Biomass Residues

Biomass fuels are characterized by what is called the "Proximate and Ultimate analyses". The "proximate" analysis gives moisture content, volatile content (when heated to 950 °C), and the free carbon remaining at that point, the ash (mineral) in the sample. The "ultimate" analysis" gives the composition of the biomass in wt% of carbon, hydrogen and oxygen (the major components) as well as sulfur and nitrogen (if any). The physicochemical properties are volatile matter, ash content, fixed carbon and chemical composition of biomass. Higher and lower heating values are thermo chemical properties which are determined. The high heating value (HHV) based on the complete combustion of the sample to carbon dioxide and liquid water. The low heating value, LHV, gives the heat released when the hydrogen is burned to gaseous water, corresponding to most heating applications and can be calculated from the HHV and H_2 fraction.

Experimental Setup

Experimental setup comprises of a piston, a cylinder, a clamper stand and a small cylindrical part required extruding briquettes from main cylinder. All the parts are made of mild steel whose tensile strength is 500 MPa which is well beyond the maximum pressure employed to the system while briquetting that is 100 MPa. A hydraulic press was required to carry out briquetting operations in above stated parts. An automatic Compression Testing Machine of 500 tons maximum capacity (available at Civil Engg. Department IITR) was used for briquetting.

Pressure Variation

This test is conducted to study the effect of pressure on the densities of logs formed. Five pressures taken in this study are 30, 50, 70, 90, 100 MPa on mango and eucalyptus leaves.

Pressure Application Rate Variation

In this test pressure application rates were varied and their effect on densities was studied. The compression testing machine had only three speeds namely low, medium and high. Corresponding rates were calculated as 0.2 -0.3 MPa/sec, 1.1-1.5 MPa/sec and 2-3 MPa/sec.

Holding Time Variation

Various holding times were employed to exploit the effect on densities of briquettes. Holding times employed were 0, 10, 20, 40 and 60 sec.

Size Variation

Material used in this test was sawdust which is sieved to four different sizes with standard sieves.

Moisture Variation

Normal floor drying was imposed on residues to get the desired moisture content for briquetting.

Density Calculations

Density was determined using every kind of briquette covered in paraffin oil (Density and weight known) and submerged in water (Density known) to determine the volume, after weighing them.

Impact Resistance Test

The impact resistance was tested by adapting the ASTM method D440-86 of drop shatter for coal.

Results and Discussions

Physico-Chemical and Thermo-Chemical Properties of Biomass Residues

Properties of the four biomass were determined to asses their suitability for the experiment. Their initial low bulk densities (<200kg/m^3) and high heating values (about more than half of those of coal found in India) make them desirable for briquetting.

Effect of Pressure Variation

Eucalyptus leaves produce better briquettes than mango leaves for all compaction pressures employed.

Effect of Holding Time

A short holding time increased the density of the logs slightly. A 10-s holding time could result in a 14% increase in log density. When the holding time was longer than 20 s, the effect diminished significantly.

Effect of Pressure Application Rate

Compaction speed or pressure application rate is an important parameter for compaction machine design. Higher production rates of the machine require faster compaction speeds. It is found that 2MPA/ sec pressure rate is optimal value for both quality and faster production of briquettes.

Effect of moisture content

Logs made at around 8% moisture content had both high-density and good long-term performance. Considering both the density and the long-term performance of the logs, moisture content of 5-12% is the appropriate range for producing good-quality logs of all the tested materials.

Effect of Particle Size

The effect of particle size over densities of produced briquettes can be seen from fig. Experiment was done on sawdust having 9.63% moisture at pressure of 70MPa and 10 sec holding time. It is seen that smaller particle size sample produces higher density log. Sawdust with 150-250 μm size produces highest densities as well as they are good at handling external forces. As the size increases the density of logs decreases.

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INTRODUCTION

1.1 Biomass Densification

Biomass densification refers to the process whereby biomass in the form of small particles, like straw, sawdust or chips, is concentrated by machines into small pellets or briquettes.

While biomass is a great renewable energy source, it is not a good fuel, because it typically contains more than 70% air and void space. This low volumetric energy density makes it difficult to collect, ship, store and use (Grover and Mishra, 1996).

Densification is a relatively new process in which the air is squeezed out at very high pressure to make pellets (using feed type machines), cubes (using alfalfa cuber) or logs (PrestoLog etc.). Best of all, for many applications almost any biomass can be used provided it is chopped fine: sawdust; agricultural residues and even municipal solid waste (Grover and Mishra, 1996).

Depending on the particular machine used, this process increases the bulk density of the biomass by about 10 to 12 times of its original bulk density. The moisture content of the compacted biomass generally should be between 7% and 14%. If it is higher, the biomass will not compact easily, if lower it will not bind together as well.

Densification is an important strategy for the biomass market because it improves the convenience and accessibility of biomass: densification reduces the bulkiness of biomass products and therefore increases their transportability (an important selling point for biomass use, as the farms and forests biomass is harvested from are often far away from its consumers). Currently, the challenge the biomass industry faces is developing a cost effective way to produce biomass fuel pellets.

Densification of loose biomass (viz., agricultural and agro-industrial wastes) is called biomass briquetting. It facilitates easy transportation, better handling and storage besides being efficient in use as an alternative fuel to coal and firewood. The high temperature developed during the high-pressure densification process assists the inherent lignin present in the biomass to bind the biomass and form a densified fuel called briquettes.

In India, briquettes are mostly manufactured from groundnut shell, saw dust, coffee husk, bagasse, mustard stalk, cotton stalk and press mud. While the southern region of India produces briquettes mostly from groundnut shell and saw dust, western and northern regions produce bagasse, groundnut shell, cotton stalk, mustard stalk and press mud briquettes. As a recent addition, municipal solid waste is also densified for use as a fuel in process industries (tea, tobacco, textile, chemical, paper, starch, tyre retreading, tiles, etc) for thermal applications (Grover and Mishra, 1996).

Briquettes find applications in process industries of any scale using either coal or firewood and in commercial and domestic sectors. In addition, briquettes are widely used in brick kilns in the northern region. Recently, briquettes have also been successfully tried in steel rolling mills and for gasification for power generation.

The two most common and prevalent briquetting technologies are

(1) Screw extruder and (2) die and punch.

Screw extruder technology produces briquettes in a continuous fashion using a pre-designed extruder and a barrel. The briquettes have a carbonized outer surface with a hole at the centre, facilitating easy travel of air around the briquettes, ensuring better combustion. Die and punch technology produce briquettes consisting of punches of briquettes locked together as a perfect cylindrical log without a central hole. The briquettes are brownish in colour without carbonized surface. While the screw extruder technology was successful in briquetting rice husk and saw dust in Europe, Japan, Malaysia, Taiwan and Thailand, it miserably failed in India and Nepal due to various reasons. The main reason attributed to this failure was the easy wear on the screw extruder (in one case it did not even last for an hour), besides high specific power consumption. Efforts by experts from Japan on working with different hard faced alloys and coating on the screw extruder did very little to improve its life (Grover and Mishra, 1996).

Further, the variety of biomass in India posed a major threat to the 'briquettability' (compatibility) of the screw extruder as different biomass called for different screw extruders and barrel designs. Moreover, briquetting of pyrolysed biomass (char) posed a severe threat to the wear and tear of the screw extruder. Considerable R&D efforts by the Indian Institute of Technology, New Delhi – sponsored by the University of Twente, The Netherlands – reported improvement on the life of the screw and reduction in specific power consumption, but unfortunately remained on a lab scale. These results are yet to be proved commercially, as there is literally no market for screw extruders in India.

However, India gained good operating experience in the die and punch briquetting machines as there are more than 150 plants installed in India with a success percentage of about 40–50. The major reasons for the failure of such plants during the 1980s and early 1990s were due to poor machine design, poor quality of machines, poor service backup, poor availability of spare parts and little awareness among the fuelwood/coal users (about the benefits of briquettes). Added to these woes were the outright discouraging signals from the bankers for lending working capital for stocking biomass. For the plant suppliers, IREDA (Indian Renewable Energy Development Agency) in India was a gold mine as they funded briquetting projects when no other financial institutions or banks were into it. As a result more plants were implemented in India financed by IREDA.

Most of these plants did not succeed due to technical, managerial and financial problems as identified by the Bharathidasan School of Energy, Tiruchirappalli, Tamil Nadu, which are given below -

Technical reasons:

Poor design, poor quality of machines, poor performance and poor service;

Managerial reasons:

First generation entrepreneurs, poor raw material sourcing, poor marketing strategy and poor operational management;

Financial reasons:

Local commercial banks simply refuse to extend working capital for biomass (which is a new and risky concept - asset for them)

IREDA, subsequently setup a technical back-up cell at the Bharathidasan School of Energy, which provided operational solutions for the plants suffering from technical problems. But little resulted to improve the financial situation since it mainly depends on the security (collateral) that the briquetter possesses and the rapport he enjoys with the local commercial banks. Nevertheless, the briquetting plants implemented in India since the mid '90s, most of them being self-financing briquettors are doing excellent business, especially in the western and southern regions. A raw estimate says that around 50,000 tones of briquettes are consumed annually by the tea industry alone in the state of Tamil Nadu, and 20,000 tones by the Indian Tobacco Company in the state of Karnataka. On an average, a typical briquetting plant of die and punch (standard capacity of 750 kg/hour for saw dust) type produces between 250 and 300 tones per month which fetches a market price between Rs1800 to Rs 2500 (inclusive of transport cost) per tone. The profit margin is so good that the payback period is well within 12 months. Briquettes when replaced for firewood and coal provide a direct cost savings on the fuel to the tune of 25% to 30 % as the combustion efficiency improves remarkably. In addition to such direct savings are the benefits of easy transportation, handling and storing during rainy seasons besides saving labour for sizing the firewood. These die and punch plants have established their viability and quick return mainly due to the availability of improved machine design and quality, good upkeep of the machinery, continued efforts on expanding the market for briquettes and continued search on sourcing biomass for consistent production and sales.

1.2 Biomass

Biomass energy is essentially derived from forest, urban, and agricultural waste.

Biomass can be divided into three categories:

- Forest biomass, which comes from branches and cutting residues, bark, sawdust, crowns, needles, and other forest waste
- Agrifood biomass, the bulk of which comes from crop and livestock production and field waste
- Urban biomass, which is made up of municipal, commercial, and industrial waste

Since biomass contains carbon and hydrogen, it can be considered a fuel. It is used in a number of areas to meet a variety of energy needs, including electricity and heat. It can also be used in the production of alcohol or biodiesel fuels for automobiles.

Biomass is an environment-friendly energy source. Biomass plays a key role in protecting the environment because it makes it possible to reuse waste, reduce landfill costs, and, by the same token, prevent soil and groundwater contamination.

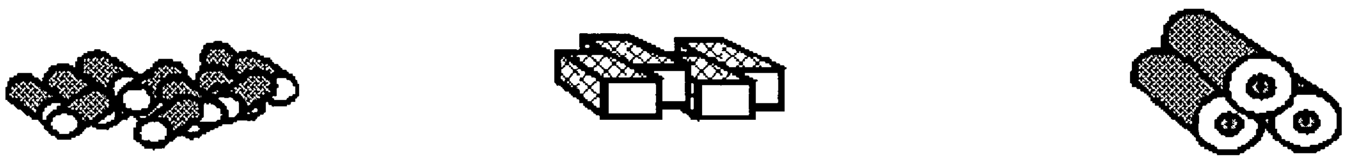
In Quebec, residual biomass represents the only alternative form of energy in large-scale use, notably in the pulp and paper and sawmill industries, where it is derived from sawmill waste such as bark or black liquor from pulp and paper manufacturing. The development of cogeneration is also becoming increasingly common in the forestry industry. Cogeneration using biomass entails burning the biomass in a boiler to produce vapor driving a turbogenerator unit that generates electricity. This is an excellent way to process and convert biomass residue that otherwise could not be used (Mesae et al., 1996).

The potential agro-residues which do not pose collection and drying problems, normally associated with biomass are rice husk, groundnut shells, coffee husk and coir waste (obtained by dry process).

At present, loose rice husk, groundnut shells and other agro-residues are being used mostly by small scale boilers in process industries. Apart from being inefficient, these boilers do not have provision to capture fly ash and unburnt carbon, with the result that extensive air pollution is being created. in Ludhiana, one of the industrialized cities of Punjab (India), about 2,000 tones of rice husk is burnt every day (Grover and Mishra, 1996).

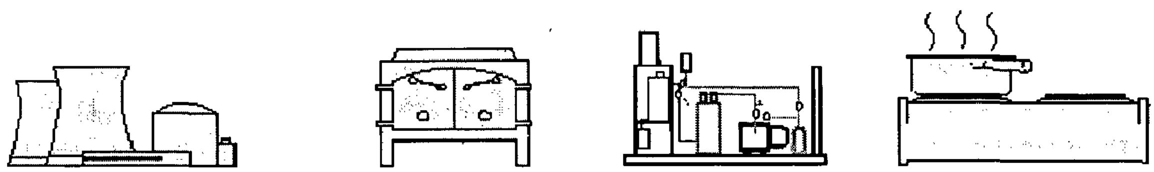
This pollution problem has become so acute that the State Government of Punjab has banned the burning of loose husk in such boilers. It is very likely that other States in India will soon follow this policy. The users have been advised to use husk either as briquetted fuel or in fluidized bed boilers with proper pollution control measures.

Figure 1.1 shows some forms of densified biomass and their uses-



Pellets Cubes Logs

Once densified, the fuel has many uses.



Co-firing with coal Home Pellet Stoves Micro power plants WoodGas Cooking

Fig.1.1 Densified Biomass Types -Pellets, Cubes, Logs and their uses

1.3 Appropriate Biomass Residues for Briquetting

1.3.1 Characteristics

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:

a. 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.

b. 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. These constituents have a tendency to devolatalise during combustion and condense on tubes, especially those of super heaters. These constituents also lower the sintering temperature of ash, leading to ash deposition on the boiler's exposed surfaces. Ash contents of some biomass residues are shown in table 1.1-

Table1.1 Ash content of different biomass types (Grover and Mishra, 1996).

Biomass	Ash content (%)	Biomass	Ash content (%)
Corn cob	1.2	Coffee husk	4.3
Jute stick	1.2	Cotton shells	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

c. Flow characteristics

The material should be granular and uniform so that it can flow easily in bunkers and storage silos.

