Design of a Bagasse Charcoal Briquette-making Device for Use in Haiti

by

Jessica Vechakul

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the
Degree of

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Signature of Author...
Department of Mechanical Engineering
May 6, 2005

Certified by...
Dr. David Wallace
Associate Professor of Mechanical Engineering
Thesis Supervisor

Certified by...
Amy Smith
Edgerton Center Instructor
Thesis Supervisor

Accepted by...
Professor Ernest G. Cravalho
Chairman of the Undergraduate Thesis Committee

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Submitted to the Department of Mechanical Engineering
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ABSTRACT

Charcoal made from bagasse, the fibrous remains of sugarcane production, has the potential to serve as an alternate cooking fuel in Haiti, where the reliance on wood has led to severe deforestation. Current production methods for charcoal briquettes range from laborious hand-forming to expensive industrial machinery. Thus, there is a need for an intermediate technology.

This thesis describes the development of an affordable, locally manufacturable, briquette-making device that produces higher quality charcoal than hand-formed briquettes. The device is intended for small-scale briquette production in rural villages to supply charcoal to local markets. Since little is known about the materials properties and characteristics of bagasse charcoal, several production possibilities have been considered and evaluated. The most important finding during this process was that impact loading is more effective than steady compression because the required forces are not easily achievable by simple mechanisms.

The final concept is a pile driver press, which uses a hammer to strike a metal piston and drive it into a tall channel to compact a column of charcoal. Several briquettes can be formed at once by using thin spacers to separate sections of charcoal within the channel. A single channel prototype has been constructed as a proof-of-concept model. Cylindrical briquettes formed using this prototype had an average density of 0.29 g/cm^3, and an average radial failure load of 390 N. Commercially available Kingsford charcoal had an average density of 0.80 g/cm^3 and the compressive strength was 590 N. Although the hammered briquettes were not as strong as commercial charcoal available in the United States, they should still be able to withstand the loads imposed during transport in Haiti. More tests and refinement of the design are needed, but overall the pile driver press has great potential to eventually be adopted in Haiti as a small-scale briquette-making device.

Thesis Supervisor: Dr. David Wallace
Title: Associate Professor of Mechanical Engineering

Thesis Supervisor: Amy Smith
Title: Edgerton Center Instructor

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Background

1.1.1. Haiti and Bagasse Charcoal

Haiti is in dire need of an alternative fuel source for cooking. Wood and wood charcoal are the primary cooking fuels in Haiti, but more than 97% of the country is deforested (Smith & Frayne, 2003). Inherently expensive, imported fuels are not a viable option, especially in rural areas where poor distribution channels make them unavailable or unreliable resources. Thus, efforts have been made to find a local source of affordable alternative fuel.

A prime alternative fuel candidate in Haiti is bagasse, the fibrous remains of sugarcane processing. It is abundant in many Haitian villages, where sugar refining is a significant portion of the economy (Kamimoto, 2005). Since bagasse has little or no nutritional value and cannot be fed to cattle, it typically accumulates as agricultural waste until it is disposed of by incineration.

In third world countries, where resources are scarce and the recycling and reuse of resources are prime concerns, turning agricultural waste into charcoal addresses several problems. For instance, it slows down deforestation since it reduces the need to cut down trees for wood fuel. Using agricultural wastes also finds use for substances that would otherwise have no value.

Although up to half of the initial energy content may be lost during the carbonization process of creating charcoal, it is not suitable to directly burn the bagasse indoors because its smoke releases harmful particulates that have been known to cause fatal respiratory illnesses (Smith & Frayne, 2003). The energy density of charcoal is higher than wood, so less mass of fuel is required to provide the same amount of heat for cooking. The transportation weight is especially important when a bag of solid fuel could weigh as much as 50 lbs, and the last leg of distribution may be traveling several miles by foot from market to home (Kamimoto, 2005).

1.1.2. Prior Work

Amy Smith, an instructor at MIT who has designed several appropriate technologies for developing countries, has led the effort to develop a method to convert bagasse into charcoal (Smith & Frayne, 2003). In 2003, Smith and several MIT students refined the process by which bagasse is carbonized in a steel drum, crushed into fines, and bound with a locally available starch called cassava to hand-form bagasse charcoal briquettes. "Fuel From the Fields" documents their work and contains preliminary field test data, indicating that the bagasse charcoal briquettes could potentially produce heat comparable to conventional wood charcoal (Smith & Frayne, 2003).

Although the prospects of bagasse charcoal seem promising, there are still several aspects related to briquette production and use that require more research for improvement. The current methods of agricultural waste charcoal production are at the opposite extremes of manual labor-intensive techniques and expensive industrial processes (Smith & Frayne, 2003).

Hand-formation of briquettes is labor intensive and time-consuming. Moreover, since the briquettes are not adequately compacted, they disintegrate before they are burned completely, leaving unreleased energy in the ashes. They also crumble into pieces with degraded heating quality during transportation over rugged terrain and rural roads (Ing, 2003).

In the charcoal industries of the third world, devices of several kinds have been developed for forming charcoal briquettes (Chardust, 2004). However, these machines are inappropriate for use at the village level. They are manufactured for mass production and large volume sales to well-populated areas and industrial centers. The amount of charcoal they are capable of producing is much more than is actually needed to supply rural markets that serve smaller, more disperse villages. These machines are also cost much more than village-level entrepreneurs can afford. They rely on mechanisms that require resources, such as extrusion screws, thrust bearings, or refined fuels, which are not readily available in villages.

In between the extremes of manual production and industrial technologies, there exist appropriate technologies for villages. Appropriate technologies should be culturally acceptable and sustainable in the community in which it is introduced. This typically means that the technology should be affordable, made with locally available materials, locally produced and maintained, and supportive of the local economy.

From September to December 2004, a team of students developed a briquette-producing screw extruder for MIT's 2.009 Product Engineering Process class (Ang, 2005). Although the Haitians reacted positively to the extruded charcoal samples, the production cost of the screw extruder was estimated to be about US$100. Since the gross national income of Haiti was estimated to be US$380 in 2003 (CIDA, 2005), it is presumed that only wealthy entrepreneurs or those eligible for microfinance loans would have access to the capital cost necessary to start charcoal production (Kamimoto, 2005).

1.2. Objectives

It is the goal of this thesis to develop an affordable device for producing briquettes at a small scale in Haitian villages. It is intended to be a simple device that can stimulate the local economy by enabling an entrepreneur to produce charcoal in smaller volumes at the village level, thereby eliminating the need for a middle man and reducing the cost of transportation in the product price. To be feasible and sustainable, the briquette-making device needs to be affordable, locally manufacturable with readily available materials, easily maintained, and most importantly, able to satisfy the needs of the community.

This thesis involves three main phases: (1) selection of design criteria, (2) creation of press mock-ups to qualitatively evaluate initial concepts, and (3) the design and testing of a prototype for a briquette-making device intended for construction with materials and fabrication techniques locally available in Haiti.

1.2.1. Selecting Design Criteria

In order to evaluate designs fairly and objectively with Pugh charts, the following set of design criteria was selected:

- Cost
- Manufacturability
- Briquette quality
- Force Multiplication
- Ease of Operation
- Production Rate
- Maintenance
- Risk of Misuse
- Intuitive mechanism
- Simplicity of design
- Reliability
- Ease of repair

1.2.2. Initial Press Mock-ups

Industrial machines make briquettes from agricultural wastes in several different shapes and sizes, using methods as different as extrusion and compression molding (Chardust, 2004). Since so little is known about bagasse charcoal, functional mock-ups were created to qualitatively evaluate a few different briquette production possibilities. The most promising mock-up embodied the concept of compression molding in series and was demonstrated in Haiti so that user feedback could be gathered regarding the appropriateness of the design and the desirability of the briquettes produced. The results of these mock-up trials helped to determine reasonable briquette size and shape, and identified impact loading as a promising mode of formation.

1.2.3. Design and Testing of a Briquetting Device

Based on the findings of the mock-up trials, a few basic impact loading models were built and used to produce sample briquettes to determine the best embodiment of the design. The ease-of-operation, projected local manufacturability, and comparative evaluation of the compressive strength of the briquettes produced identified a hammer-impacted piston and side-loading channel as the most promising design. A proof-of-concept model was built with a single channel, but another prototype with multiple channels to enhance productivity will be built and evaluated in Haiti.

Although the burn properties of the briquette are also of critical importance, the structural strength of the briquette was the first guideline in evaluating various production methods. The structural strength of the briquette is influenced by how well it is compacted, and determines whether it is strong enough to sustain transportation. Standard procedures for the physical testing of fuel briquettes to determine material properties included compressive strength as well as impact, abrasion, and water resistance (Richards, 1990). In order to simplify the testing and allow for more concentration on the design, the briquettes produced by the prototypes were tested only for compression strength. Further testing may be considered once briquettes pass this initial criterion of adequate compressive strength.

1.3. Summary of Results

1.3.1. The Final Design

Steady compression mechanisms were not feasible to produce the required magnitude of force so impact-loading mechanisms were pursued. The final design concept emulates the mechanism of a construction pile driver in which a heavy weight is used to strike a metal stake, driving it into the ground. For the pile driver press shown in Fig. 1.1a and b, a hammer is used to strike a metal piston, forcing it downward within a tall, hollow channel to compress a column of charcoal. Thin metal spacers divide the charcoal column into four different layers so that four individually molded briquettes are produced per column per compression cycle. To expedite filling and unloading of briquettes, the channel can be placed on its side and opened lengthwise to provide a large access area. An optional design feature is a center shaft that can be placed in the channel before compression to produce briquettes with central holes. Although tests have been conducted to demonstrate the feasibility of this concept for a single square channel, the implementation of the final design with multiple channels will be accomplished in Haiti.

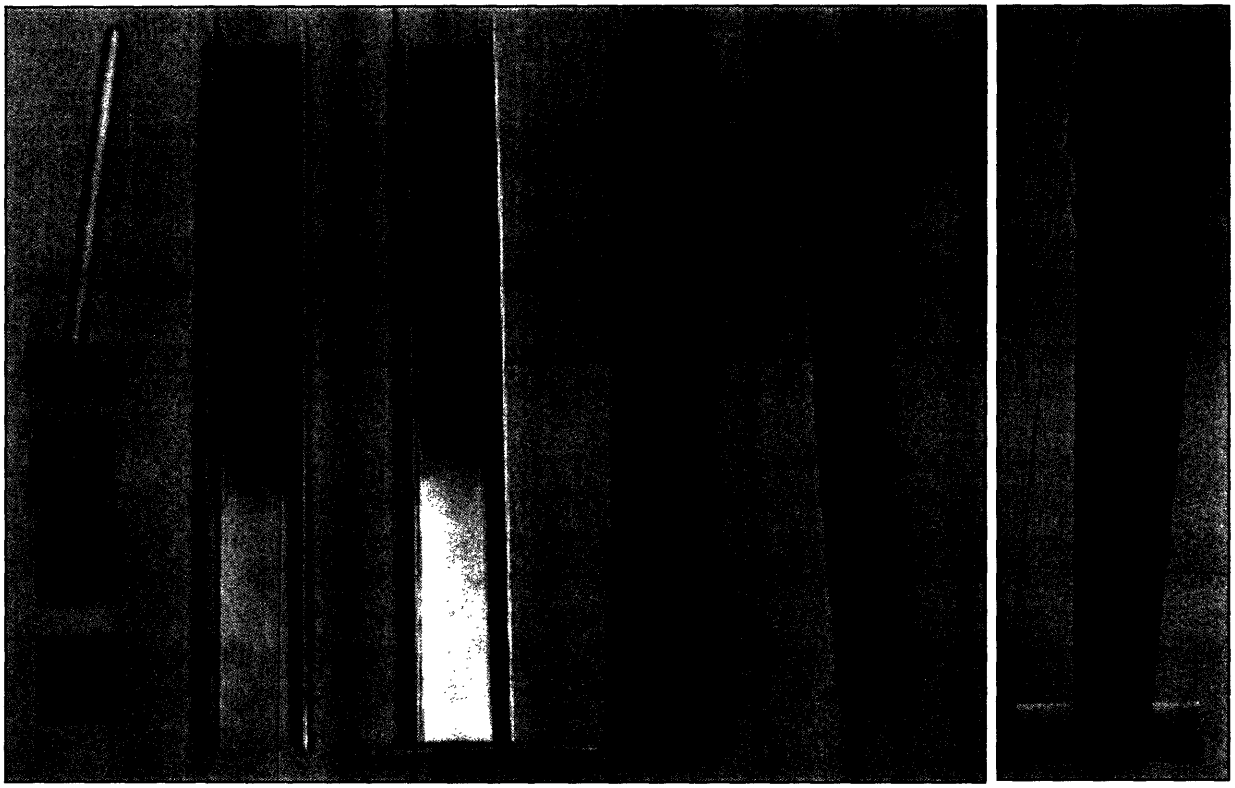


Fig.1.1a. Final design: central shaft, spacers, channel halves, piston, hammer. 1.1b. Assembled.

1.3.2. Work Done

Although not much quantitative data is known about the bagasse charcoal, it was possible to design, test, and evaluate concepts qualitatively. Three initial press concepts were tested with PVC mock-ups. These trials showed that upper-body strength was not sufficient to generate enough force to extrude the charcoal through a reduced cross-section and that compression molded briquettes were stronger than those that had been cut down to size. The most promising concept was in-series formation, which was achievable by stacking layers of charcoal between spacers in a column that could be compressed with one stroke to form several individual briquettes simultaneously.

Several designs were considered that would enable briquettes to be formed in series. However, the actual force produced by the 2.009 extruder was estimated to be in the range of 3-6 kN, and therefore all concepts relying on steady compression with body weight were eliminated. Impact-loading in the form of a pile-driver design proved to be the most promising. Single-channel prototypes that could produce up to four cylindrical or box-shaped briquettes per compression cycle were made and tested. In June 2005, a multi-channel prototype will be demonstrated, adapted to local materials, and trial tested for user feedback in Haiti.

2. SELECTING DESIGN CRITERIA

2.1. Haitian Input

The first step was to confer with the target users about what they expected in terms of a briquette-making device or a suitable briquette. In January 2005, Amy Smith brought some samples of 2.009 extruded charcoal to show community partners in Fonds de Blancs in Haiti, and gauge their response to the possibility of producing briquettes with a device rather than by hand.

Fig. 2.1a. Haitian charcoal-maker.

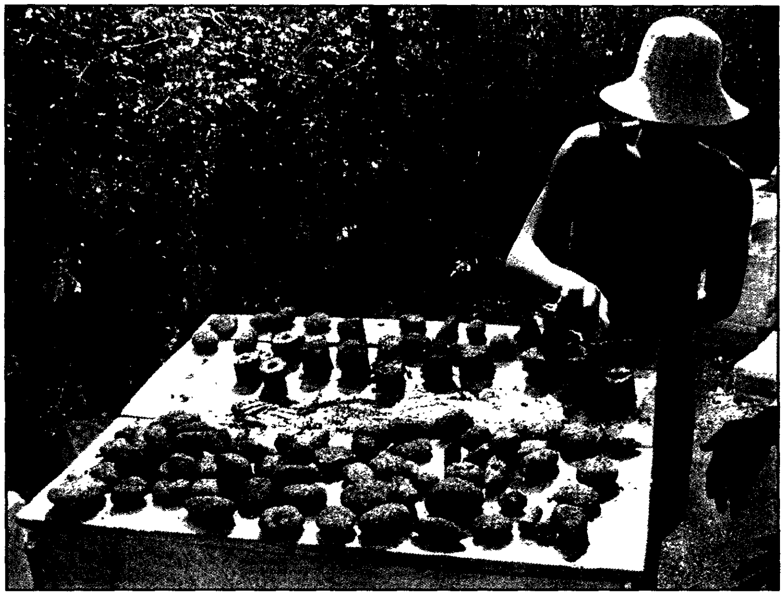


Fig.2.1b. Charcoal briquettes curing in the sun in Haiti.

2.2. Datum selection

The Haitians were impressed with the 2.009 charcoal, commenting especially on how its material density was significantly higher than that of any briquette they had previously seen. Based on their positive reaction, it was decided that the optimal press should be able to produce briquettes with properties similar to that of the 2.009 extruded charcoal. The 2.009 charcoal extruder was thus selected to be the datum against which all other designs are to be measured.

2.3. Description of design criteria

The criteria described in Table 2.1 on the following page were selected with the awareness that the briquette-making device should be an appropriate technology. It should be affordable, locally manufactured and repairable with readily available materials. It should also be an elegant solution that meets the needs of the target users.

Table. 2.1: Description of design criteria

Design Criteria	Description
Cost	Designs with that require fewer parts and simpler manufacturing methods will be lower in the cost.
Manufacturability	Designs that require more manufacturing steps, production time, and complex machinery for construction rate lower in the manufacturability.
Briquette quality	Possible press designs will be evaluated based on the likelihood that they will be able to produce briquettes of adequate quality, regarding material density, compressive strength, and energy density.
Force Multiplication	The effectiveness with which the device utilizes the force applied by the user to compress the briquettes will determine its degree of efficient force utilization.
Ease of Operation	The amount of effort required for operation and the number of operational steps per cycle will be considering in evaluating a design's ease of operation.
Production Rate	The number of briquettes that can be produced per operational cycle and the time it takes to complete each cycle will determine the production rate.
Maintenance	Designs with fewer moving parts will be less likely to wear or break, so they should be more easily maintained.
Intuitive mechanism	To encourage the continuation of the spirit of co-creation with the Haitian community partners, the intuitiveness of mechanisms will also be an important criterion for the design of the press
Simplicity of design	As with any design, the most elegant solution is preferable. A simpler design will be less likely to fail and will probably require less maintenance.
Reliability	Materials, time, and money are wasted due to equipment failures or product flaws. The performance of the press should be consistent.
Ease of repair	All things eventually break. When the press breaks, replacement parts should be affordable and locally available. The press should be easily serviceable by the user or local repairman.
Risk of Misuse	The likelihood that someone will use the press incorrectly or for any purpose other than that for which it was created with determine the risk of misuse. Presses that have loose parts or valuable components will be considered to be higher in risk because the press may be misused, and it will no longer be effective as a briquette-making device.

3. INITIAL PRESS MOCK-UPS

Before any experiments were done to determine any material properties for the bagasse charcoal, three PVC mock-ups were built and tested to qualitatively evaluate the potential of a few different production processes. PVC was chosen as a prototyping material because it is available in Haiti, easy to machine and join, light-weight for transportability, and available in similar component shape and sizes as steel. Future prototypes may also be constructed from PVC, but the final model is expected to be primarily composed of welded steel.

3.1. Comparative Evaluation of Functional Mock-ups

Although the 2.009 screw extruder was chosen as a datum, it was deemed sufficient to do a comparative evaluation of just the three mock-ups against each other with regards to the criteria described in Section 2. In the Pugh chart shown in Table 3.1, each mock-up received a score of -, 0, or + for each criteria depending upon whether it was the worst, mediocre, or best mock-up of the three. After the Pugh chart is a more detailed description of the different mock-ups and their advantages and disadvantages.

From this evaluation, the clover press was found to be the most promising concept because of its simplicity and ability to form several briquettes without requiring cutting of an extruded mass. Its underlying principle is in-series formation, in which the briquettes are stacked in layers within the channel and formed individually by compression molding with the user's body weight as the driving force.

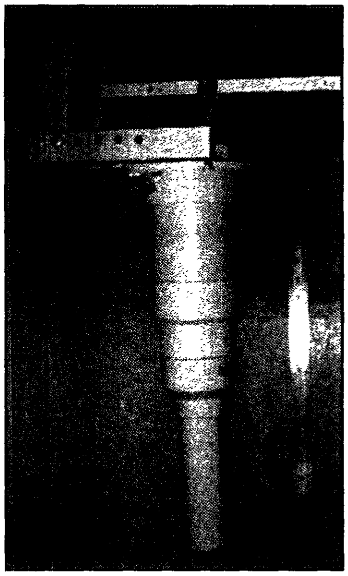


Fig. 3.1a. Lever-arm extruder.

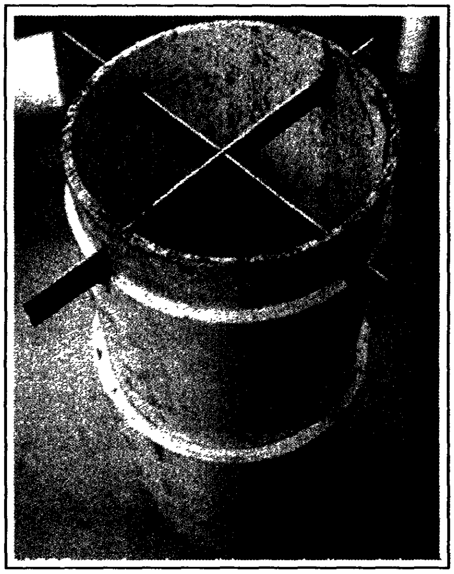


Fig. 3.1b. Exit-blade press.


Fig. 3.1c. Clover Press.

Although not much quantitative data is known about the bagasse charcoal, it was possible to design, test, and evaluate concepts qualitatively. Three initial press concepts were tested with the PVC mock-ups shown in Fig. 3.1: (1) lever-arm extruder, (2) exit-blade press, and (3) clover press. Extrusion through a reduction in cross-sectional area required too much force for a lever-arm mechanism driven with the upper body. Cutting briquettes produced weak surfaces that were more fragile than faces formed directly by molding. In series-formation with the clover press was the most promising concept because charcoal separated into layers by thin spacers would be compressed simultaneously into fully-formed briquettes that required no cutting. Thus, the clover press was deemed to be the best initial mock-up. It produced briquettes of a quality that was in between that of the 2.009 extruded charcoal and that of hand-formed briquettes.