1.3.2 Biomass Material

Some of the appropriate agro-residues are described below:

a. 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 flow ability, 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.

b. Mango Leaves

Mango leaves have ash content of 13.36% this is far more than mango wood which is 2.84% and volatile matter around 73.04%.

c. Eucalyptus Leaves

Eucalyptus leaves have ash content of 7.29%and VM 79.24%. These give good logs when densified. Crushing is an important factor before densifying leaves.

d. Wheat straw

Wheat straw produces logs which are stronger while handling but logs produced suffer from low densities at every compaction pressure. Also it has the lowest heating values among the materials used.

e. Sawdust

As far as materials are concerned sawdust comes out to be the best material for compaction. At 70 MPa it gives better densities as well as better performance over wheat straw, mango and eucalyptus leaves.

f. 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 18.42 MJ/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.

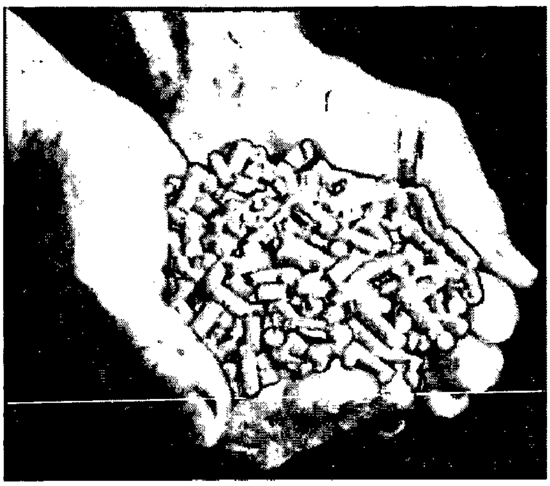
At present, this pith is available from sugar mills at much lower costs. This is a potential material for briquetting.

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 of Karnataka and Kerala.

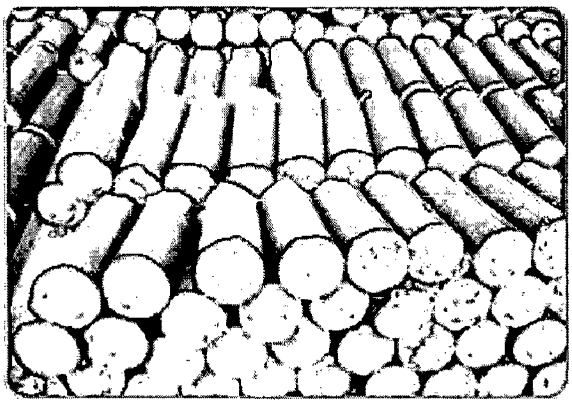
Mustard stalks: Like cotton sticks, it is also an appropriate material for briquetting.

Others: Other potential biomass residues suitable for briquetting are lentil stalks, sawdust, and lantana camera in hilly areas, tea wastes, and coir pith.

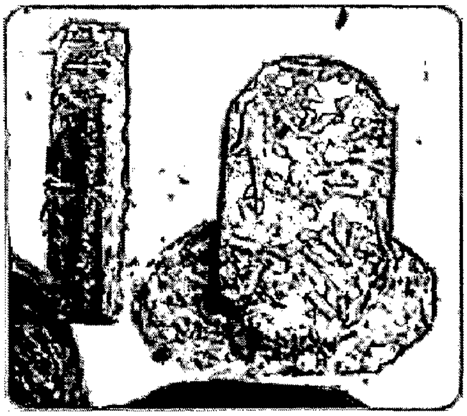
1.4 Briquetting



Biomass pellets



Wood briquettes



Corn stalk briquettes

Fig. 1.2 Biomass Pellets and Briquettes

Figure 1.2 shows biomass pellets, wood briquettes and corn stalk briquettes prepared under various pressure and other conditions.

Advantages associated with biomass fuel pellets include:

• Reduced amount of dust and waste produced in consumer end-use.

• Reduced storage costs, as they take up less space than non-densified biomass.

• More efficient combustion control because fuel pellets are uniform in size and their flow into combustion boilers can be better regulated.

1.5 Technologies for Briquetting

1.5.1 Screw Press and Piston Press Technologies

High compaction technology or binder less technology consists of the piston press and the screw press. Most of the units currently installed in India are the reciprocating type where the biomass is pressed in a die by a reciprocating ram at a very high pressure. In a screw extruder press, the biomass is extruded continuously by a screw through a heated taper die. In a piston press the wear of the contact parts e.g., the ram and die is less compared to the wear of the screw and die in a screw extruder press. The power consumption in the former is less than that of the latter. But in terms of briquette quality and production procedure screw press is definitely superior to the piston press technology. The central hole incorporated into the briquettes produced by a screw extruder helps to achieve uniform and efficient combustion and, also, these briquettes can be carbonized. The piston presses which are currently operating in India are also known as ram and die technology. In this case the biomass is punched into a die by a reciprocating ram with a very high pressure thereby compressing the mass to obtain a briquette. The briquette produced is 60 mm in external diameter. This machine has a 700 kg/hr capacity and the power requirement is 25 kW. The ram moves approximately 270 times per minute in this process. Table 1.2 shows comparison of screw press to piston press-

Table 1.2 Comparison of a screw extruder and a piston press (Grover and Mishra, 1996)

	Piston press	Screw extruder
Optimum moisture content of raw material	10-15%	8-9%
Wear of contact parts	low in case of ram and die	high in case of screw
Output from the machine	in strokes	continuous
Power consumption	50 kWh/ton	60 kWh/ton
Density of briquette	1-1.2 gm/cm³	1-1.4 gm/cm³
Maintenance	high	low
Combustion performance of briquettes	not so good	very good
Carbonisation to charcoal	not possible	makes good charcoal
Suitability in gasifiers	not suitable	suitable
Homogeneity of briquettes	non-homogeneous	homogeneous

At present, screw press and piston press technologies are becoming more important commercially.

1.5.2 Hydraulic piston press

Another type of briquetting machine is the hydraulic piston press. This is different from the mechanical piston press in that the energy to the piston is transmitted from an electric motor via a high pressure hydraulic oil system. This machine is compact and light. Because of the slower press cylinder compared to that of the mechanical machine, it results in lower outputs. The briquettes produced have a bulk density lower than 1000 kg/m³ due to the fact that pressure is limited to 40-135 kg/h. This machine can tolerate higher moisture content than the usually accepted 15% moisture content for mechanical piston presses. Fig. 1.3 shows a MTS Sintech® 60/D materials testing workstation (hydraulic press) used for biomass densification. This is a type of hydraulic press. A tube and plunger apparatus was constructed for use with the machine at Iowa State University so biomass samples could be compacted.

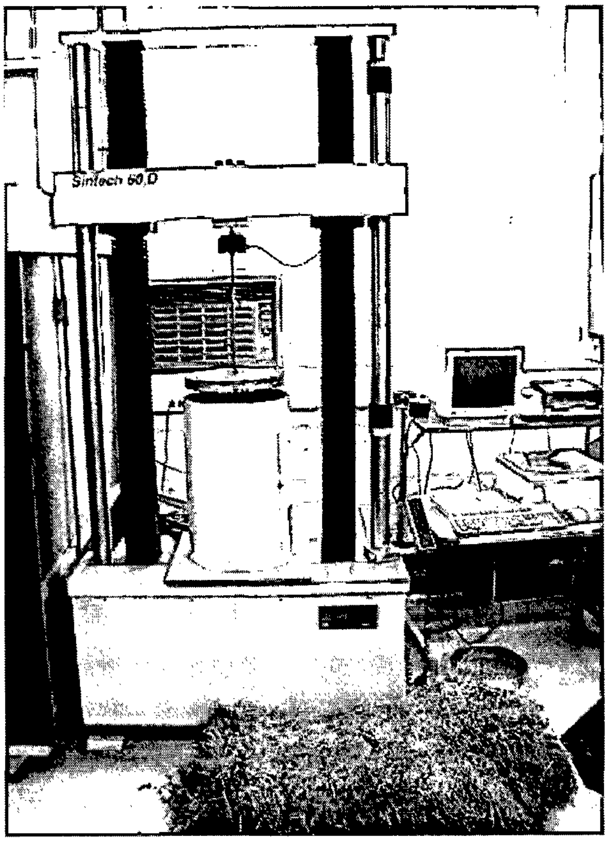


Fig. 1.3 MTS Sintech® 60/D Materials Testing Workstation used for biomass densification. (Hydraulic press) (Pelt, 2003)

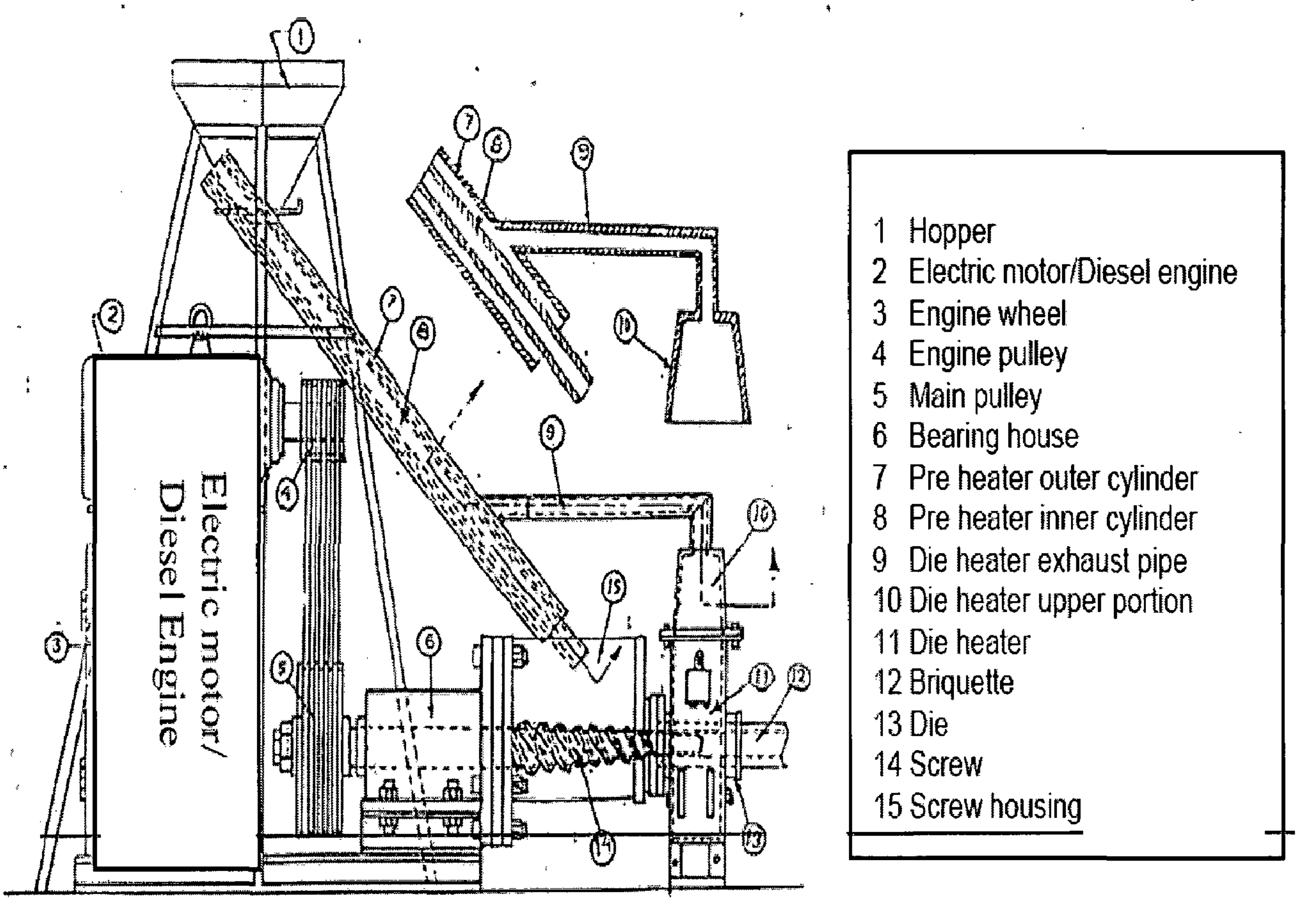


Fig 1.4 Screw Press with biomass stove die-heater (Moral and Ali, 2000)

Fig 1.4 shows schematic diagram of the briquetting system run by diesel engine/electric motor with biomass stove die-heater. It is an example of screw press. This system is modeled by Moral and Ali in 2000 at Khulna University of Engineering & Technology (KUET), Bangladesh.

1.5.3 Palletizing

Palletizing is closely related to briquetting except that it uses smaller dies (approximately 30 mm) so that the smaller products are called pellets. The palletize has a number of dies arranged as holes bored on a thick steel disc or ring and the material is forced into the dies by means of two or three rollers. The two main types of pellet presses are: flat and ring types [3]. The flat die type features a circular perforated disk on which two or more rollers rotate. The ring die press features a rotating perforated ring on which rollers press onto the inner perimeter. Some of the technical features of both types are given below:

	Flat type	Ring type
Disk diameter (mm)	300-1500	250-1000
Track surfaces of rollers (cm^2)	500-7500	500-6000

Large capacity palletizes are available in the range of 200 kg/h to 8 ton/h. Thus, pellet press capacity is not restricted by the density of the raw material as in the case of piston or screw presses. Power consumption falls within the range of 15-40 kWh/ton.

1.6 Compaction Characteristics of Biomass and Their Significance

In order to produce good quality briquettes, feed preparation is very important. Feed parameters are discussed in this section, as these play a practicable role in briquetting technology.