Fig. 3.2a 3"OD extruded briquette

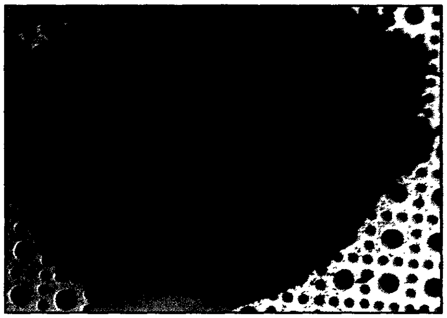


Fig. 3.2b 2"OD clover briquette

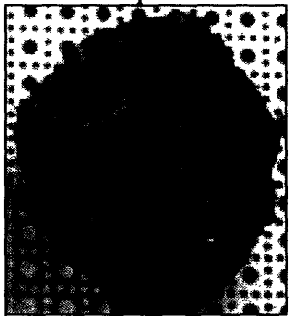


Fig. 3.2c Handformed

Table 3.1: Comparative evaluation of functional mock-ups

Criteria	Lever-Arm Extruder		Exit-Blade Press		Clover Press	
Cost	-	Requires assembly of several small parts and connectors.	+	Low-cost PVC parts need minimal modification. Low-skill required.	0	Requires steel, welding, and skilled worker.
Manufacturability	-	Requires cutting of several parts, and joining with glue, welds, & fasteners.	+	Requires only a large pipe (PVC or steel) with a slit cut in wall for 2 metal blades.	0	Odd geometry requires skillful cutting. Joining, and welding.
Briquette Quality	-	Does not exit press intact. Press did not work as intended.	0	Two cut surfaces in wedge-shaped briquette are weak, and crumble easily.	+	Formed surfaces are strong. Requires line break to separate clover leaves.
Force Utilization	-	Reducer causes large resistant force. Using arms is insufficient to extrude.	0	Blades impede the flow of material. Large cross sectional area reduces force per area.	+	No inhibition of material flow. Applied force is countered only by wall friction.
Ease of Operation	-	Unwieldy to use. Hard to extrude and retract piston. Must cut briquettes.	0	Difficult to force charcoal through blades. Must cut briquettes upon exit.	+	Easy to compress with body weight. Need to insert spacers but no cutting.
Production Rate	-	Extrusion batch process. One log cut into several briquettes.	0	One large log, divided into 4 narrow logs upon exit. Logs cut into several briquettes.	+	Clover leaves break into 3 briquettes with 4 layers of clovers per cycle.
Maintenance	-	Several small moving parts may need repair or replacement.	0	Blades may bend or become dull easily and need replacement.	+	Welded steel ram and channel should be very durable.
Intuitive mechanism	-	Hard to visualize linkage motion and dimensions if modifying lever-arm.	+	Cross-sectional area, shape, column height, & orientation of blades are only variables.	0	Hard to visualize optimal cross-section if changing number of channels or shape.
Simplicity of design	-	Most complex design. Many components. Moving linkages.	+	Simplest design. Only 2 main components.	0	Complex geometry, but only 2 main components.
Reliability	-	Piston often jams. Does not work as intended.	0	Difficulty of extraction depends on quality of charcoal. More fibrous harder to cut.	+	Relatively consistent performance. May vary slightly with user's weight.
Ease of repair	0	May be difficult to obtain proper fasteners. Slow disassembly.	+	Blades easily removed and replaced. No specific parts required.	-	Would have to buy or make entirely new part. Odd geometry hard to replicate.
Risk of Misuse	-	Several parts and linkages may be used as scrap material.	0	Press is easy to disassemble. Channel might be stolen and used as a pipe section.	+	Welded steel. Unlikely to be used for anything else due to its awkward shape.
Total	-12	Complex design. Hard to model compression. Small moving parts require multi-step assembly. Need more force than achievable with lever. Low quality briquettes. Slow production rate.	5	Simplest design with minimal modifications of pre-fabricated components. Large cross-section needs great force. Blades impede compression and degrades briquette quality.	6	Awkward shape requires skilled manufacturing. Welding jigs may facilitate assembly. Durable if made from welded steel. Spacers increase production without degrading surface quality or compression pressure.

3.2. Lever-arm extruder

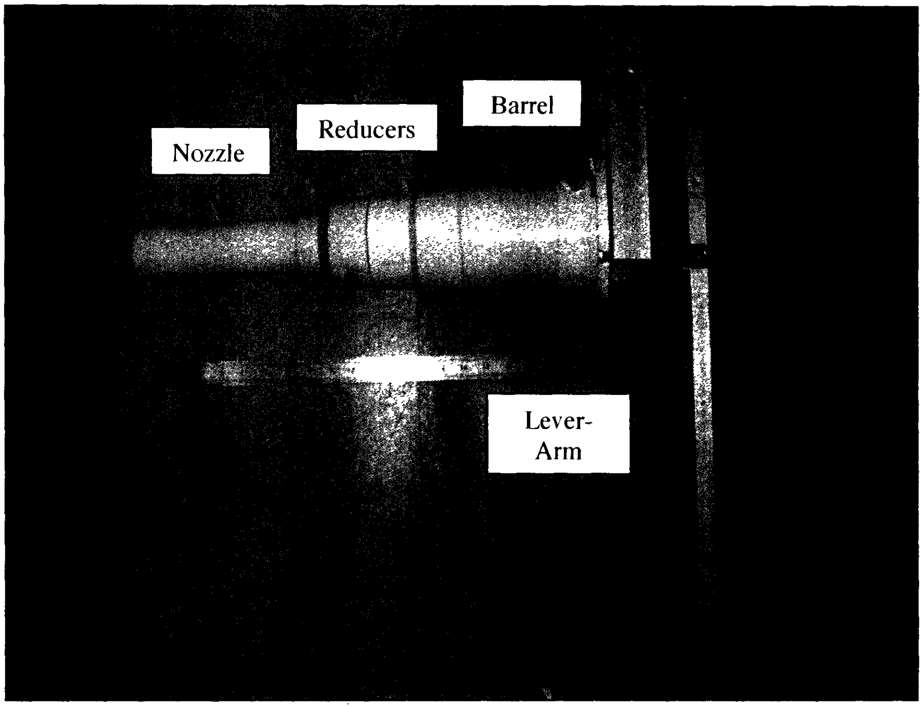


Fig.3.2 Lever-arm extruder

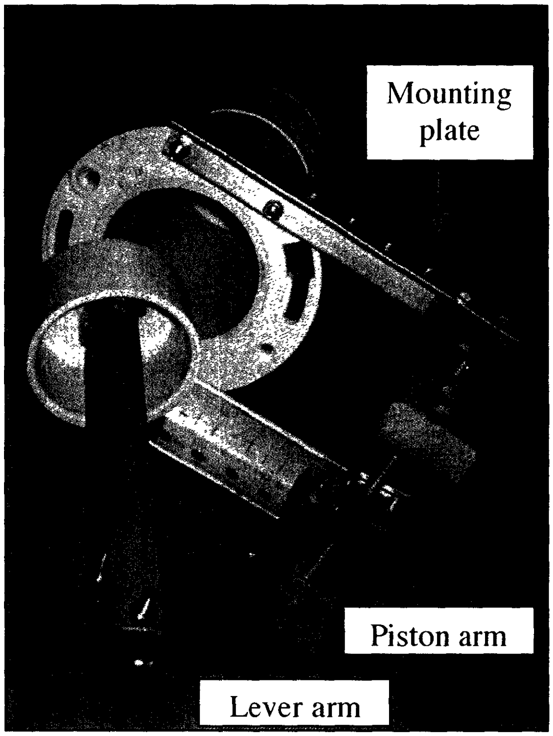


Fig. 3.3a. Design A: Mounted lever arm

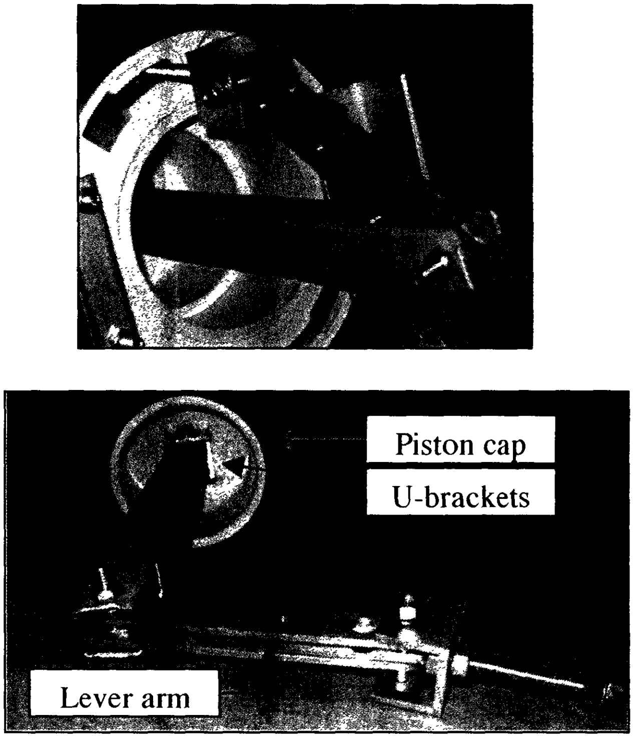


Fig. 3.3b. Design B: Detachable lever arm

3.2.1. Description of design

The lever-arm extruder shown in Fig. 3.2 consisted of a 7" long x 2" diameter nozzle, a 3-to-2-inch angled step reducer, a 4-to-3-inch angled step reducer, a 6" long x 4" diameter barrel, a toilet flange, and a lever-arm mechanism attached to a piston. The piston is the cap for a different grade of 4" diameter PVC pipe than the 4" diameter barrel. As shown in Fig. 3.3, the piston is bolted to a U-bracket bearing made out of 1" aluminum box extrusion. The piston arm is the link between the piston and the 30" lever arm. In design A, the lever arm is connected to the flange of the barrel via two mounting plates (made of 9" long x 1.5" wide right angle extrusions), and two 6" long wooden beams creating an offset pivot point. In design B, the lever arm is connected to a U-bracket, which is attached to a 3" threaded bolt. The bolt may be easily locked to the flange by inserting the bolt head in a slot and rotating to slide the bolt into the narrower end of the slot.

3.2.2. Advantages and disadvantages

Force:

The lever arm allows the user to apply more force on the piston than simply pressing with his arm muscles. However, it was difficult for a second person to hold the barrel in place while the user was applying the force or attempting to retract the piston.

Complexity of design:

The lever-arm mechanism has several parts, such as bolts, nuts, and threaded rod which may be unavailable at the village level or labor intensive to reproduce. The press manufacturing process may be slowed down by the assembly of several small parts, for which alignment and fitting are important. The more parts there are that are essential to the design, the more time it takes to construct, assemble, and maintain. It also seems as though this design would be unwieldy unless it had a stand on which to mount the press and elevate the nozzle to keep the extruded charcoal from being impeded from exiting. The detachable lever mechanism of design B requires fewer parts than design A, but does not provide as much mechanical advantage. The lever mechanism must also be detached every time the barrel needs to be reloaded, increasing the operational complexity.

Operational ease:

Before any charcoal exits the press, the empty space from the two-step reduction in diameter and long nozzle must be filled. The first batch that exits the press is not well-compressed. Much of the charcoal mixture is also wasted after each pressing cycle because it remains in the reduction and nozzle sections of the press. A piston could be made to fit the exact inner contours of the press, but it would be a bit difficult to manufacture. Due to the complexity of the inner contour, the press could also be difficult to clean after each use.

As the length of the barrel is increased, the frequency with which the user must load new charcoal into the press decreases. However, extending the barrel requires the lever-arm mechanism to be longer with a greater pivot offset, or a more complex mechanism to avoid collisions of the piston arm with the sides of the barrel. To decrease the length over which the charcoal is compressed and minimize the amount of charcoal that remains in the press, the 4" diameter barrel and same lever-arm mechanism were bolted to a 4-to-2-inch curved reducer with no nozzle. However, the curved surface in the reducer seemed to direct the flow of charcoal towards the central axis, rather than out of the exit end of the press, making it extremely difficult to push any charcoal out of the press.