For densification of biomass, it is important to know the feed parameters that influence the extrusion process. For different briquetting machines, the required parameters of raw materials like their particle size, moisture content, temperature are different. These are discussed below.

a. Effect of particle size (Reece, 1966)

Particle size and shape are of great importance for densification. It is generally agreed that biomass material of 6-8 mm size with 10-20% powdery component (< 4 mesh) gives the best results. Although the screw extruder which employs high pressure (1000 - 1500 bar), is capable of briquetting material of oversized particles, the briquetting will not be smooth and clogging might take place at the entrance of the die resulting in jamming of the machine.

b. Effect of moisture

The percentage of moisture in the feed biomass to extruder machine is a very critical factor. In general, it has been found that when the feed moisture content is 8-10 %, the briquettes will have 6-8% moisture. At this moisture content, the briquettes are strong and free of cracks and the briquetting process is smooth. But when the moisture content is more than 10%, the briquettes are poor and weak and the briquetting operation is erratic.

c. Effect of temperature of biomass (Reece, 1966)

By varying the temperature of biomass the briquette density, briquette crushing strength and moisture stability can be varied. In a screw extruder, the temperature does not remain constant in the axial direction of the press but gradually increases. Internal and external friction causes local heating and the material develops self-bonding properties at elevated temperatures. The addition of heat also relaxes the inherent fibers in biomass and apparently softens its structure, thereby reducing their resistance to briquetting which in ~~turn results in a decreased specific power consumption and a corresponding increase in~~ production rate and reduction in wear of the contact parts. However, the temperature should not be increased beyond the decomposition temperature of biomass which is around 300 °C.

d. Effect of temperature of the die (Reece, 1966)

The distinctive feature of a screw type briquetting machine is that heat is applied to the die 'bush' section of the cylinder. This brings about two important operational advantages. The machine can be operated with less power and the life of the die is prolonged. Further, the surface of the briquette is partially carbonized/torrified to a dark brown color making the briquette resistant to atmospheric moisture during storage. The temperature of the die should be kept at about 280-290 °C If the die temperature is more than the required one, the friction between the raw material and the die wall decreases such that compaction occurs at lower pressure which results in poor densification and inferior strength. Conversely, low temperature will result in higher pressure and power consumption and lower production rate.

e. Effect of external additives

The briquetting process does not add to the calorific value of the base biomass. In order to upgrade the specific heating value and combustibility of the briquette, certain additives like charcoal and coal in very fine form can be added. About 10-20% char fines can be employed in briquetting without impairing their quality. Further, only screw pressed briquettes can be carbonized. When carbonized with additives in the briquette to make dense char coal, the yield is remarkably increased. However, depending upon the quality of charcoal and coal powder, various formulations can be evolved for optional results. In piston press technology the effect of particle size and moisture content is similar to that of the screw press. But in this case preheating of raw material is not employed and the die is not heated. In fact the die needs cooling for smooth briquetting.

1.7 Appliances of Biomass Briquettes

Briquettes can be used in any appliances meant for burning wood or coal. However, certain changes in operating parameters especially regarding the distribution of primary and secondary air will have to be incorporated into the conversion. One should first understand the specific characteristics of briquetted biomass before taking steps to make changes in appliances. Briquettes have a density twice that of common fuel wood. Porosity is very low and, accordingly, char produced during combustion is denser than wood or biomass charcoal. Moreover, screw pressed briquettes with a central hole have better combustibility than ram pressed solid briquettes and are considered to be better fuel than coal, wood and solid briquettes. This is mainly due to: (1) the larger surface area per unit weight or volume for the same size; (2) in spite of low porosity the effective thickness or resistance for release of volatiles is relatively much less and thus their flammability is much higher; and (3) char left after combustion is also twice as dense as wood and it burns slowly due to higher ash content. Since inventory of this char is much higher for the same thickness of bed, the briquettes have a higher heat capacity i.e., they retain heat for a longer period and keep the appliance ata higher temperature which then facilitates easy ignition of fresh fuel charges.

1.7.1. Combustion in Stoves

Solid briquettes (SB) are considered unsuitable for cook stoves and give excessive smoke unless broken into small pieces of 1-2 cm in thickness. Screw pressed briquettes (SPB) are easy to burn and give better combustion than wood. Since the density of these briquettes is higher than wood, the amount of air required is correspondingly greater for the same volume of briquettes. Moreover, SPB should be placed in a vertical position as far as possible so that the air can easily pass through the central holes. These can be broken into suitable sizes so as to fit well n the combustion chamber. The specific air requirement for these briquettes is about 1.6Nm³/hour per kWh of heat output. For burning briquettes provision should be made to have side entry holes in the casing of stoves for ingression of secondary air. Alternatively, a hollow cylinder made out of a perforated sheet (holes size 3-5 mm) having diameter about 50 mm less than the inner diameter of stove can be placed in the stove chambers over the grate. The holes in this cylinder will facilitate the entry of distributed secondary air. This cylinder will also prevent the flame from touching the casing of the stove thereby conserving radiation losses.

1.7.2. Combustion in Furnaces

Both types of briquette are suitable for industrial furnaces which are meant for burning coal/wood but SPB fuels because of their homogeneous structure and configuration give much better performance than SB and other fuels. The power density is at least twice that of coal, provided secondary and primary air are properly distributed and the installed blowers supplying air have the requisite capacity .SB fuels have a tendency to break during combustion and the resulting products depending upon size, either get entrained with gases or tend to pass through the grate into the ash pit or block the grate. This tends to reduce their combustion performance. SPB fuels, on the other hand, do not have these tendencies and give much better combustion performance. While burning briquettes of either type, the operating parameters, especially with regard to distribution of primary and secondary air, have to be manipulated. Compared to coal these briquettes need more secondary and less primary air. When compared to wood, because of the higher density, the amount of air needs to be increased but its distribution components should be maintained at the original ratio. However, the specific consumption of total air in terms of Nm^3/hr.kWht remains the same.

1.7.3. Applications

The briquettes are particularly recommended for:

Boilers	For steam generation
Food processing industries	Distilleries, bakeries, canteens, restaurants and drying etc.
Textile process house	Dyeing, bleaching etc.
Agro-products	Tobacco curing, tea drying, oil milling etc.
Clay products	Bricks kilns, tile making, pot firing etc.
Domestics	Cooking and water heating
Gasification	Fuel for Gasifier
Charcoal	Suitable for making charcoal in kilns

1.8 Aims and Objectives of the Proposed Work

Based on the literature survey as detailed in Chapter- 2, and works reported in India, the aims and objectives of the work covered in this thesis may be specified as follows:

1. To characterize and analyze different biomass residues for their physicomechanical, physicochemical and thermo chemical properties.
2. To study the effect of compaction pressure on the densities of briquettes produced.
3. To study the effect of pressure application rate on the densities of briquettes produced.
4. To study the effect of moisture content of biomass residues on the densities of briquettes produced.

5. To study the effect of holding time on the densities of briquettes produced.
6. To study the effect of sizes of biomass residues on the densities of briquettes produced.
7. To calculate impact resistance index of various biomass residues.

CHAPTER 2

LITERATURE REVIEW

In its natural form, most biomass is difficult to utilize as a fuel because it is bulky, wet, and dispersed. Disadvantages of biomass as an energy source include inefficient transportation and large volumes required for storage. Solving these problems is where biomass densification gains extreme importance. Biomass densification is defined as compression or compaction of biomass to remove inter- and intra-particle voids Compression baling can reduce biomass volume to one-fifth of its loose bulk volume.
The first United States patent for biomass densification was issued in 1880 to William Smith (U.S. Patent No. 233,887). He compressed the sawdust and other waste from a sawmill at a temperature of 66°C (150°F) using a steam hammer. Burmistrova (1963) described densification testing on various kinds of hay. Dry hay required stronger compression forces and produced bales of lower bulk density than wet hay. More moisture in the biomass decreases friction when the material is being compressed. Therefore, the same stress on wet biomass produces more deformation than on dry biomass. Biomass densification can also reduce the moisture content of a material by "squeezing" some of the moisture out during compression. Burmistrova concluded moisture content is the variable with the greatest effect on compression. Sitkei (1986) reached the same conclusion (Babu, 2001).

The various researches in the field of biomass densification are cited below:

Bhattacharya et al. (1985)
The potential of the use of densified rice husks and sawdust in Thailand is analyzed from an energy viewpoint. A survey of densified fuel manufacturers and the market was conducted and a number of densification machines were found to be lying idle, chiefly due to lack of a market for the fuel. An economic analysis of briquette making from sawdust is presented and explanations for the partial commercial failure of this technology detailed.

Felkera et al. (1999)

A 216 kW biomass harvester, modified from a John Deere silage harvester, was held tested in Texas and New Mexico to examine the productivity and cost of harvesting shrubs and small trees for energy purposes. The harvester was tested on mesquite (Prosopis glandulosa var. glandulosa) in Texas and salt cedar (Tamarisk pentandra) and pinyon (Pinus edulis)/juniper (Juniperus monosperma) stands in New Mexico. While the harvester severed and chipped a few individual 20-cm basal diameter trees, the harvester was much more efficient harvesting dense stands of small trees that were less than 10-cm in basal diameter. During the course of these trials, major modifications were made to increase the efficiency of the cutter head and the materials handling system. After these modifications, when harvesting mesquite stands less than 10-cm in basal diameter, the machine harvested at the rate of 0.95 ha h^-1 with a fresh weight harvest production of 7050 kg h^-1. Using $70 h^-1 operating cost data for similar commercial equipment, we estimated an energy cost of $1.00 kJ^-1 which compares favorably to energy sources such as low sulfur Wyoming coal, natural gas and fuel oil. The swath harvester described here did not bale the chips. However, baling trials with 3 commercial balers found that 2 commercial balers could pick up dense windrows of the chips and make a satisfactory 300 kg square bale and a 595 kg round bale. The large square bale with a density of 319 kg m^-3, provides an opportunity for full load potential of flat bed truck trailers to be realized. As the harvester is built on an agricultural frame, it is not sufficiently robust to operate in a forestry environment. A commercial version will need to be built on a high clearance, heavy duty frame with 4 wheel drive similar to a forestry skidder. Brown Bear Corporation, the company that manufactures the cutter head, is anxious to build this harvester for a purchase price of about $280000. We estimate that an annual demand for about 12000 Mg of biomass at $9 per green Mg will be necessary to justify the purchase of the first harvester. The market potential for non-energy related biomass i.e., potting soil base, landscape mulch, wood chips for bioremediation, mesquite barbecue products, appears sufficiently great in some locations to justify purchase of the first commercial version of a harvester.

Tavares et al. (1999)

In this article a study is made of a series of briquettes made from forest or industrial waste, some types of which have not to date been used in briquettes. They are evaluated from both an energy and economic viewpoint. Lignocellulosic densification improves the briquettes' behavior as a fuel by increasing the homogeneity and by being easier to transport and manage. Lignocellulosic binder less briquettes' characteristic net heating value (LHV) and remaining amount of fuel during combustion (Weight) have been investigated to obtain a general expression function of production and raw material factors. In both cases the main factor is the fixed carbon in a quadratic way as all the factors are easily measurable.

Chin and Siddiqui (1999)

Biomass material, including sawdust, rice husks, peanut shells, coconut fibers and palm fruit fibers, was densified into briquettes at modest pressures of 5±7 MPa using a piston and die type of press. The briquettes were tested to evaluate their relaxation behavior, mechanical strength and burning characteristics. The sawdust briquettes were found to have better overall handling characteristics. But briquettes of different biomass materials required different optimum conditions of fabrication and generally showed a promising potential for further development.

Li and Liu (2000)

High-pressure binderless compaction of wood processing residues and other biomass waste materials, including hardwood, softwood, and bark in the forms of sawdust, mulches, and chips, were studied. A piston-and-mold (punch-and-die) process was used to produce densified logs (slugs) under room temperature and at pressures ranging from 34 to 138 MPa. The properties of the logs including density, abrasion resistance, impact resistance, compressive strength, water resistance, and long-term performance were tested. The effects of moisture content, compaction pressure, compaction speed, pressure holding time, and particle size and particle shape were studied. It was found that the necessary moisture for producing good-quality logs ranges from 5 to 12% for all the woody materials studied, and the optimum moisture content is in the neighborhood of

8%. It was also found that mulch is the easiest form to be compacted into dense and strong logs, sawdust is the second, and chips the last. For the mulches, a compaction pressure of 70 MPa can produce high-quality logs. For sawdust, a minimum pressure of 100 MPa is needed to form good logs. And for chips, no good logs can be made even at pressure as high as 138 MPa. The logs produced under optimal conditions had dry densities near or higher than 1 g/cm3. Such high density facilitates storage, handling and transportation of biomass. The dense logs also have high-energy content per unit volume, making it easier to be cofired with coal in power plants.

Granada et al. (2001)

Briquetting of biomass can be done through various techniques. The present work describes the process of designing a taper die and its optimization for use in a hydraulic machine. The application of an experimental design technique, and the later statistical analysis of the results is presented, applied to a laboratory hydraulic press densification process of lignocelluloses biomass. The most appropriate experiment type is determined for a first set of experiments; calculating, among other things: minimum number of tests to carry out to obtain binding conclusions, most influential factors, and search paths to improve fuel quality. Another experiment type is determined for a second set of experiments, taking account of the most influential factors (pressure, temperature and moisture content), and also the number of tests to carry out considering the improvement of density and friability. Finally, an approximation study of the best product allows conclusions to be reached on product behavior beyond the experimental design range factors.

Pelt. (2003)

Several biomass samples of soybean straw, dry corn stalks, wet corn stalks, and dry alfalfa hay were compression tested. The objectives of this experiment were to (1) define a relationship between bulk density and applied pressure for several samples of corn stalks, soybean straw, and alfalfa hay, and curve fit the results using Equation 1 that models biomass densification, and (2) observe similarities or differences in the values for the constants k and n due to differences in moisture or type of biomass.

$\gamma = kp^n$

where: γ = bulk density, kg/m3

k = constant

p = pressure, kPa

n = exponential constant

Biomass samples were tested with an MTS Sintech® 60/D Materials Testing Workstation using a 2224 N (500 lb) load cell and a crosshead movement of 12.7 cm (5 in) per minute. The samples were compressed within a PVC tube having a 39-cm (15.4-in) inside diameter and a 56-cm (22.0-in) height. In increasing order, the average k-value for each material tested was 25 (dry corn stalks), 36 (soybean straw), 49 (wet corn stalks), and 56 (dry alfalfa hay). The most difficult biomass material to compact, from the four tested, was dry corn stalks. This experiment also indicates dry biomass is tougher to compact than wet biomass. In decreasing order, the average n-value for each material tested was 0.29 (dry corn stalks), 0.24 (soybean straw), 0.24 (wet corn stalks), and 0.23 (dry alfalfa hay). An ANOVA test determined that the k-values are statistically different for each material. However, an ANOVA test did not conclusively prove the n-values of the different biomass materials are different.

Sokhansanj and Turhollow (2003)

Loose plant-based biomass has a low bulk density ranging from 50-130 kg/m3 depending on the plant species, particle density and particle size. Biomass densified into bales and cubes increases its bulk density to 120-500 kg/m3. The handling properties of pellets and cubes are similar to those for grains. The existing, well-developed, conventional bulk handling equipment can be used to handle pelleted and cubed biomass. Although cubed biomass is easier and safer to handle and store, it is more expensive as a feedstock for a conversion plant than biomass bales. The objective of this research was to develop a base cost for cubing using the existing technology. The delivered cost of corn stover bales delivered to a biorefinery 64 km (40 miles) away from an intermediate storage, including a final grinding, was estimated at \$60.15/dry Mg (\$54.57/dry ton), whereas for corn stover cubes the cost is \$71.92/dry Mg (\$65.38/dry ton). These costs included \$11/dry Mg (\$10/dry ton) payment to the farmer. The difference between the cost of baled and cubed biomass was in capital equipment and operation costs. Development of innovative densification and bulk handling technologies are proposed to decrease densification costs to or below the cost of baled biomass.

Ali and Moral (2004)

Biomass residues constitute the biggest source of energy in Bangladesh, where the share of bio-energy in the total energy consumption is more than 65%. The available residues include rice husk, wheat husk, sawdust, rice straw etc. These residues have low heating value per unit volume and high transportation and storage costs when used in as received condition; these difficulties can be largely overcome through briquetting. A project aimed at promoting briquetting technology in Bangladesh through adaptive research, demonstration and dissemination was implemented by the Department of Mechanical Engineering, Khulna University of Engineering & Technology (KUET) during 1997-2004. The major achievements of the research are the enhancement of screw life and reduction in briquetting energy consumption, leading to reduction in the production cost of briquettes. Within this project, three technology packages were developed by KUET on improved heated-die screw-press briquetting system, each consisting of a machine to produce briquette, selected accessories, and a stove to burn briquettes efficiently. Accessories developed included a biomass pre-heater, die-heating stove and a smoke removal system. With the packages developed, it is possible to produce rice husk briquettes at a cost of about Tk. 1.75 per kg (1 US$ = Tk 60 Tk; which is competitive with the cost of fuel wood in the local market. Thus, the future prospect of biomass briquetting technology in Bangladesh appears to be very promising.

Debdoubi et al. (2004)

The aim of this study is to prepare a solid fuel from the most abundant biomass of morocco that can be used by the local population, and in particular by the rural ones, instead of the wood of forest, which is less available and its exploitation is negative for the environment. Esparto is the most available biomass, with a production of 560 000 tons annually of dry matter approximately. However, briquettes of esparto have low calorific power and their mechanical properties are bad. To improve the quality of the briquettes and to have an economically competitive product at the same time, the esparto was partially pyrolyzed at temperatures between 160_C and 400_C, and the pressure of densification has been examined. The combustion profile of the samples has been studied by applying the derivative thermogravimetry technique, and the mechanical properties of the briquettes were tested to evaluate the impact resistance and water resistance.

This study showed that strong briquettes can be obtained with a higher calorific value when the esparto is partially pyrolyzed, and a relatively elevated densification pressure is applied.

Mani et al. (2005)

Corn stover is a major crop residue for biomass conversion to produce chemicals and fuels. One of the problems associated with the supply of corn stover to conversion plants is the delivery of feedstock at a low cost. Corn stover has low bulk density and it is difficult to handle. In this study, chopped corn stover samples were compacted in a piston cylinder under three pressure levels (5, 10, 15 MPa) and at three moisture content levels (5%, 10%, 15% (wb)) to produce briquettes. The total energy requirement to compress and extrude briquette ranged from 12 to 30 MJ/t. The briquette density ranged from 650 to 950 kg/m3 increasing with pressure.

Moisture content had also a significant effect on briquette density, durability and stability. Low moisture stover (5–10%) resulted in denser, more stable and more durable briquettes than high moisture stover (15%).

Badger and Fransham (2005)

ROI BioOil plants can be made modular and transportable, allowing them to be located close to the source of biomass and the subsequent transportation of high energy density BioOil to a central plant. Conversely, one central BioOil plant could supply several energy users in distributed locations, or several plants could supply numerous end-users, just as in the petroleum industry.

Renewable Oil Internationals LLC (ROI) is one of several developers of fast pyrolysis technology. The production of BioOil can convert raw biomass into a low-viscosity liquid that, depending on the moisture content of the feedstock, increases the energy density of biomass by a factor of 6 to 7 times over green wood chips. The increase in energy density increases the amount of energy that can be hauled by standard tanker trucks versus a chip trailer van by a factor of two. Capital costs, exclusive of land costs, are comparable for a 50MWe biomass handling system at the power plant. Land area requirements for fuel storage and handling are reduced roughly half for BioOil systems versus solid fuel handling systems. No analysis was made of operating and maintenance costs.

Mazzu (2006)

An animal traction piston press was studied for applications in developing countries, aimed at producing biomass briquettes as alternative household fuel. Experiments were carried out with different biomasses for determining the minimum compaction pressure and the relationship between applied pressure and volume reduction. Two cams were designed for moving the machine mechanisms: their shape was determined with the aim of minimizing the applied draft force, considering the experimentally determined biomass behavior. The machine was prototyped and tested in Senegal, giving satisfactory results.

Samaniegoa et al. (2006)

Brazil is the largest world charcoal producer. Surface kilns with semi-spherical form built with bricks with or without recovery of by-products called ''Tail Quente'' are the most important systems used for charcoal production. The un-recovered pyrolysis products released to environment by this technology are major pollutants.

Some alternatives integrating existing or improved carbonization units within a global biomass economy are presented. In these alternatives the carbonization reactors can be used for primary biomass conversion, for densification, for power and heat production or as core technology in new bio-refineries. Some of the technical and economical limitations to implement these concepts are discussed.

CHAPTER 3

EXPERIMENTAL

In context to the objectives of this dissertation work, a brief experimental program was envisaged and here it is described in details below.

3.1 Biomass Collection and Preparation

The biomass materials were obtained from nearby Roorkee Town. Initial moisture was quiet high (about 25-37%), so biomass residues were dried by normal floor drying. Four types of woody materials –mango leaves, eucalyptus leaves, wheat straw, and mango sawdust were studied. The materials were obtained from sawmills and farms, and were tested while they were fresh, i.e., stored for less than three months. The sawdust was sieved to remove particles larger than 1.2mm before use. Different moisture contents for the compaction tests were achieved by air drying - spreading the materials on the floor in the laboratory under room temperature and natural venting. It is found that in three days (with normal humidity conditions) moisture come down to 8 to 9%.

Mango and Eucalyptus leaves were crushed in a grass cutter and then dried. The maximum size thus produced was 1 inch. Wheat straw was used as it is found from crusher machines after drying. Sawdust was sieved to four different sizes to determine the size effect on densities of log formed.

All residues were then stored in airtight plastic bags for their uses in different experiments.

3.2 Physico-Chemical and Thermo-Chemical Properties of Biomass Residues

Biomass fuels are characterized by what is called the "Proximate and Ultimate analyses". The "proximate" analysis gives moisture content, volatile content (when heated to 950 °C), and the free carbon remaining at that point, the ash (mineral) in the sample. The "ultimate" analysis" gives the composition of the biomass in wt% of carbon, hydrogen and oxygen (the major components) as well as sulfur and nitrogen (if any). The physicochemical properties are volatile matter, ash content, fixed carbon and chemical composition of biomass. Higher and lower heating values are thermo chemical properties which are determined. The high heating value (HHV) based on the complete combustion of the sample to carbon dioxide and liquid water. The low heating value, LHV, gives the heat released when the hydrogen is burned to gaseous water, corresponding to most heating applications and can be calculated from the HHV and H_2 fraction.

Literature survey indicates that there is no standard procedure evolved to determine these properties. So ASTM standard methods for solid fuels such as coal and coke have been adopted.

3.2.1 Proximate Analysis

The Proximate Analysis (D-3172-73 through D-3174-82 and D-3175-82 Anon., 1993) gives the moisture content, fixed carbon, volatile and ash content of biomass. As the biomass materials were highly volatile, the sparking fuel procedure was used. Moisture content was determined according to ASTM D 3173. A small amount of each biomass was finely ground and sample of one gm. each was taken in silica crucibles at 104 °C in a hot air oven for one hour and weight loss represents the moisture content. Other samples were taken in silica crucibles at 750°C in a muffle furnace for 1 hour and remaining weight was ash content. For VM samples were taken in crucible with lid and heated at 950 °C for only 6 min. after cooling in desiccator and the difference in wt. is due to loss of volatile matters after deducting the corresponding moisture determined previously. Fixed carbon was determined by subtracting moisture, VM and ash from one.

3.2.2 Ultimate Analysis

Ultimate analysis is performed on finely ground and oven dried samples to find out the wt. fractions of C, H, N and S. This is done using CHNS Elemental Analyzer (available at Chemistry Department IITR). The test conditions were combustion temperature of 920 °C and reduction temperature of 640°C.The ash content was previously determined separately following the standard procedure There is no direct method to calculate the percentage of oxygen in biomass so it is calculated by subtracting C, H, N and ash percentages from 100.

3.2.3 Heating Values

The higher heating value of a sample is determined in a bomb calorimeter according to ASTM- D 2015-17. Samples were ground to 250 μm (60 meshes) screen size. One gm of each sample was palletized by mixing a little water and then dried. The pellets were burned in the bomb in presence of oxygen at 30 atm. The higher heating values were determined from the temperature rise of water and the heat capacity of the system.

3.3 Densification of Biomass

3.3.1 Experimental Setup

Experimental setup comprises of a piston, a cylinder, a clamper stand and a small cylindrical part required extruding briquettes from main cylinder. All the parts are made of mild steel whose tensile strength is 500 MPa which is well beyond the maximum pressure employed to the system while briquetting that is 100 MPa. A hydraulic press was required to carry out briquetting operations in above stated parts. An automatic Compression Testing Machine of 500 tons maximum capacity (available at Civil Engg. Department IITR) was used for briquetting. The dimensional details of each component is given at figures from 3.1 to 3.4-

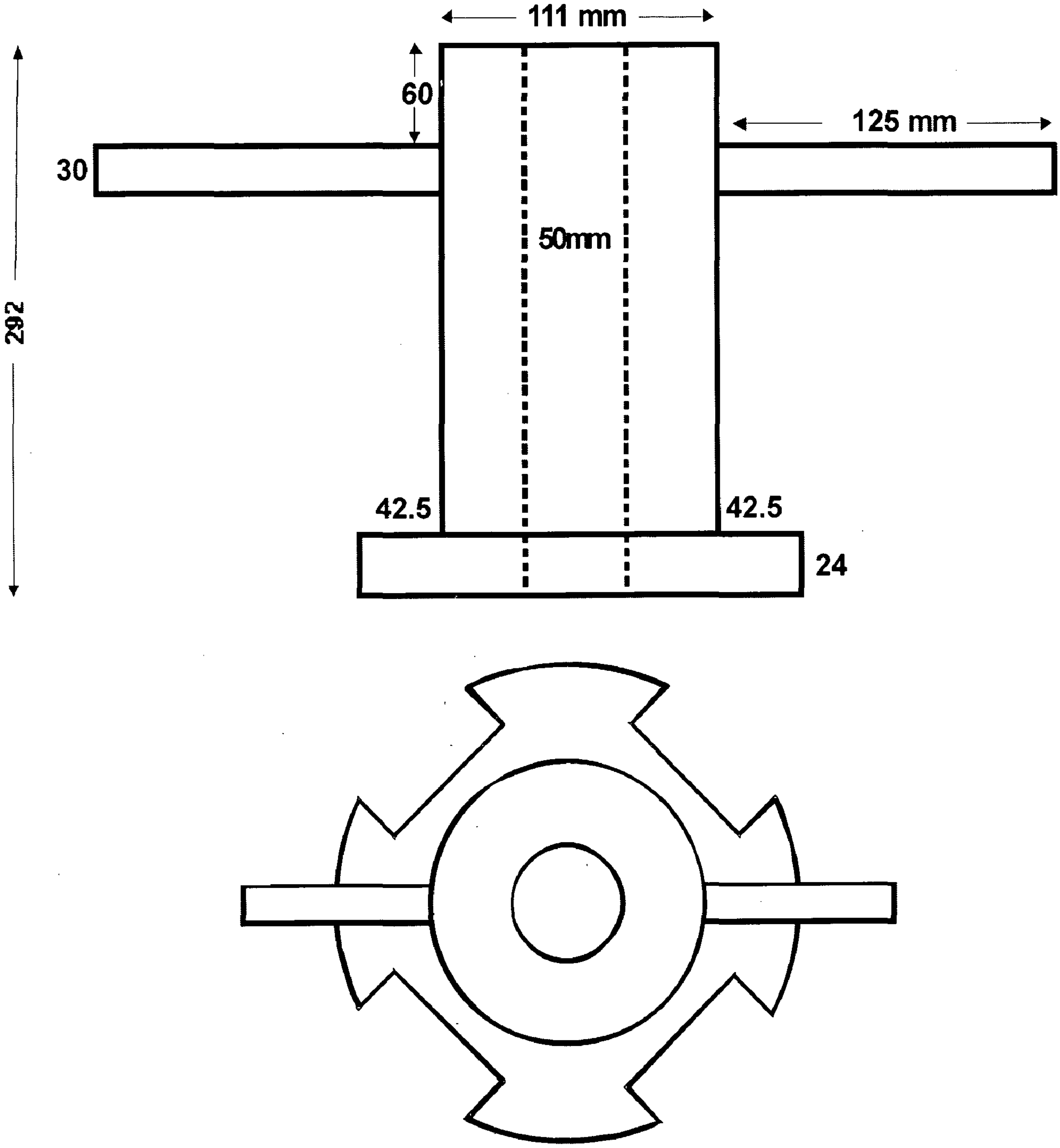


Fig.3.1 Details of Cylinder Assembly (dimensions in mm)

Fig 3.1 shows the dimensional diagram of cylinder which is 292 mm long with a bore dia of 50 mm. A set of handle 125 mm each, was fixed to it by welding to facilitate lifting and removal of briquettes from cylinder. Dimensional details of stand assembly are shown by fig 3.2.