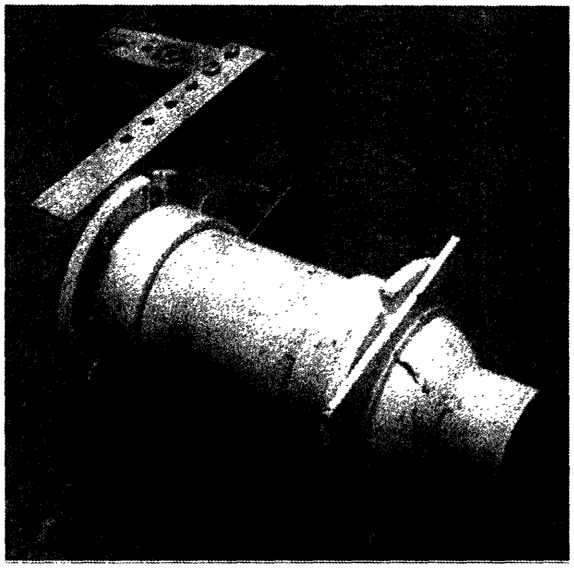


Fig. 3.4. Curved reducer extruder.

Cutting briquettes:

Either a separate cutting mechanism is required, or the user must manually cut the charcoal extrusion after it exits the press. This is an additional operational step that produces areas of weakness along the cut surfaces. Any cutting creates rougher surfaces than those formed by compression. These rough cut edges crumble much more easily than the formed edges.

3.3. Exit-blade press

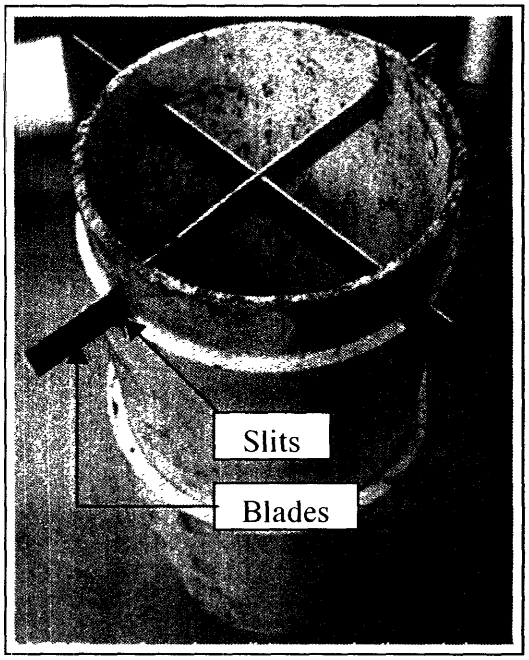


Fig. 3.5a. Exit-blade press.

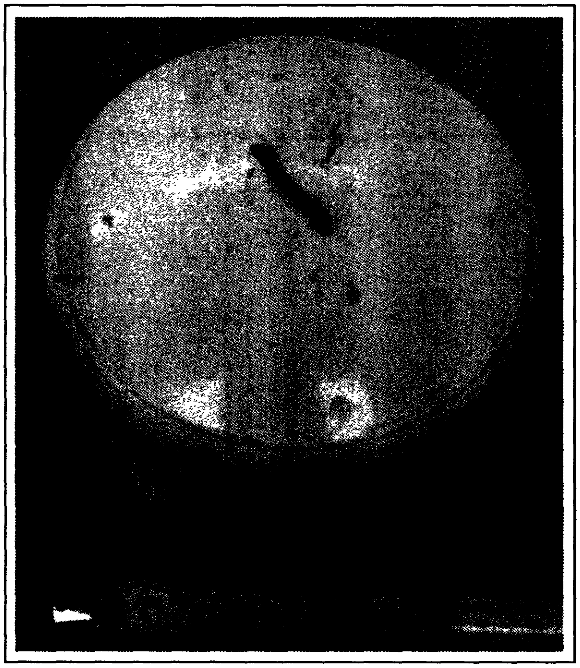


Fig. 3.5b. Piston cap measuring 4"OD.

3.3.1. Description of design

Four slits in the axial direction were cut near the exit end of a 4" diameter barrel. One long edge of two thin metal plates were sanded to produce a sharp cutting edge. Two metal plates were inserted into the slits in the barrel, which held the plates orthogonal to each other. The plates served as crude blades which formed an X at the end of the barrel and cut the extruded charcoal into four triangular wedge-shaped logs as the charcoal was forced out by a piston ram.

3.3.2. Advantages and disadvantages

This exit-blade press is extremely simple. It requires almost no modification of pre-fabricated components. No end cap is needed if the press is placed on a hard flat surface while the charcoal is compressed. Difficulties arise when the barrel must be lifted or tilted on an incline while the user pushes the compressed charcoal out through the blades. Not only is it difficult to hold the barrel steady, but it requires a great deal of force to push the piston down. It is possible that the high fiber content of the test batch of charcoal mixture made it difficult for the blades to divide the different sections.

3.4. Clover Press

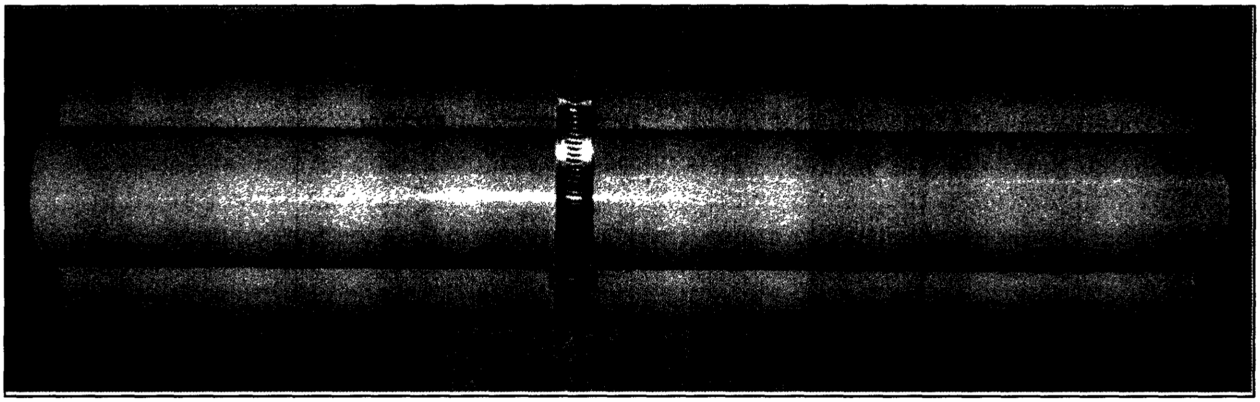


Fig. 3.6 Clover barrel held by hose clamp while glue is curing.

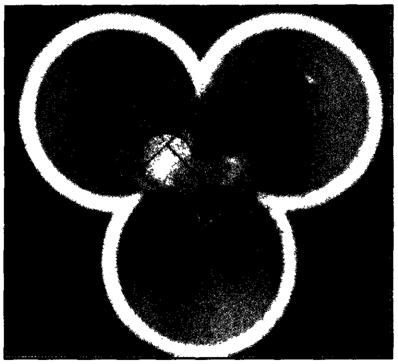


Fig. 3.7a Barrel cross-section

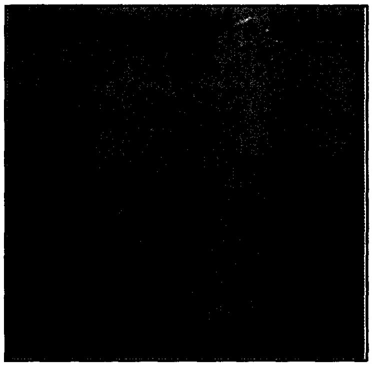


Fig. 3.7b Plastic spacer

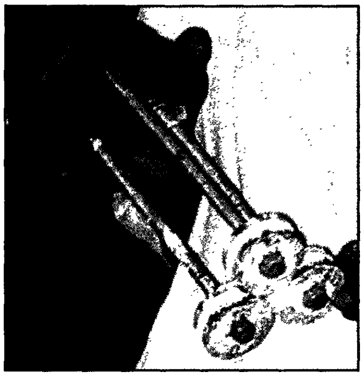


Fig. 3.7c Clover-shaped ram

3.4.1. Description of design

The clover press design was intended to increase the output by forming several layers in series and three channels in parallel without any need for cutting. Each clover-shaped layer could be broken in to three circular leaves because the inner section holding the leaves together had much less area compared to the actual leaves.

The clover press consists of three 2" ID by 20" long PVC tubes with an arc length section cut out in a milling machine. The pipe was glued together with a binder made especially for PVC. While the glue dried, a hose clamp was used to hold the three tubes in place. After the glue cured, the barrel was cut in half with a band saw to produce two 10" long clover barrels. It was assumed that it would be easier to cut the barrel in half than to produce two separate barrels. Two barrels were desirable in case one failed in testing.

A clover-shaped ram was made by cutting off a 0.25" cross section from the end the barrel, and tracing that inside geometry on a piece of 0.25" thick PVC sheet. Two clover-shaped plates were cut out with a band saw and and sanded with a belt sander to ensure a good fit in the barrel. Holes were drilled in the center of all the leaves of the clover plates. Holes of the exact same pattern were drilled into a piece of 0.5" thick wood. The wooden board was secured against the heads of three 8" long carriage bolts by nuts. The two PVC clover plates were then secured about 1" apart from each other by nuts near the end of the bolts. The space between the clover plates were meant to prevent misalignment.

3.4.2. Advantages and disadvantages

Force:
Without a lever-arm, the greatest force that could be applied on each layer was a function of the user's weight. From the quality of the briquettes that were produced, it seems that this force is sufficient to produce briquettes that do not fall apart, but are also not very dense.

Operational ease:
To fill the press, the user would have to set the clover barrel on a hard relatively flat surface, and scoop charcoal into the barrel, insert a thin plastic clover-shaped spacer, scoop in more charcoal, and repeat until the channel was filled. This did not take a great deal of time, and could be done faster with practice or a funnel.

The ram was not made to be long enough to push the briquettes out of the barrel. It was assumed that the barrel could simply be lifted off the ground and the briquettes would fall out or could be pulled out easily. However, it seems as though it would have been useful make a longer ram and to put handles on the barrel to allow the user to push the ram with his feet while holding onto the barrel with his hands.


Fig. 3.8a Filling


Fig. 3.8b Compressing


Fig. 3.8c Extract


Fig. 3.8d Un-cut briquette

Manufacturability:
The clover press was the only design that required machining for accuracy and two full days to make components and wait for the glue to cure. If the PVC tubes were to be cut by a table saw rather than a milling machine, a jig would have to be built to ensure that the tubes were cut at the correction angle and depth. The PVC gluing agent is not very thick and requires the surfaces to match as closely as possible with as much binding area as possible. If the angles and depth of the faces are cut well, the glue binds quite strongly and nothing is needed for radial reinforcement. However, if the angle and depth were not cut accurately, the glue may not be able to hold the tubes together or leakage may be a problem. When PVC tubes are cut along their central axis, the inherent stress from extrusion causes the tube to twist slightly. Thus, it is important to clamp the tubes together to ensure a tight fit even if the cuts are very accurate. The PVC binder also produces noxious fumes and thus must be used in a well-ventilated area.

It is possible that the press could be made out of steel tubing, which is available in the same dimensions as PVC. If the tubes were welded together instead of glued, the cuts would not have to be as accurate because strong welds can be made over gaps along the order of 1/8". The ram could probably also be welded together with steel rods and sheets rather than assembled with threaded rods, bolts, wood, and PVC.

Cutting briquettes:
The spacers were made from thin plastic sheets. In Haiti, they could be made from flattened cans, from which a village metal worker could cut out the clover shapes. These might be more available and cheaper than sheet metal or plastic sheets. Pieces of a plastic bag are also another alternative that was not tested.