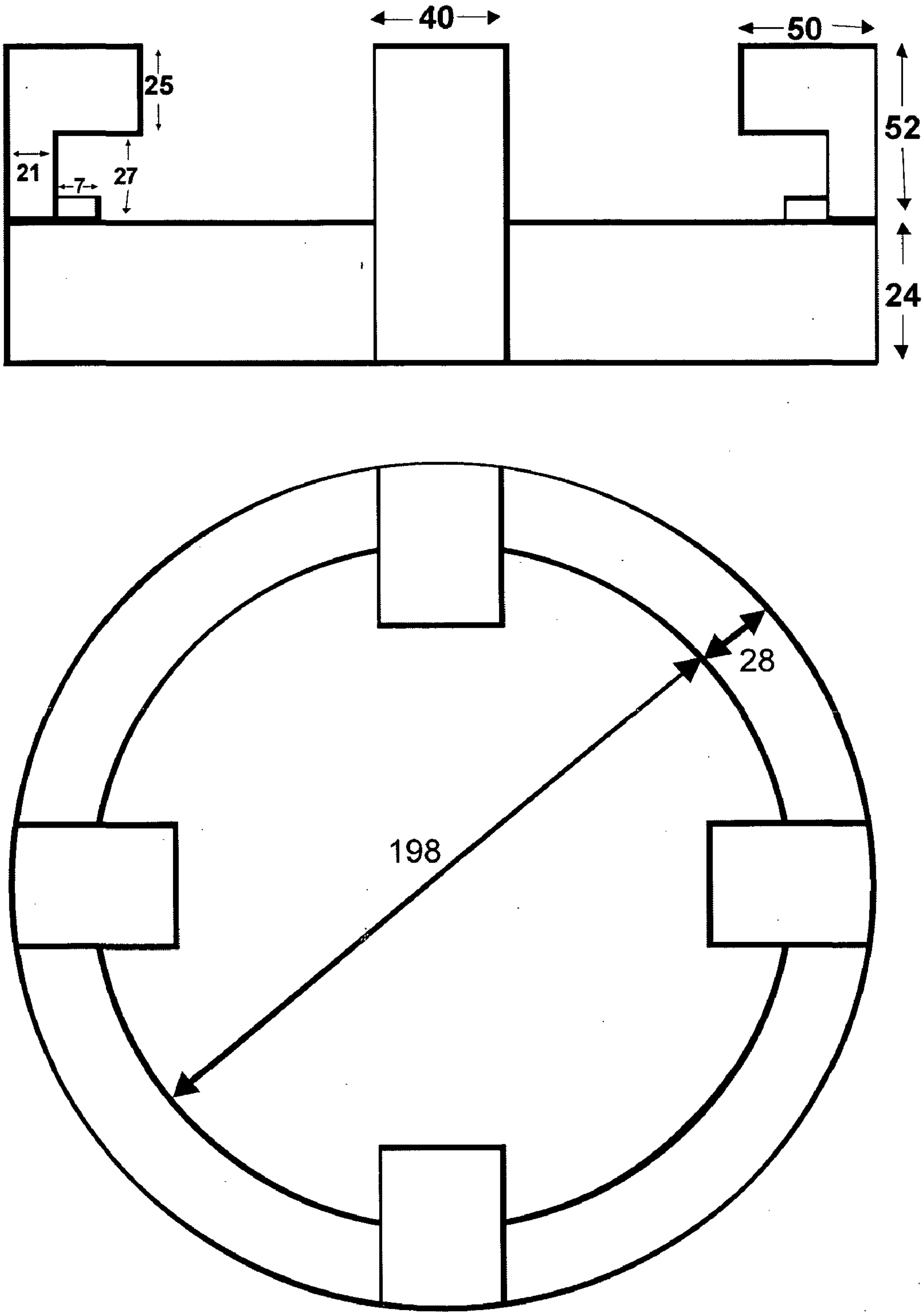


Fig 3.2 Details of Stand Assembly (dimensions in mm)

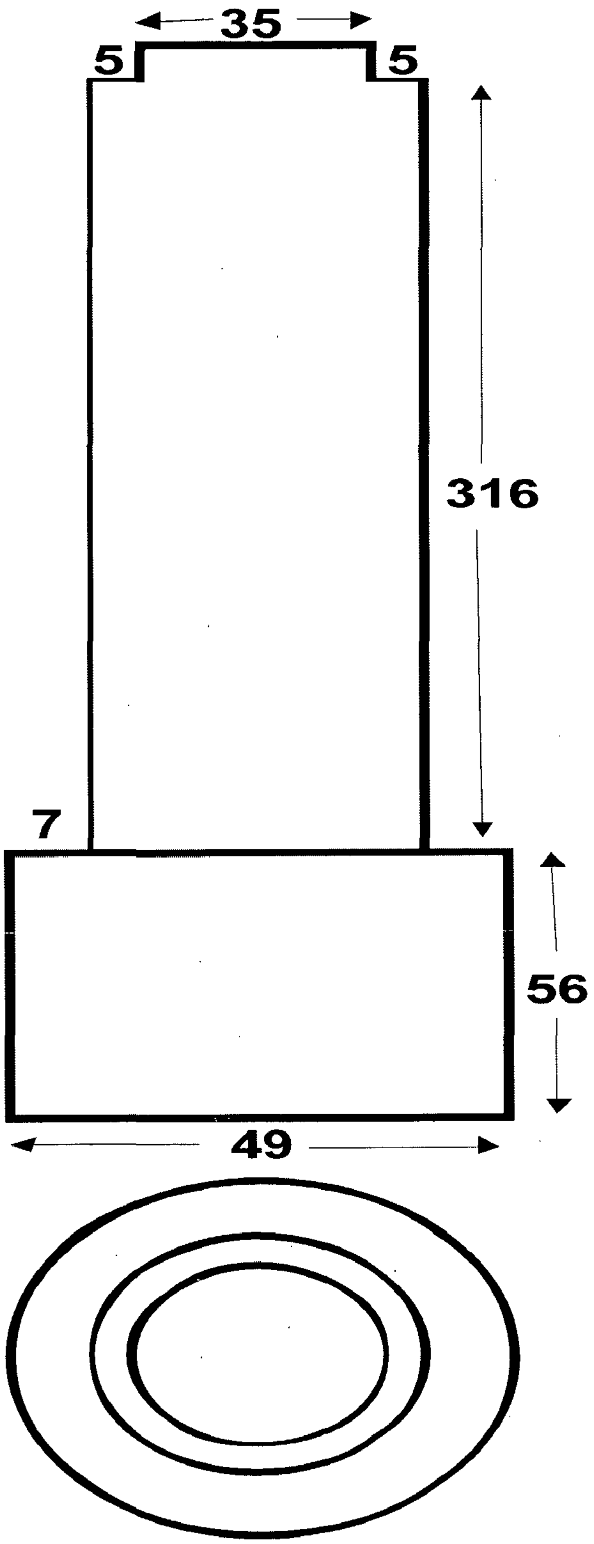


Fig 3.3 Details of Piston Assembly (dimensions in mm)

Fig 3.3 shows dimensional details of piston which 372 mm long and its base diameter is 49 mm .This is one mm smaller than the bore of cylinder to ensure smooth penetration.

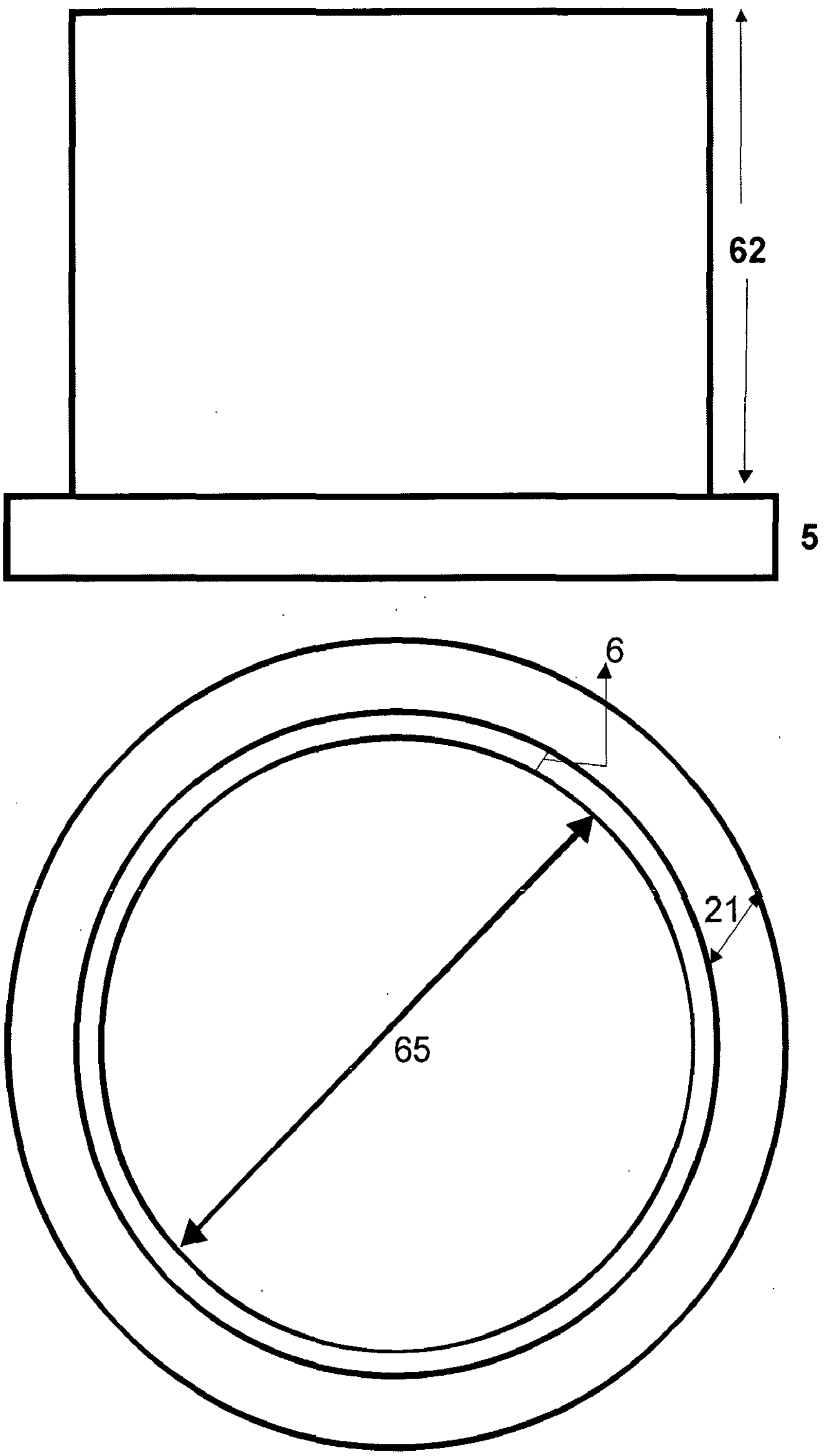


Fig 3.4 Details of Extrusion Assembly (dimensions in mm)

Figure 3.4 shows a small cylindrical component required to extrude the briquette from the cylinder after densification. Some pressure has to be applied on piston after placing the cylinder on shown part to take out briquette from cylinder.

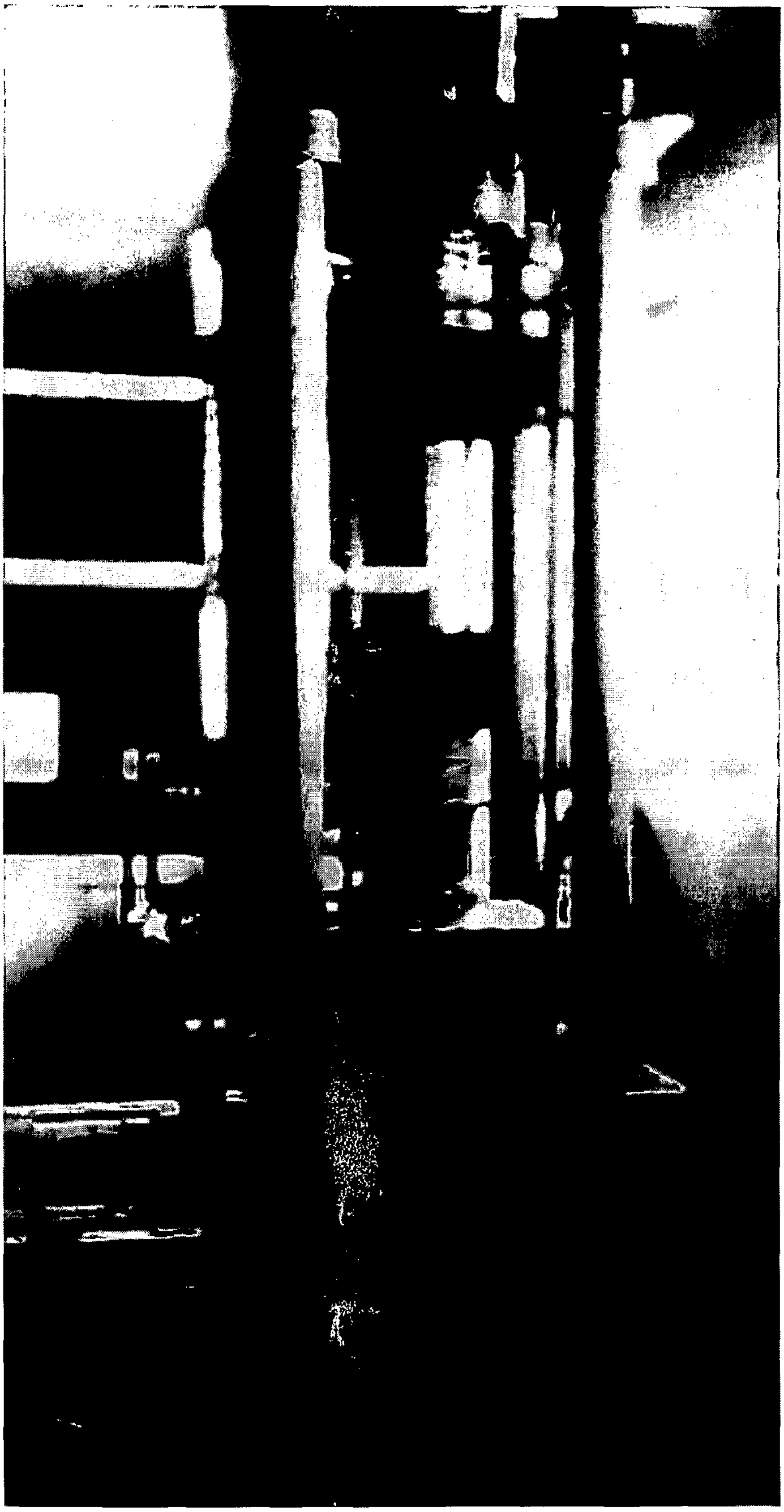


Fig 3.5 Compression testing Machine (500 tones)

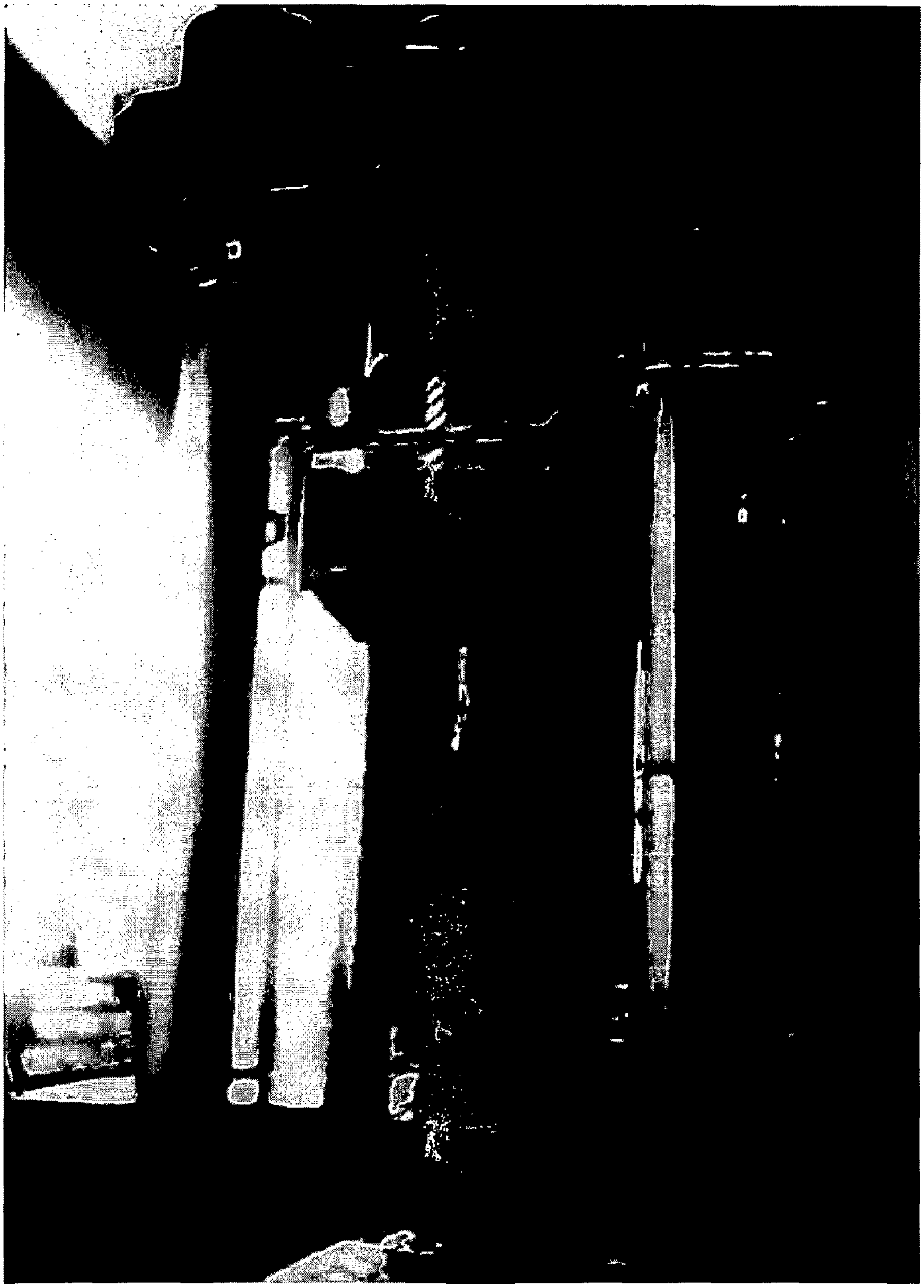


Fig 3.6 Compression Testing Machine (another view)

Fig 3.5 shows the hydraulic compression testing machine (with the capacity of 500 tons) that is used in experiment to compress the biomass into briquette. This machine is installed at Civil Engg. Department, IITR, Roorkee. Fig 3.6 provides another view of this machine.

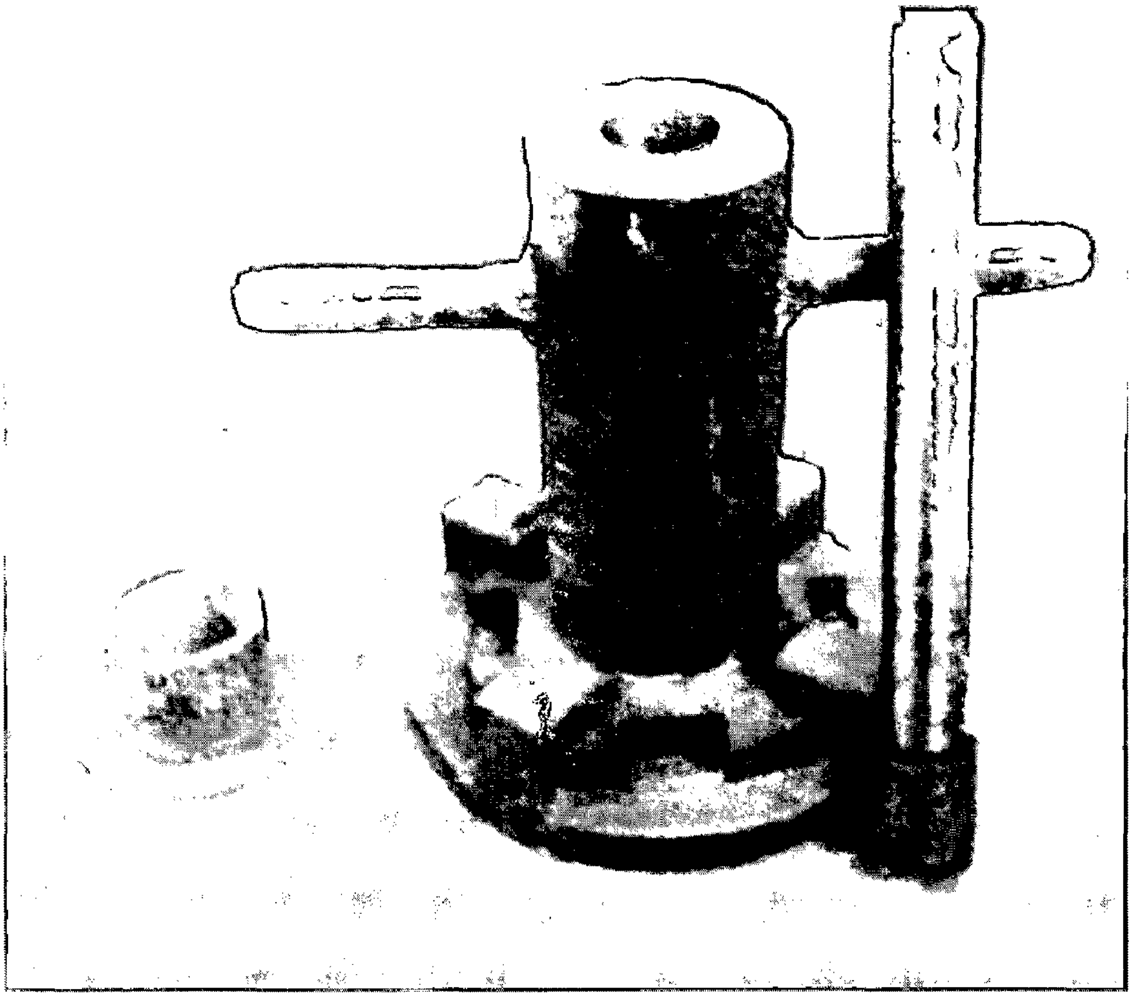


Fig 3.7 Experimental Setup used with Compression Testing Machine
(Cylinder, piston, stand and extrusion assembly)

All the components viz. cylinder, piston, stand and extrusion assembly – are shown in fig 3.7.

3.3.2 Pressure Variation

This test is conducted to study the effect of pressure on the densities of logs formed. Five pressures taken in this study are 30, 50, 70, 90, 100 MPa. Materials taken in this test were mango and eucalyptus leaves, and test conditions were-

Mango Leaves:

Moisture – 11.16%

Pressure application rate - 0.3 MPa/ sec

Holding time – 0 sec

Eucalyptus Leaves:

Moisture – 7.90%

Pressure application rate - 0.3 MPa/ sec

Holding time – 0 sec

3.3.3 Pressure Application Rate Variation

In this test pressure application rates were varied and their effect on densities was studied. The compression testing machine had only three speeds namely low, medium and high. Corresponding rates were calculated as 0.2 -0.3 MPa/sec, 1.1-1.5 MPa/sec and 2-3 MPa/sec. Material used was mango leaves with 8.6% moisture, 10 sec holding time and pressure used was 100 MPa.

3.3.4 Holding Time Variation

Various holding times were employed to exploit the effect on densities of briquettes. Holding times employed were 0, 10, 20, 40 and 60 sec. Material used was sawdust with 11.25% moisture, 0.2 MPa/sec rate and 100 MPa pressure.

3.3.5 Size Variation

Material used in this test was sawdust which is sieved to four different sizes with standard sieves. Four different sizes were –

1000 – 1200 μm

850 – 1000 μm

550 – 850 μm

150 – 250 μm

Moisture - 9.63%

Pressure - 70 MPa

Holding Time - 10 sec

3.3.6 Moisture Variation

This test was conducted on sawdust with 10 sec holding time, pressure of 100 MPa. Sawdust was sieved to remove particles above 1200 μm size. Various moisture content used were 4.46, 8.34, 9.63, 12.68, 13.65%.

3.3.7 Density Calculations

Density was determined using every kind of briquette covered in paraffin oil (Density and weight known) and submerged in water (Density known) to determine the volume, after weighing them. The densities of the logs were measured 2 min after the logs were ejected from the mold. The 2-min density was chosen because most of the logs underwent expansion (spring back) after ejection and most rapid expansion occurred within the first 2 min. Again densities of the logs were tested 24 h after the logs were made and stored in air-tight bags.

3.3.8 Impact Resistance Test

The impact resistance was tested by adapting the ASTM method D440-86 of drop shatter for coal. The logs were dropped twice for 1.83m onto a concrete floor. An impact resistance index (IRI) introduced by Richards was used to evaluate the impact resistance of the logs. The IRI is calculated from IRI= (100*N)/n, where N is the number of drops, and n is the total number of pieces after N drops. Because two drops were used as standard, the number of drops N in the above equation is always 2, and maximum value of IRI is 200. When the number of pieces was counted in a test, the small pieces that weigh less than 5% of the initial weight of the log was not included in the calculation of the IRI. After the first drop, all the pieces that weigh less than 5% of the original weight of the log were not collected and dropped for the second time.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Physico-Chemical and Thermo-Chemical Properties of Biomass Residues

4.1.1 Proximate Analysis

The Proximate Analysis was done according to standard- D-3172-73 through D-3174-82 and D-3175-82. As the biomass materials were highly volatile, the sparking fuel procedure was used (Anon., 1993). The results of proximate analysis done on the residues used in this experiment are listed in table 4.1.

Table 4.1 - Proximate analysis of Biomass Residues

Biomass	Proximate Analysis (as received basis)				HHV MJ/Kg
	Moisture (wet %)	Ash (dry%)	Volatile Matter (dry %)	Fixed Carbon (dry %)	
Mango leaves	8.6	13.36	73.04	13.60	19.17
Eucalyptus leaves	7.90	7.29	79.24	13.47	19.42
Sawdust	9.63	2.84	86.51	10.65	19.18
Wheat straw	8.09	8.90	71.30	19.80	17.51

The high heating value of these biomass residues was also determined as per the method described in experimental program and given in the same table, it may be noted that mango leaves had the highest ash content of 13.36%. While sawdust having only 2.84% ash content. The volatile matters are 86.51 % in sawdust. Eucalyptus leaves had the highest value corresponding to 19.42 MJ/Kg which makes it most attractive fuel among these biomass residues.

4.1.2 Ultimate Analysis

Ultimate analysis is performed on finely ground and oven dried samples to find out the wt. fractions of C, H, O, N and S. There is no direct method to calculate the percentage of oxygen in biomass so it is calculated by subtracting C, H, N and ash percentages from 100.

Table 4.2 - Ultimate Analysis of Biomass Residues

Biomass	Ultimate Analysis (Dry basis)				
	C	H	O	N	S
Mango leaves	40.73	5.49	49.60	1.06	0.00
Eucalyptus leaves	49.76	6.78	33.38	0.77	0.00
Sawdust	44.07	5.76	50.16	0.00	0.00
Wheat straw	43.20	5.01	39.40	0.61	0.00

From the table we concluded that carbon content is maximum (49.76%) for eucalyptus leaves with minimum (33.38%) oxygen. This is the reason that the heating value is highest of eucalyptus leaves. As was expected the Sulpher content is NIL for all the biomass residues.