The broken edges of the briquette were much rougher and tended to crumble more easily than the relatively smooth formed edges. This suggests that rather than having a cutting or breaking mechanism to split larger charcoal pieces exiting the press, the press should be designed to form the smaller briquettes directly.

3.5. Best Mock-up: Clover Press

3.5.1. Summary of Results

All three functional mock-ups were tested in the lab at MIT with a charcoal mixture of low quality because better material was not available at the time. The bagasse was not fully carbonized, with visible pieces of unburned structural fibers. This material was not as brittle as carbonized bagasse and may have contributed to the difficulty of compressing it. The cassava binder also contained too much water, and was not as sticky as it should be. The quality of the charcoal mixture seems to have significant influence upon the ease of briquette formation and quality. Thus, the performance of these mock-ups do not reflect the full potential of these concepts, and the disadvantages described above may not afflict future prototypes embodying these concepts.

Lever-Arm Extruder

Unlike the other two mock-ups, the lever-arm extruder requires moving linkages, and complex analysis of compression pressure and material flow. Although the 2.009 screw extruder was a successful implementation of a reduction in cross sectional area, modeling the compression characteristics is very complicated. It seems that it was much easier to force the charcoal through the reduction in cross sectional area if the material is rotated by a screw rather than pushed directly by a piston. Due to the complexity, analytical uncertainty, and difficulty of modification inherent in this design, the lever-arm extruder was deemed to be the poorest choice because it did not work as intended.

Exit-Blade Press

Although the exit-blade press was preferable for its simplicity, its underlying concept of forming briquettes in parallel and its reliance on cutting to increase briquette yield were problematic. Compressing a charge with a large cross-sectional area, and attempting to dividing it lengthwise to increase the number of briquette logs fourfold was ineffective. Forming in parallel divides the force over a larger cross sectional area, thereby decreasing the corresponding compression pressure. Cutting the briquettes also weakens and degrades the surface along which the lines of separation. Long cuts through comparatively narrow cross-sections are difficult to execute well and will most likely degrade the strength and structural integrity of the resulting briquette sections. Thus, the exit-blade press was not poorest option, but also not the most promising.

Clover Press

The clover press was a combination of briquette formation in series and in parallel. The most notable feature of the clover press was that it utilized spacers to separate different levels of charcoal to enable formation in series. The spacers also formed distinct clover-shaped briquettes that did not require an extra cutting operation to separate them from each other. Formation in series is inherently better than formation in parallel because there is hardly any reduction in effective compression pressure with increasing depth. Friction of the charcoal against the channel walls does decrease the force that is felt by briquettes at lower levels, but this effect is negligible when compared to the applied force.

The three channels that comprise the leaves of the clover were also a more effective form of parallel formation than the cutting mechanism of the exit-blade press. The parallel channels of the clover press were mostly enclosed, joined only at the center of the clover along a line that could easily be broken and did not require cutting which degrades the briquette surfaces. The triangular wedges formed by the exit-blade press also has more corners and acute edges which are more susceptible to wear than the curved surfaces of the mostly cylindrical briquettes formed by the clover press. Thus, the clover press was the most promising design of the three mock-ups.

3.5.2. Feedback from Haiti

In January 2005, Amy Smith demonstrated the clover press in Haiti. The Haitians were optimistic about the clover press and used it to make some briquettes, offering many helpful comments and suggestions. The simple design of the clover press was easy for the users to understand intuitively, allowing them to think of their own ways to improve upon it. They liked the idea of using spacers in the clover press to form briquettes in series because it eliminated the need for cutting. Although the press was not refined and the ram did not allow the user to push the columns of charcoal completely out of the press, the Haitians did not mind having to unscrew the top plank of the ram to do so. Thus, it seems likely that the Haitians would opt for a cheaper but more operationally complex design.

3.6. Implications for Final Design

Based on the mock-up trials, it was determined that the briquettes should be formed in individual channels with spacers separating various layers to increase production via formation in series without requiring cutting. There should be no change in cross section, as with the lever-arm extruder, and no division of the briquette column in the direction of compaction, as with the exit-blade press.

Since curved surfaces are more durable than edges or corners, it seems reasonable to start experimenting with cylinders rather than squares or hexagons. Spheres or ovoids are not feasible since formation in series with flat spacers produces flat upper and lower surfaces. The clover press produced 2"OD x 1"H cylindrical briquettes, which seemed to be a reasonable size and were comparable in volume to commercial barbeque briquettes. Assuming prefabricated cylindrical pipes of about 2"ID will be available in Haiti, the next prototypes will be made with the same materials.

4. INVESTIGATION OF PRESS CONCEPTS

4.1. Selection of Best Concept: Pile Driver

Since the Haitians responded so positively to the 2.009 extruded charcoal, it was used as a guideline for evaluating briquette quality. The mechanism by which the 2.009 extruder compressed the charcoal is not clearly understood so the required compression pressure was unknown (Ang, 2005). Using a hydraulically operated universal testing machine, several 2"OD x 1"H cylindrical briquettes were formed at 3 kN, 6 kN, 9 kN, 12 kN, and 15 kN (Bateman & Harrison & Ljubicic, 2005). By qualitatively comparing those briquettes with samples of 2.009 extruded charcoal that had been machined to be approximately the same dimensions, the required force was estimated to be between 3-6kN. To generate this force with just gravity alone would require approximately 300-600 kg or 650-1300 lbs, or a mechanism that could multiply a person's body weight by 6-13 times. Although that force multiplication is possible with these principles, it would require long moment arms, which lead to more expensive machines and possibly more complicated systems. Thus, all initial concepts that relied upon the underlying principle of simple force-multiplying mechanisms, such as lever-arms and ratchets, were eliminated.

Based on the Pugh Chart on the following page, it seemed as though the pile driver would be the most promising concept. It is a simple design that can be portable, and has the potential to produce greater forces with impact loading rather than constant pressure. The following sections detail the experiments that were conducted to test the viability of the pile driver concept.

Table 4.1: Evaluation of press concepts with 2.009 extruder as the datum

Wt.	Criteria	Extruder (Datum)	Hydraulic	Screw Press	Ratchet Clamp	Pile Driver	Pulley
3	Cost	0	+ + +	+ + +	+ + +	+ + +	+ + +
2	Energy Input	0	- -	- -	- -	- -	+
1	Briquette Quality	0	-	-	-	-	-
1	Output	0	-	-	-	-	-
2	Maintenance	0	- -	0	0	+ +	- -
2	Intuitiveness	0	0	+ +	+ +	+ +	+ +
1	Manufacturability	0	- -	0	+ +	+ +	- -
1	Ease of Operation	0	0	-	-	-	-
1	Risk of Misuse	0	+	+	+	-	-
1	Intuitive mechanism	0	-	0	0	+	+
1	Production Rate	0	-	-	-	-	-
1	Force Utilization	0	-	-	-	-	-
1	Locally Available Materials	0	+	+	+	+	+
	Total	0	-6	0	2	3	-3

4.2. Hydraulic Press

4.2.1. Description of design

Having parallel channels that could compress multiple columns of charcoal simultaneously was one main advantage of the clover press prototype. However, ensuring equal levels of charcoal in the different channels was a concern.

A hydraulic press would rectify the problem by ensuring that an equal amount of pressure would be applied on each column of charcoal. The user would apply a force F_1 on the driving piston above the fluid reservoir, which would maintain constant pressure, and push the channel pistons equally at force F_2 to compress the charcoal. Although the distance that the channel pistons travel may vary with different amounts of charcoal in each channel, each charcoal column would experience the same compression force. An incompressible, locally available fluid such as water could be used to transmit constant pressure to all of the channels. If the press leaks, the spill would not be hazardous and water could easily be replaced. The seals could be either rubber O-rings or a locally available material such as leather or rubber inner tubes.

To load the charcoal into the channel, the top portion of the press containing the pistons would be removed by disengaging the side latches. The channels can be filled by the same method as the clover press. Charges of charcoal would be separated by spacers so several briquettes can be formed in series without requiring cutting. To unload the channels, the bottom panel would be opened and the user could push on the reservoir piston to push the channel pistons through the entire length of the channel.

If the press became too tall for the user to step on the driving piston above the reservoir, an eternal reservoir could be place to the side with a tube connecting the fluid to a chamber above the channel pistons.

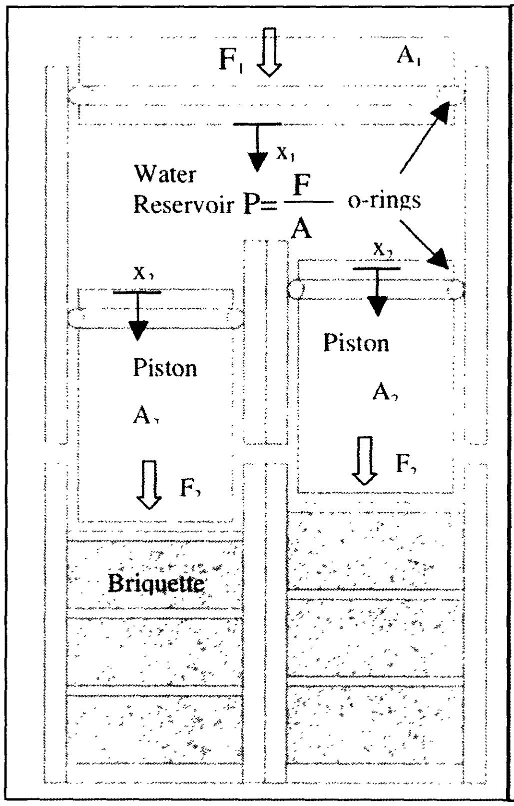


Fig. 4.1a Hydraulic Press Schematic.

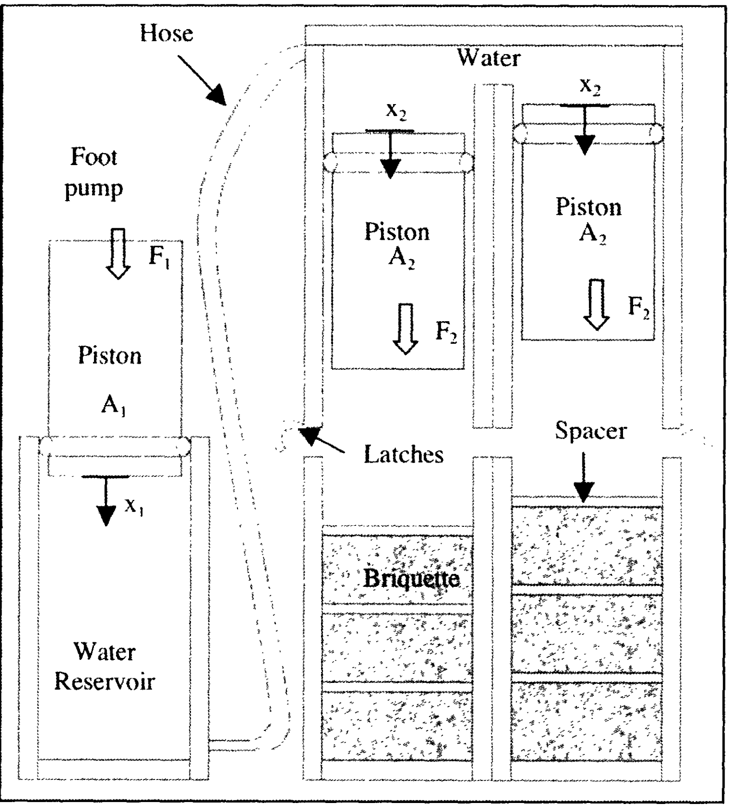


Fig. 4.1b Hydraulic press with separate reservoir.