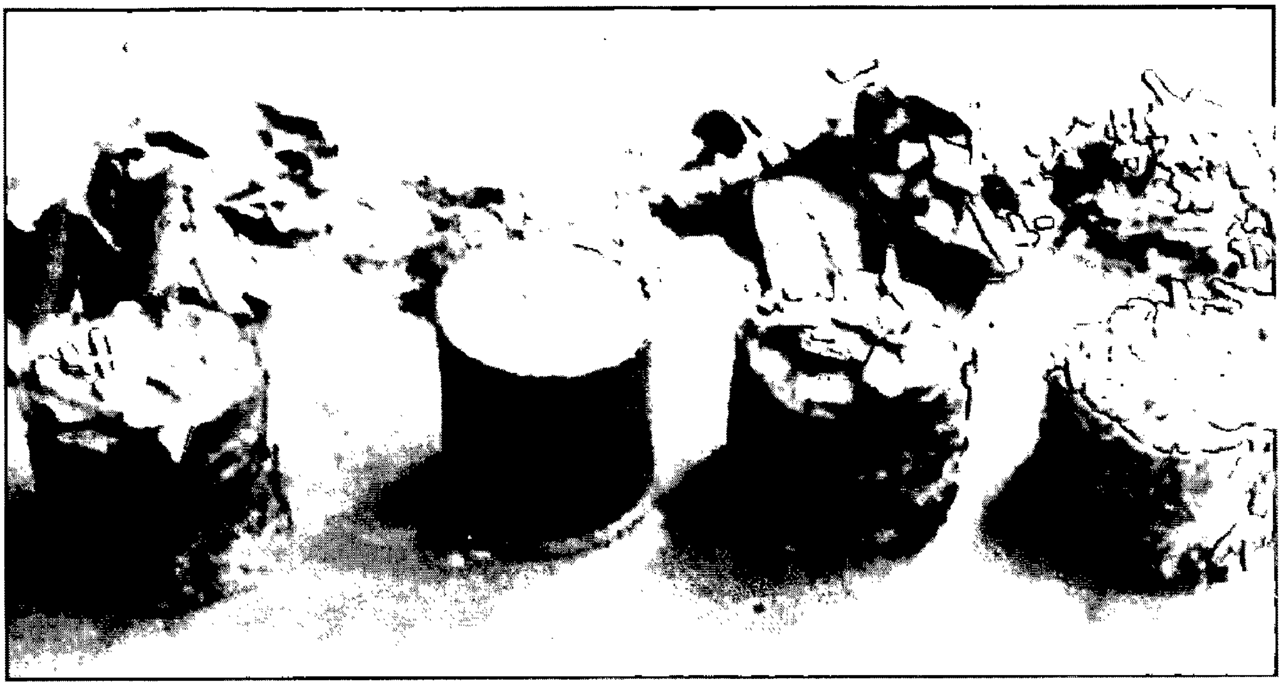


Fig 4.1 Biomass Residues and Corresponding Briquettes

Fig 4.1 shows briquettes of eucalyptus leaves, sawdust, mango leaves and wheat straw with corresponding material used, from left to right. All shown briquettes were prepared under 100 MPa compaction pressure and all materials are shown as they were received from fields and sawmills.

4.2 Effect of Pressure Variation

Figure 4.2 shows the effects of compaction pressure for both mango and eucalyptus leaves for 0-sec pressure holding times on the density of the logs at two different moisture contents. The curves for all the cases have the same pattern: the density of the logs increased with the compaction pressure. The figure also shows that the leaves with 7.90% moisture produced stronger (denser) logs than that with 11.16% moisture.

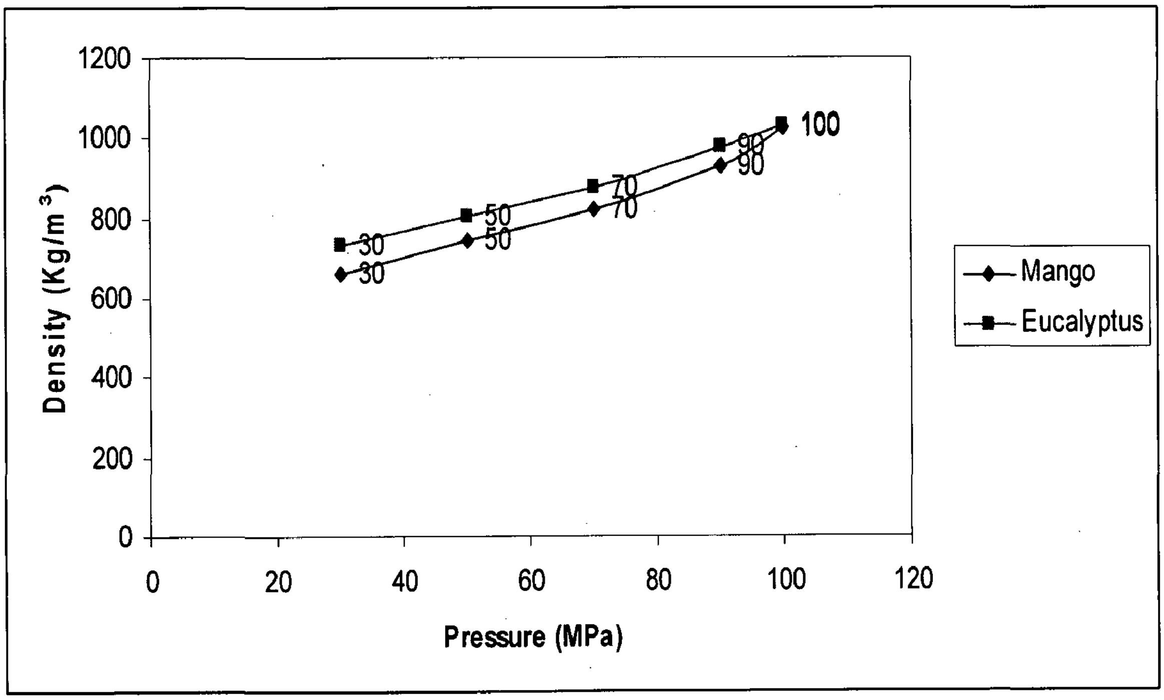


Fig 4.2 Density vs. pressure for briquettes made of mango and eucalyptus leaves (holding time 0 sec)

4.3 Effect of Holding Time

The effect of holding time variation during compaction was studied extensively using sawdust at pressure of 100 MPa and at different holding times ranging from 0 to 60 s. Fig. 4.3 shows the variation of the densities of the logs with the pressure holding time. The logs were made of sawdust with 11.25% moisture content and compacted at 100 MPa pressure. The densities of the logs were measured both 2 min and 24 h after ejection from the mold. It can be seen that a short holding time increased the density of the logs slightly. A 10-s holding time could result in a 14% increase in log density. When the holding time was longer than 20 s, the effect diminished significantly. The two curves in the figure indicate that the initial densities (measured at 2 min after ejection) of the logs were always higher than the density after 24 h. This means that the logs have expanded considerably in 24 h. The two curves in Fig. 4.3 have similar shape. This means that holding time has little effect on the expansion rate of the logs.

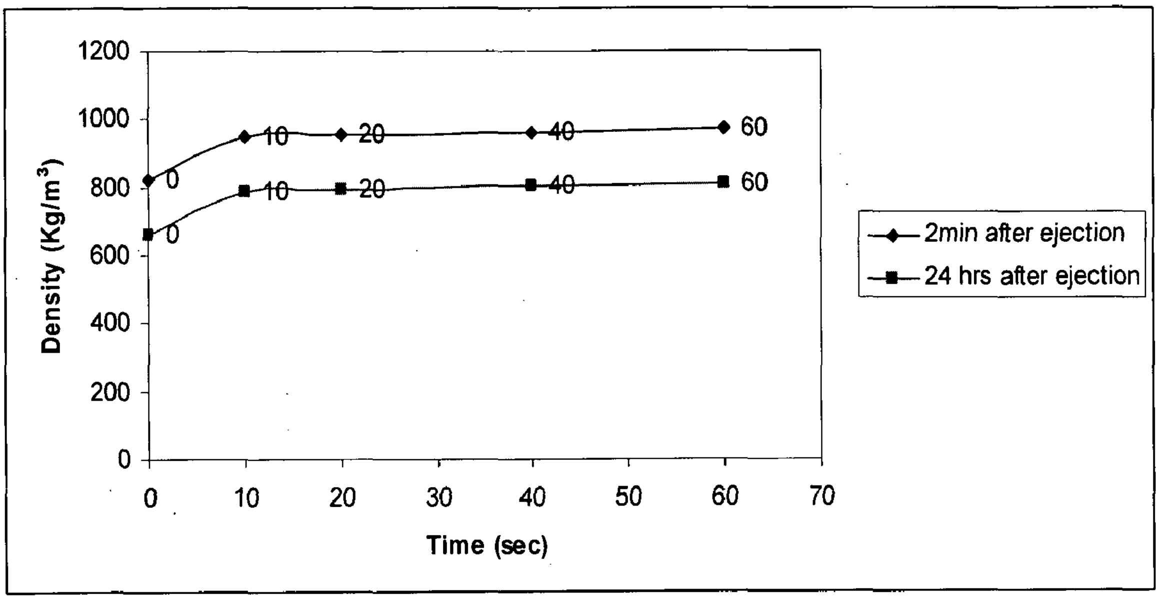


Fig 4.3 Density vs. holding time using mango leaves with a compaction pressure of 100 MPa

4.4 Effect of Pressure Application Rate

Compaction speed or pressure application rate is an important parameter for compaction machine design. Higher production rates of the machine require faster compaction speeds. The effect of compaction speed was studied for mango leaves by examining the differences in densities of logs compacted at different speeds. The ultimate pressure for compaction of the logs was 100 MPa. The compaction speed was varied from 0.2 to 3.0 MPa/s. The moisture content of the mango leaves was 8.6%. The variation of the dry densities of the logs (measured 2 min. after ejection) with the compaction speed is plotted in Fig. 4.4. It can be seen that when the compaction speed was lower than 3 MPa/s, the density of the logs decreased with the increase in compaction speed. It can be seen from fig. that the curve goes flatter reaching 3 MPa/s.

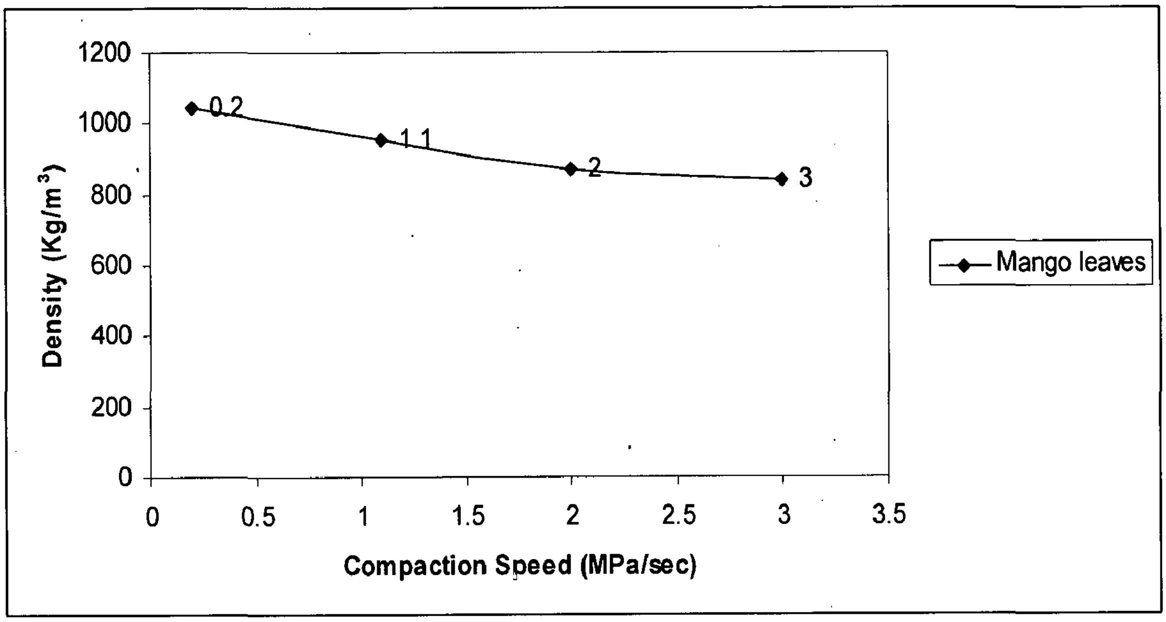


Fig 4.4 Density vs. compaction speed variation for briquettes made from mango leaves at 100 MPa compaction pressure and 8.6% moisture content

4.5 Effect of moisture content

The effect of moisture content on the properties of the logs was studied extensively for sawdust. Fig. 4.5 shows densities of the logs made at 100 MPa with 10 sec holding time as a function of the moisture content. The density was measured 2 min after ejection from the mold. When the moisture was higher than 13%, the logs had low densities and were easy to disintegrate when subjected to small handling forces. At about 4% moisture content, logs with the highest density were produced. However, the logs with initial moisture contents equal or less than 4% could not maintain good quality for long. They tended to absorb moisture from the air and expanded significantly, becoming fragile in a few days. Logs made at around 8% moisture content had both high-density and good long-term performance. Considering both the density and the long-term performance of the logs, moisture content of 5-12% is the appropriate range for producing good-quality logs of all the tested materials. The optimum moisture content is in the neighborhood of

8%. This optimum moisture content can be achieved within three days by indoor natural drying of the materials with initial moisture content over 40%.