4.2.2. Press mechanics

F_1 : Driving force
x_1 : Throw of driving piston
A_1: Area of driving piston
F_2 : Compressing force
x_2: Throw of channel piston
A_2: Area of channel piston
P : Pressure of fluid in reservoir
n : Number of channels
W: Work done

The pressure in the reservoir is equal to the driving force divided by the area of the driving piston. The pressure is also equal to the compressing force divided by the area of the channel piston. Therefore, the compressing force is equal to the driving force times the ratio between channel area and driving piston area. If the channel area is less than the driving piston area, the compressing force will be less than the driving force so there is a force reduction unless the channels are larger in cross sectional area than the reservoir.

$$P=F/A \qquad F_2=PA_2=F_1A_2/A_1 \qquad F_2<F_1 \text{ if } A_2<A_1$$

The volume displaced by the driving piston is equal to the volume displaced by all the channel pistons combined. The throw of the channel piston is equal to the throw of the driving piston times the ratio between reservoir cross sectional area and the total cross sectional area of the channels.

$$\Delta x_1 A_1 = n\Delta x_2 A_2 \qquad \Delta x_2 = (\Delta x_1 A_1)/(nA_2)$$

The work done is equal to the force times the distance traveled. Thus, there is an inverse relationship between the force ratio and the throw ratio. If force is decreased from input to output, the throw is increased, and vice versa.

$$W = F\Delta x$$

4.2.3. Advantages and disadvantages

Intuitiveness:

Hydraulic mechanisms are inherently less intuitive than purely mechanical systems. If the total cross sectional area of all the channels nA_2 were greater than the cross section of the driving piston A_1, the throw of the channel pistons x_2 would be less than the throw in driving piston x_1 and the channel force F_2 would be greater than the applied force F_1. The force multiplication is indirectly proportional to the cross sectional area increase and reduction in throw.

Our community partners would probably be less familiar with hydraulic designs and less likely to improve the design or understand and maintain the device as well as a purely mechanical design.

Locally available materials:

Rubber O-ring seals sitting in grooves cut into the outside of the pistons would prevent leakage. If O-rings are not available, leather seals or bicycle inner tube may be alternatives, but maintenance might be troublesome. It may also be hard to find or replace tubes or connectors that would be necessary for the reservoir model.

Maintenance:

It is likely that this hydraulic system will require more frequent maintenance than mechanical systems because the seals will wear out and need adjustment or replacement. The fluid may also need to be refilled periodically even if there are negligible leaks.

Manufacturability:

Several parts are required to implement this design. It would take longer to make several pistons for each channel, than to have just one reusable piston. With a concern about sealing, the tolerances must be quite high, which would require more skill and attention to detail.

4.2.4. Assessment

The added complexity of making pistons and a reservoir with seals and a possible external fluid delivery system does not justify the benefits of this design. Its main advantages are to eliminate the variability of pressure and the possible disadvantages from the variation of charcoal levels in each column. However, in testing the clover press, these issues were not great concern. The briquettes at each level may not be the same height and the density may vary slightly from column to column, but the variation is not very big. The clover ram also did not misalign or jam even when there were different levels of charcoal in the channels.

4.3. Screw Press

4.3.1. Description of design

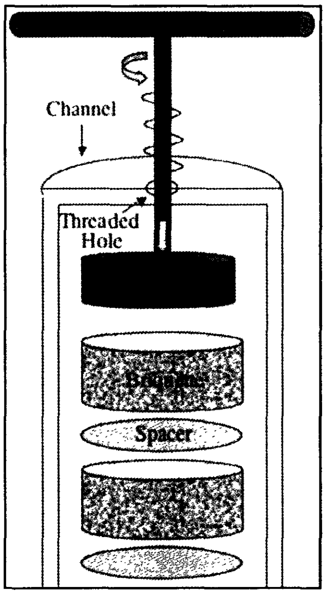


Fig. 4.2a. Internal view.

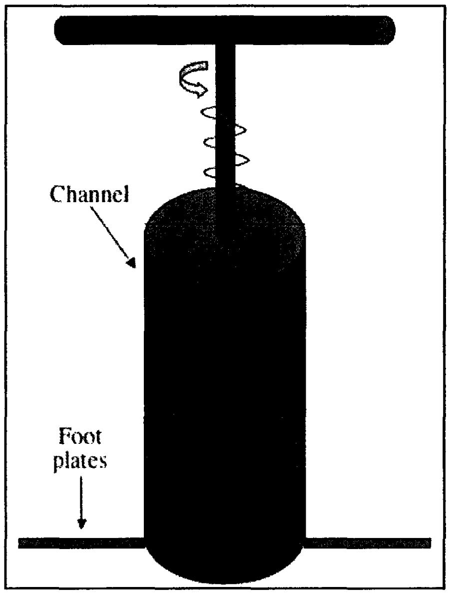


Fig. 4.2b. External view, closed.

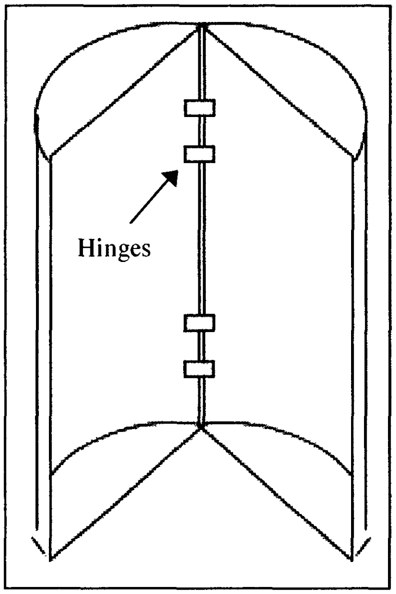


Fig.4.2c. Open channel

The screw press is intended to combine the simplicity and speed of being able to compress the charcoal with a piston, like in the clover press, with the added force that can be applied by engaging a screw with a long lever arm. The bottom section of the piston shaft is smooth to allow it to pass freely through a threaded hole when the user is compressing the charcoal by pressing down. Once the charcoal is mostly compacted, the threads on the piston shaft engage with the threaded hole and allow the user to complete the compaction by tightening the screw. The top portion of the piston shaft may be smooth to allow the user to press the column of compacted charcoal through the press when unloading.

One alternative to avoid complications due to variation in the level of charcoal is to compress the charcoal in only one channel. Although this approach has the benefit of applying all the input force on one channel instead of dividing it among multiple channels, the output per batch is decreased and the number of operational iterations must be increased to maintain the same output volume. One way to account for the additional operational time is to improve the method of loading and unloading.

Instead of filling the charcoal in the small opening at the top of the channel, the channel could be cut in half along the central axis, providing a larger area for loading. Discs, such as tin can lids could be inserted at evenly spaced intervals into the trough of charcoal, eliminating the previous need to multitask by alternatingly pouring in charges of charcoal and dropping spacers in between each charge. The two halves of the channels form troughs, which can be clamped together by a latch, hose clamp, or similar mechanism. To unload, instead of having to force the charcoal through the entire channel out the opposite end, the user would only have to release the clamp, separating the two troughs.

4.3.2. Advantages and disadvantages

Locally available materials:
It may be difficult to find threaded rod and smooth out the end to allow it to pass through the threaded hole.

Repairability:
If the screw jammed or ruined the threads on the channel, it would be difficult to repair the parts. The user would have to buy a new replacement part, which would be quite a significant portion of the original capital cost since the press consists of only two components which are the ones most likely to break. The manufacturer could design for failure with a small ring threaded on the inside that could be inserted into the mouth of the channel so that if the threads are ruined, only this threaded cap must be replaced and not the entire channel.

Production time:
It may take too long to turn a screw to achieve enough force. This is not an improvement over the 2.009 extruder because it requires some of the same motions but is a batch process rather than continuous.

4.3.3. Assessment

Tightening a screw with a long lever arm would probably be time consuming because the vertical displacement of the piston per revolution of the screw is small (though you could adapt the pitch). There are also concerns about the availability and cost of screws and taps. This design requires a screw similar to the 2.009 extruder but does not have as many advantages, and the channel would be harder to manufacture and maintain. This design may even be more costly than the extruder for these reasons.

4.4. Pulley Press

4.4.1. Description of design

A rope fixed at one end to a stationary point or the channel, could be looped around several pulleys in such a way as to multiply the compressing force by the number of times the rope was looped. In both designs shown below, pulling the rope closes the distance between the pulleys, forcing the piston downward into the channel.

In the boa constrictor design, in Fig. 4.3a shown on the next page, the user would pull on two separate ropes, forcing each side of the pulley down independently. These two ropes could also be linked by a beam so that each side of the piston will experience the same force pushing it downward. The ropes are looped multiple times around the same pulleys, so multiple pulleys do not need to be constructed. When the rope is pulled taut it will be wrapped tightly around both beams.

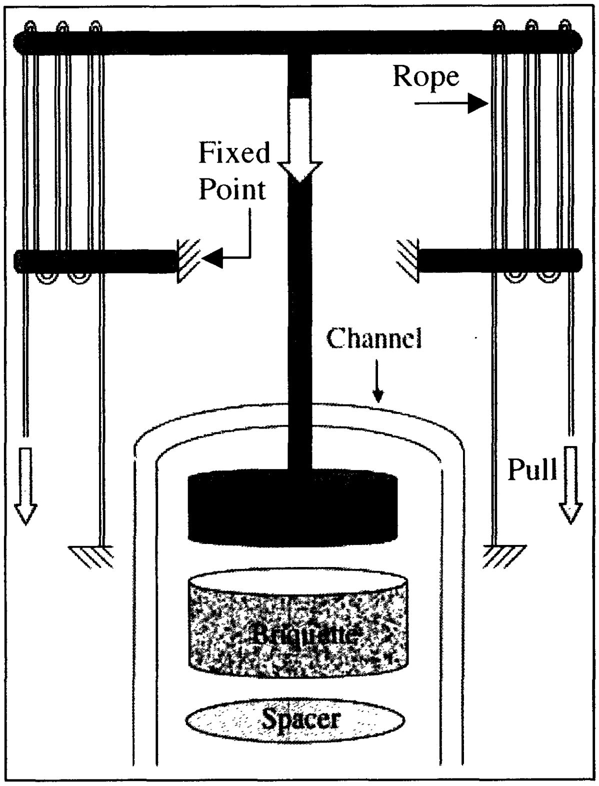


Fig. 4.3a. Boa constrictor design.

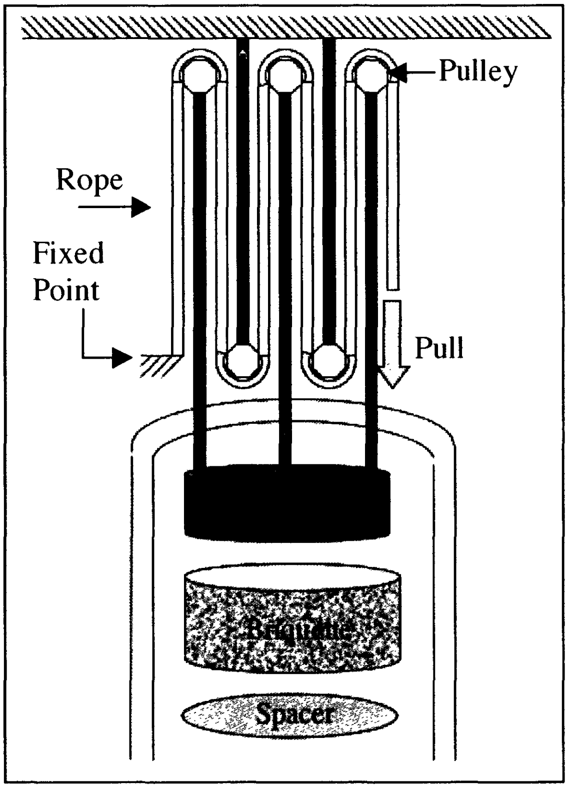


Fig. 4.3b. Planar path design.