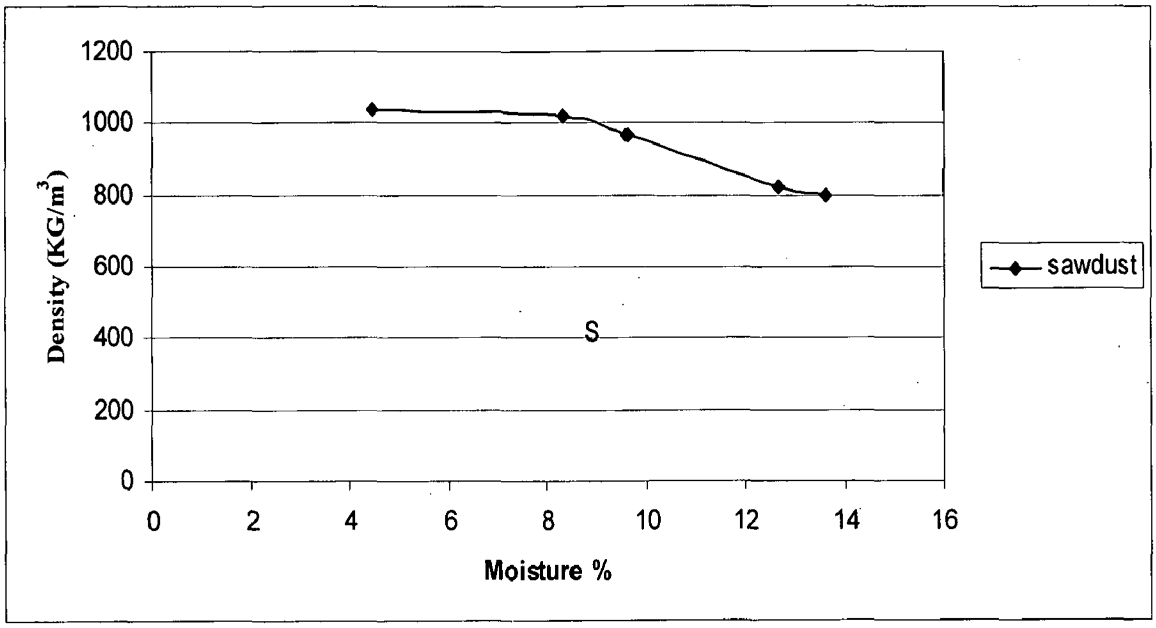


Fig 4.5 Density vs. moisture (%) for logs made of sawdust at 100 MPa and holding time of 10 sec

4.6 Effect of Particle Size

The effect of particle size over densities of produced briquettes can be seen from fig. Experiment was done on sawdust having 9.63% moisture at pressure of 70MPa and 10 sec holding time. Material used in this test was sieved to four different sizes with standard sieves. Four different sizes were –

1000 – 1200 μm

850 – 1000 μm

550 – 850 μm

150 – 250 μm

It is seen that smaller particle size sample produces higher density log. Sawdust with 150-250 μm size produces highest densities as well as they are good at handling external forces. As the size increases the density of logs decreases.

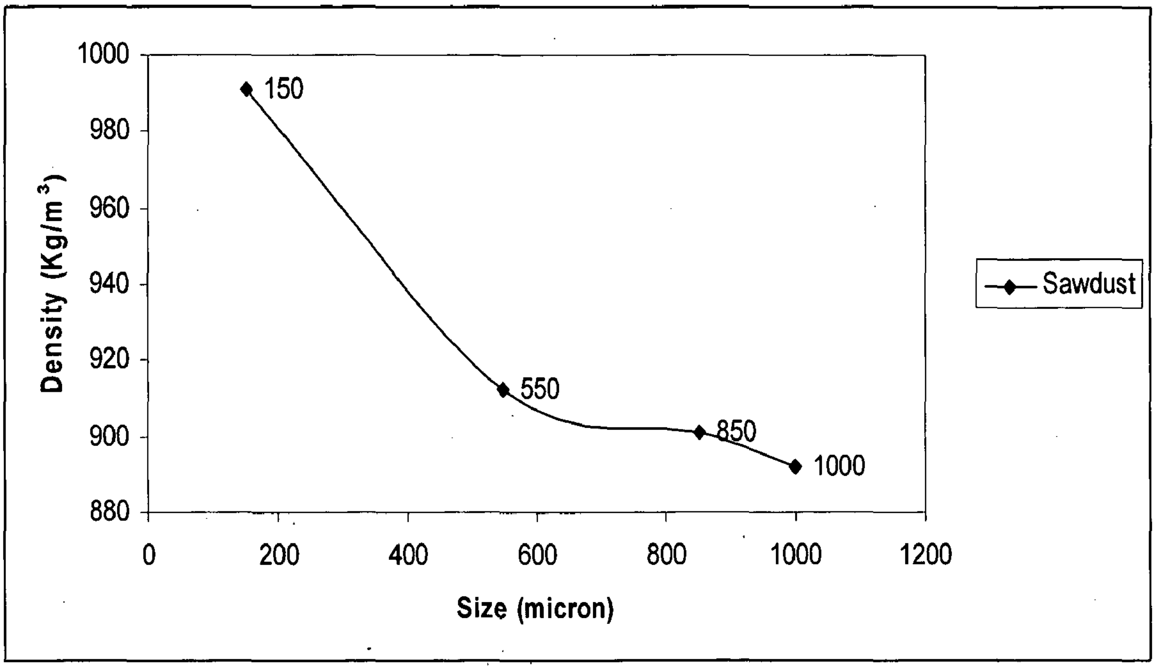


Fig 4.6 Effect of size of biomass residue (sawdust) on density of briquettes produced at 9.63% moisture and compaction pressure of 70 MPa

4.7 Impact Resistance Test

The impact resistance was tested as explained in experimental part by adapting the ASTM method D440-86 of drop shatter for coal. The logs were dropped twice for 1.83m onto a concrete floor. An impact resistance index (IRI) introduced by Richards was used to evaluate the impact resistance of the logs. The IRI is calculated from IRI= (100*N)/n, where N is the number of drops, and n is the total number of pieces after N drops. Because two drops were used as standard, the number of drops N in the above equation is always 2, and maximum value of IRI is 200. When the number of pieces was counted in a test, the small pieces that weigh less than 5% of the initial weight of the log was not included in the calculation of the IRI. After the first drop, all the pieces that weigh less than 5% of the original weight of the log were not collected and dropped for the second time. Impact resistance index along with other properties of the biomass residues tested in this study are listed in the table 4.3 below –

Table 4.3 - Properties of the logs made of different woody materials under different pressure and moisture conditions (as received basis)

Material	Moisture (%)	Compaction Pressure (MPa)	Dry density (g/cm3)	Impact resistance Index
Mango Leaves	8.6	100	1.0277	133
		90	0.9313	100
		70	0.8202	80
		50	0.7421	40
		30	0.6602	<20
	11.16	100	0.9474	100
Eucalyptus Leaves	7.90	100	1.0345	200
		90	0.9793	200
		70	0.8752	133
		50	0.8064	100
		30	0.7300	40
Sawdust	9.63	100	0.9646	133
		70	0.9010	133
	8.34	100	1.0388	133
	12.68	100	0.8214	57
Wheat Straw	8.09	70	0.5825	200
	7.23	70	0.5227	200

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Preliminary Experiments

Preliminary experiments were conducted to determine the physicomechanical, physicochemical and thermo chemical properties of biomass materials relevant to their uses in experiment. The physicomechanical properties include bulk density and particle size. Physicochemical properties include moisture, volatile matter, fixed carbon, ash content and chemical composition (C, H, O and N) of residues. The thermo chemical properties include the heating values.

5.1.1 Physicomechanical Properties

1. The bulk densities of four biomass materials including mango leaves, eucalyptus leaves, sawdust and wheat straw were in the range of 75 to193 kg/ m^3.
2. The physical shapes and sizes of the biomass materials were complex. In the absence of suitable established method of determining their sizes, the sieve analysis has been adopted.

5.1.2 Physicochemical Properties

1. The average volatile matter contents of the biomass materials were in the range of 71.30 to 86.51 with wheat straw having the lowest value and sawdust having the maximum value.
2. The ash content of the biomass materials was found to be 13.36% for mangoleaves, 8.90% for wheat straw, 7.29% for eucalyptus leaves and 2.84% for mango sawdust. These values are comparable to reported values.

3. The nitrogenous compound of the biomass materials varied from 0.28% to 1.069%. These are very low concentrations and therefore the biomass materials used in this study are environmentally good fuels.

5.1.3 Thermo chemical Properties

1. The higher heating values of the biomass materials were in the range of 17.51 MJ/Kg (wheat straw) to 19.42 MJ/Kg (eucalyptus leaves).
2. In general, the heating values of the biomass materials were more than half of that of coal found in India. This factor makes them considered as important potential source of energy.

5.2 Materials for Compaction

As far as materials are concerned sawdust comes out to be the best material for compaction. At 70 MPa it gives better densities as well as better performance over wheat straw, mango and eucalyptus leaves. Among leaves eucalyptus is a better option as it has high heating values and it gives better logs than mango leaves at every pressure employed in this study. Wheat straw produces logs which are stronger while handling but logs produced suffer from low densities at every compaction pressure. Also it has the lowest heating values among the materials used.

5.3 Densification of Biomass

Bulk densities of the biomass used in this study were in the range of 75 to193 kg/ m^3 before densification and after densification densities are in range of 730 to 1044.2 kg/ m^3, which are about 9- 10 times higher than the previous ones. Biomass in the form of briquettes is readily much more economical for transportation and burning operations.

Biomass is available in plenty in India and after densification its importance can not be neglected in any way.

This study suggests that briquettes made at around 8% moisture content had both high-density and good long-term performance. Considering both the density and the long-term performance of the logs, moisture content of 5-12% is the appropriate range for producing good-quality logs of all the tested materials. While, optimum moisture content is around 8%. This optimum moisture content can be achieved within three days by indoor natural drying of the materials with initial moisture content over 40%. Also, the compaction rate affects both the densities and production rate of briquettes. So it is an important factor to be considered. The rate of 2 MPa/sec is a better choice for optimum production and quality of logs too. A 10 sec holding time can add further to the quality of logs improving densities at same pressure as well as their long terms performances in handling of logs. Crushing of biomass has to be done before briquetting for better compaction. Optimum pressure that is found in this study was 70 MPa. At this pressure logs formed have good densities along with better performance while transportation and handling. Also it is not a quite high pressure to attain which requires making bulky machines for compaction.

5.4 Recommendations

In this dissertation work a number of consideration come out those may be of interest in the progress of work in the field of densification of biomass.

- An exhaustive data base providing the availability of biomass from forest, agriculture and agro industries available in India should be developed.
- All the physicomechanical, physicochemical and thermo chemical properties of biomass should be determined to asses their suitability for densification.
- Developed densification machines should be tested with different biomass.
- Efforts must be made by the government to motivate this industry.
- Special binders have been developed by some foreign industries, which facilitates the compaction process can add to better quality of briquettes in India also.

- Biomass preheating should be tested at the developed densification plants for optimization of process.
- Industrial area should be planned in a way that transportation cost to be low. Industries requiring briquettes can have their own plantation area and a briquetting plant also.
- An economic evaluation of the briquetting plant may be undertaken.

REFERENCES

Anon. Annual Books of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA 19103 (1993).

Badger, Phillip C. and Fransham, Peter *Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs—A preliminary assessment, Biomass and Bioenergy*, vol. 30 (2006) pp. 321–325

Bhattacharya, S.C., Bhatia, R., Islam, M.N., and Shah, N., *Densified Biomass in Thailand: Potential, Status and Problems,* Biomass, vol. 255 (1985) pp. 0144-4565

Cabe, W.L. and Smith, J.C. *Unit operations in chemical engineering*, pp943, (1956).

Chin, Ooi Chin, Siddiqui, Kamal M. *Characteristics of some biomass briquettes prepared under modest die pressures* ,Biomass and Bioenergy , vol.18 (2000) pp.223±228

Debdoubi , A , amarti , A. El, E. Colacio , *Production of fuel briquettes from Esparto partially pyrolyzed*, Energy Conversion and Management, vol. 46 (2005) pp.1877–1884

Felkera, Peter, McLauchlanb, Robert A. , Conkeyb, Andrew, Brownc, Stan, *Case study: Development of a swath harvester for small diameter (<10 cm) woody vegetation,* Biomass and Bioenergy, vol.17 (1999) pp.1±17

Gangawati, P. B., Prasad, B. and Mishra, I. M., "Fluidization characteristics of agricultural and forestry residue type biomass for thermal gasification". National Seminar on Future Trends in Mech. And Industrial Engg., IIT Roorkee, Roorkee and Institution of Engineering (India) Roorkee Sept. 29-30, 651-656 (2000).

Granada , E. , Gonzalez , L.M. Lopez, Mıguez , J.L. , Moran , J. *Fuel lignocellulosic briquettes, die design and products study*, Renewable Energy, vol. 27 (2002) pp.561–573

Grover, P.D. & Mishra, S.K. *BIOMASS BRIQUETTING: TECHNOLOGY AND PRACTICES*, FAO Regional Wood Energy Development Program in Asia, (1996).

Iyer, P. V. R., Rao, T. R., Grover, P. D., and Singh, N.P.(Eds), "Biomass thermo-chemical characterization" second edition Biomass Gasifier Action Research Centre, Chemical Engineering Department, IIT Delhi (1997).

Li, Yadong , Liu, Henry, *High-pressure densification of wood residues to form an upgraded fuel,* Biomass and Bioenergy ,vol.19 (2000) pp.177-186

Mazzu, Angelo *Study, design and prototyping of an animal traction cam based press for biomass densification,* Mechanism and Machine Theory, vol.42 (2007) pp. 652–667.

Moral, M., Ali, Nawsher *Briquetting of Biomass in Bangladesh*; Proceeding of World Renewable Energy Congress, vol. VI (WREC 2000) pp. 2402-2405

Pelt, T. Van *"Maize, Soybean, and Alfalfa Biomass Densification",* Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, Manuscript EE 03 002. May, 2003

Reece, F.N., *Temperature, Pressure and time relationships in forming dense hay wafers, Trans*, A.S.A.E., 9, 749, (1966).

Samaniegoa, M.R. Pela ez, Perezc, M. Garcia, Corteza, L.B., Rosillo, F., Mesae, J. *Improvements of Brazilian carbonization industry as part of the creation of a global biomass economy*, Renewable and Sustainable Energy Reviews, (2006).

Sokhansanj, S. and Turhollow. A. F. Baseline *Cost for Corn Stover Collection,* Applied Engineering in Agriculture, vol. 18 (2003) pp. 525-530

Sudhagar Mani, Lope G. Tabil , Shahab Sokhansanj, *Specific energy requirement for compacting corn stover*, Bioresource Technology ,vol.97 (2006) pp.1420–1426

Tavares, J.L.M. , Ortiz, L. , Granada, E. , Viarc, F.P. *Feasibility study of energy use for densificated lignocellulosic material (briquettes),* Fuel, vol.79 (2000) pp. 1229–1237

"Thermal Data for Natural and Synthetic Fuels" (Gaur and Reed, Dekker, 1998)

Yuvaraj, N, Babu, Dinesh *Biomass densification - a solid (fuel) solution*, TERI Newswire, 7(23), (2001)