In the planar path design, in Fig. 4.3b, the user pulls on one rope which is fixed at one end and winds back and forth between several pulleys in a continuous plane. When the rope is pulled taut, it straightens out, and minimizes the distance between the upper and lower pulleys. There are also many other pulley systems that could be implemented.

4.4.2. Press mechanics

T: Tension in rope
P: Force on piston
F: Force on one pulley

n: Number of pulleys
y: Distance traveled by piston
d: Distance traveled by rope

$F = 2T$
$P = 2Tn$
$d = 2yn$

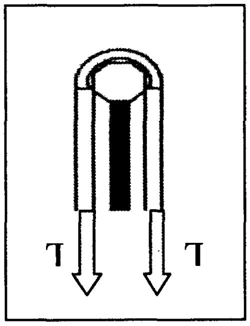


Fig.4.4 Tension in rope on pulley

The force exerted on each pulley is equal to the tension in the rope multiplied by double the number of times the rope is wrapped around the pulley. The force exerted on the piston is equal to the force exerted on one pulley times the number of pulleys. However, the distance the rope must travel is twice the distance the piston travels times the number of pulleys. Thus, if the piston force is 10 times the pulling force, the rope must also travel 10 times the distance that the piston travels.

4.4.3. Advantages and disadvantages

Variable force multiplication:
It would be easy to change the force multiplication by wrapping the rope an extra time or one less time around the pulleys for the boa constrictor design. The planar rope path design could also be modified by adding extra pulleys or not wrapping the rope around all the pulleys.

Manufacturability:
The boa constrictor design would be easier to make since it requires two rods as opposed to several independent pulleys. Having to make and assemble all the parts for the planar rope path design would be very time-consuming and laborious. The entire press would also have to be quite big, to allow for enough room between pulleys.

Locally available materials:
Ropes are readily available in most places. However, the durability of the rope may be a concern. The rope must be able to withstand a considerable amount of force.

Maintenance:
The rope and pulleys may need periodic maintenance because it will probably wear out with time. The ropes may fray or the pulleys may become misaligned or bent.

Ease of operation:
Since the distance the rope must travel is likely to be quite far, a separate winding mechanism may facilitate the process but will also increase the complexity and cost significantly. Another pulley system or alternate mechanism is also needed to lift the piston out of the channel after it has compress the charcoal.

Production time:
Considering the distance that the rope must travel to produce a significant force multiplication, it may take a considerable amount of time to complete one compression cycle. It would also take time to retract the piston and load and unload the charcoal channels. The process will probably be slowed by occasional jamming of equipment.

4.4.4. Assessment

This design seems to be too complex and requires a great deal of material, which suggests that it would also be quite expensive. It requires several operational steps, some of which seem as though they would take a long time to complete. There are also issues with maintaining the press since the ropes will probably wear out or jam from time to time.

4.5. Ratchet Clamp

4.5.1. Description of design

The ratchet clamp design is intended to allow the user to disengage the ratchet mechanism and compress the charcoal as much as possible with body weight, and then compress it further by pumping a lever arm that engages a ratcheting mechanism.

The ratchet should disengage to allow the shaft to slide freely when the lever arm is raised, but when the lever arm is lowered, it must be able to force the shaft downward.

The ratcheting mechanism would not necessarily need a shaft with teeth and a pawl. It is possible that frictional forces would be sufficient to engage the lever arm. The shaft may be scored to increase the friction coefficient without greatly increasing the complexity of manufacturing.

4.5.2. Press mechanics

L: Length of lever arm
d: Distance from shaft to pivot
F_1 : Driving force
F_2 : Compressing force
M: Moment about pivot

The moment about the pivot is equal to the driving force times the length of the lever arm and it is also equal to the compressing force times the distance from the shaft to the pivot. Therefore, the compressing force is equal to the driving force times the ratio between the length of the lever arm and the gap between the shaft and the pivot.

$$M = F_1L = F_2d$$

$$F_2 = F_1L/d$$

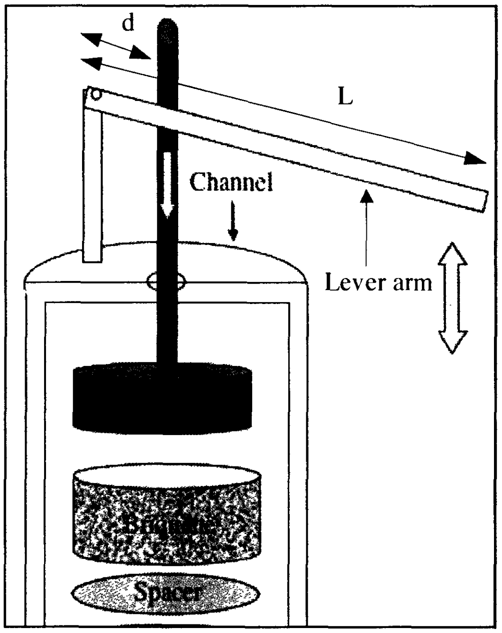


Fig. 4.4. Rachet schematic

4.5.3. Advantages and disadvantages

Limited achievable force:
There is a point beyond which the lever arm cannot be feasibly be lengthened without making the press unwieldy and cumbersome. Also, with a toothless shaft the friction limits the amount of force the user can apply before slipping occurs.

Durability:
Constant rubbing would wear down a toothless smooth or scored shaft, reducing the friction.

Manufacturability:
It may be take a high level of precision to align the lever arm with the shaft so that it disengages when lifted and engages when pushed downward. Assembly would require more steps than designs that are fixed permanently together without pivots and the need for closely fitting shafts.

4.5.4. Assessment

The main disadvantage of this design is that there is a limit to the ratio of force multiplication achievable by increasing the length of the lever arm. It might also be tiresome to lift the piston out of the channel because previous trials with the lever-arm extruder indicated that the piston had a tendency to jam. If a lever-arm mechanism is to be used, it should allow the user to apply more force than with his arms and not require the piston to be manually lifted.

4.6. Pile Driver

4.6.1. Description of design

A weight acts by sliding upon a rod to hit the piston. This mechanism results in impact loading, which may be more powerful than steady force loading. The final design concept emulates the mechanism of a construction pile driver in which a heavy weight is used to strike a metal stake, driving it into the ground.

4.6.2. Press mechanics

KE: Kinetic energy
PE: Potential energy
g: Gravity
m: Mass of object sliding on rod
h: Initial height of mass above piston
v_1: Velocity user gives to the mass
v_2: Velocity of mass before striking piston
F: Force of impact on piston
d: Distance traveled by piston

$$\begin{array}{ccccc} \text{Stage 1} & & \text{Stage 2} & & \text{Stage 3} \\ KE_1 + PE_1 & = & KE_2 + PE_2 & = & KE_3 + PE_3 \\ \frac{1}{2} mv_1^2 + mgh & = & \frac{1}{2} mv_2^2 + mg(0) & = & \frac{1}{2} m(0)^2 + Fd \end{array}$$

Governing equation: $\frac{1}{2} mv_2^2 = Fd$

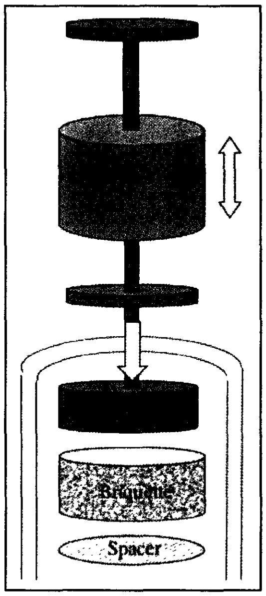


Fig.4.5 Pile driver schematic

Assuming that the principle of conservation of energy applies between stage 1 when the mass has just begun to move with initial velocity downward, stage 2 when the mass has transferred all of its gravitational potential energy to kinetic energy, and stage 3 when the mass impacts the piston, the basic mechanics of the pile driver can be analyzed.

At stage 1, the kinetic energy is dependent upon the mass of the sliding object and the downward velocity that the user initially gives it, which the gravitational potential energy is dependent upon the height of the object above the piston. At stage 2, all the initial gravitational potential energy has become kinetic energy, causing the mass to move faster. The kinetic energy of the piston at stages 1 and 2 were zero because the piston was not moving. The piston was also at the designated point of zero potential energy at stages 1 and 2. Thus, the energy of the piston is not shown in the equations above until stage 3. At stage 3, the sliding object is no longer moving and has used all its previous kinetic energy from stage 2 to do work upon the piston by moving it a distance d with force F.

If it is assumed that all the force imparted upon the piston by the sliding object is also transferred by the piston to the charcoal, the compressive force is essentially dependent upon the mass of the sliding object and how fast it is moving before it hits the piston. These calculations are rough estimates and are based on general assumptions, but they explain the basic mechanics of the pile driver.

The distance the piston travels decreases with each impact because the charcoal becomes denser and harder to compress. However, the compressive force also increases with decrease in piston travel, so it is possible produce more compressive force with the same magnitude of initial velocity.

4.6.3. Advantages and disadvantages

<u>Ease of operation</u>:
It may be more strenuous for the user to lift and push a heavy weight onto the piston, than to use his own body weight with a mechanism to generate the compacting force.

<u>Simplicity</u>:
The design is very intuitive and simple. It should be easy to manufacture without many complex parts.

<u>Achievable force</u>:
The effective compressive force increases with the number of impacts and with the decrease in piston travel. This is possible without having to increase the initial velocity or the mass. If the mass is increased slightly, it has a great influence on the effective force because it is multiplied by a factor of the velocity squared. Thus, it is possible to generate great forces without increases in the amount of input force.

4.6.4. Assessment

The pile driver is the most promising concept because of its simple design, intuitive mechanism, manufacturability, and ability to generate higher forces without increased effort or changes to the press structure. The most important variables governing the effective compression pressure are also easily variable. The mass can be increased without changing the design of the rest of the structure. The user can also impart greater initial velocity to the sliding object to produce a more powerful impact. The cross-sectional area of the channel can also be reduced to increase the effective compression pressure for a fixed amount of applied force.

5. FINAL DESIGN: IMPACT-LOADING

The pile-driver press is similar to construction pile drivers. Pile drivers typically force metal stakes into the ground by hoisting up a heavy weight with a cable and allowing it to fall on the stake. The pile-driver press similarly uses a heavy weight to impact a metal piston, forcing it downward into a channel to compress a column of charcoal. Although a cable and hoisting mechanism may be considered for later designs, the most recent prototype is meant to be used with a hammer.

The final prototype consisted of an aluminum 18" long 2" square channel with a matching steel piston. After the channel is filled and stood upright, the user hits the piston with a hammer to compress four layers of charcoal, sandwiched between aluminum spacers. The channel has a U-shaped cover that is removable to allow the user to fill charcoal into and extract charcoal from the channel side-ways rather than at the small openings at the ends of the channel. A central shaft was also designed as an optional design feature to produce briquettes with a central hole. With a hammer weighing about 4 lbs, it was possible to compress four briquettes by a height change ratio of about 3.5:1 after about 7 impacts. The briquettes with holes were able to withstand an average of 200 N of compressive force before breaking while those without holes could withstand an average of 170 N.

Before this final design was conceived, a few prototypes were made to experiment with relevant aspects concerning impact loading, such as briquette shape, column height, and mechanism of impact. These tests showed that using the piston as a pounding device did not generate enough force, and only compacted two stacked briquettes by a height change ratio of about 2:1 after about 6 impacts.

5.1. Pounding experiment

Using a heavy piston to pound the charcoal is meant to simulate the effects of impact loading rather than the steady pressure loading of previous prototypes. A hammer was not used to hit the piston directly because the blows had the potential of damaging the piston. However, this test showed that pounding the charcoal was not sufficient to produce adequate briquettes. There was only a 2:1 reduction from the initial to the final height of the charcoal column. Although this was similar to the results of the clover press, the pounded cylinders had a third of the cross-sectional area of the clover press and therefore should have been denser. As compression tests in Section 5.4 show, the pounded briquettes performed the most poorly out of all the prototype briquettes, and were able to withstand a force of only 41N, which was an order of magnitude lower than briquettes formed by hammering the piston.

5.1.1. Description of equipment and procedures

A 2”ID x 4”L steel pipe was used as the channel for the briquette-making die. It was filled loosely with charcoal, and a thin disc made out of aluminum sheet metal was inserted at the top and in the middle of the channel so that two briquettes could be formed simultaneously. A piston, weighing 4.205 kg was allowed to rest upon it and changed the height of the charcoal column by 15 mm with only its weight.

The piston was lifted until the bottom was barely in the channel and pushed downward, striking and compacting the charcoal column. After each impact, a line was drawn on the die at the rim of the channel, marking the height of the submerged portion of the die. To extract the briquettes, an arbor press was used to push the charcoal column completely through the channel.

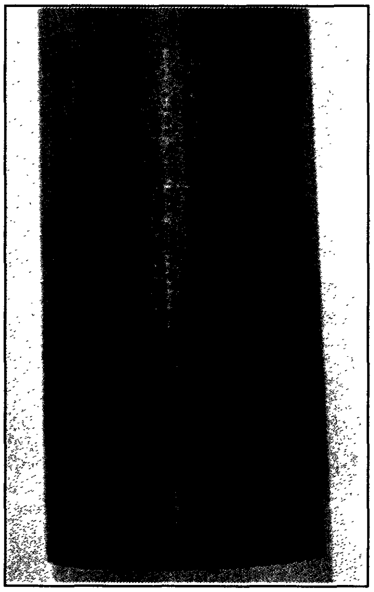


Fig. 5.1 Equipment. Fig 5.2 Marked piston.

5.1.2. Observations

Extraction difficulties

One of the two briquettes formed during this test was broken during the extraction procedures. The wet briquettes were not strong enough to withstand much loading or impact forces and should not be allowed to drop even a few inches to the ground during extraction. Section 5.3 describes the alternative loading and extraction mechanism of the side-loading box that does not require the briquettes to be pushed through the channel and caught individually.

Limited striking distance

The piston could only be lifted to a maximum distance of about 50 mm before striking the charcoal because it could not be removed and forced accurately into the channel for each strike. If the channel had been longer to allow for a greater distance of travel, pounding is likely to have produced significantly higher forces, which would have been more effectively in compacting the charcoal. Alternatively a heavier piston could be used to generate the same amount of force without requiring the user to expend as much effort accelerating it to give it an initial velocity. However, the disadvantage to making the piston heavier is to make it harder and more awkward to lift and handle.

Briquette quality

The briquette had quite a grainy texture that seemed similar in appearance to briquettes of similar dimensions that had been formed in an instrumented press at 1000N (Bateman & Harrison & Ljubicic, 2005). However, after drying, the briquette could be compressed by squeezing it with one's fingers and a fibrous crushing sound similar to the rustling of leaves could be heard. The hand-formed and clover briquettes were not squeezable, suggesting that the pounded briquette was formed under lower forces than could be applied manually.

The briquette also seemed to be flakier than the other briquettes that had been formed manually or by previous prototypes. This is possibly because the charcoal mixture was quite dry before it was loaded into the press or because it was left to dry in the oven for 5 days rather than overnight. It was theorized that the force of the sharp impacts may have also caused the sides to be flakier in comparison to steady loading, but subsequent tests with hammer blows do not produce briquettes with the same flakiness.

Compaction ratio

The ratio between initial (104 mm) and final height (56 mm) of the charcoal column was approximately 2:1. This is comparable to the clover press briquettes although the outward appearance of the two briquettes were quite different with the pounded briquette having noticeably bigger charcoal fibers and a flakier texture.

5.1.3. Analysis

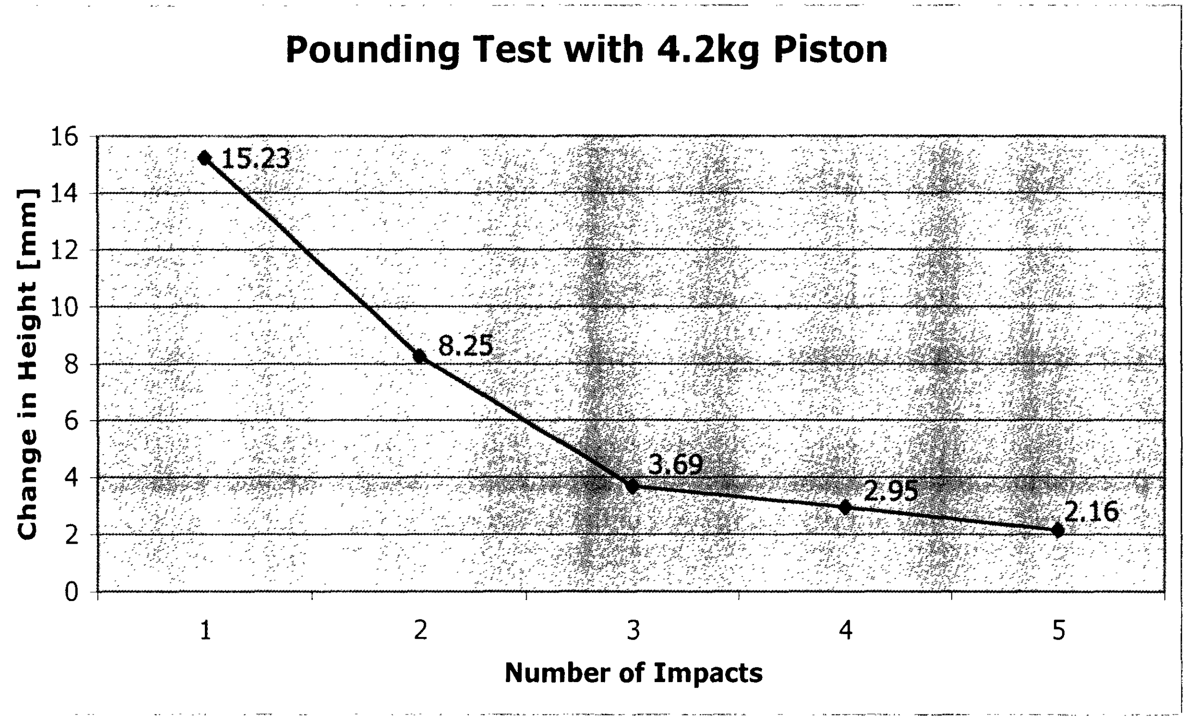
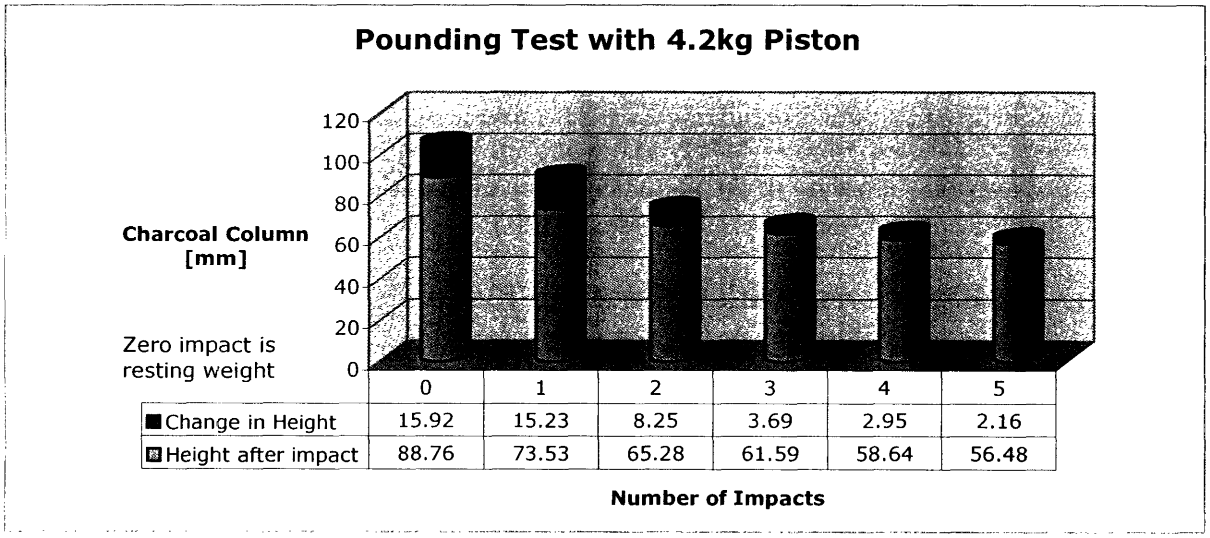


Fig. 5.3 Change in charcoal column height after five impacts with a 4.2 kg mass

There was a negligible change in the height of the charcoal column after 5 impacts so it was not deemed worthwhile to keep on pounding the charcoal. However, in hindsight, it might have produced greater compressive forces to continue hitting the charcoal with minimal changes in displacement.



	0	1	2	3	4	5
■ Change in Height	15.92	15.23	8.25	3.69	2.95	2.16
▨ Height after impact	88.76	73.53	65.28	61.59	58.64	56.48

Fi

Fig.5.4. Visual representation of change in column of charcoal after five impacts.

Table 5.1 Percentage of height reduction after each pounding impact.

Number of Impacts	Briquette Height [mm]	Percentage of Start Height
0	52	100%
0 (with weight of piston)	44	85%
1	37	70%
2	33	62%
3	31	59%
4	29	56%
5	28	54%

5.1.4. Advantages and Disadvantages

Cultural acceptability

This design is similar to the way women pound cassava with a mortar and pestle, and for this reason, it would presumably be more culturally acceptable than designs that did not have a counterpart device that was already being used in the target region.

Simplicity and durability

Since this prototype consists of three main pieces (steel channel, bottom plate, and piston), with no small intricate or mechanized parts, it is likely to perform reliably for a great deal of time without maintenance. Replacement parts would be easily obtained since the press would be manufactured from local materials. For example if spacer were lost, replacement spacers could easily be made.

Manufacturability

All components could be made from slight adaptations to pre-fabricated parts. The channel could be an unmodified steel pipe. The piston could be solid metal rod or steel pipe that was sealed at the bottom end. The bottom plate could be as simple as a plank of wood or a plank of wood with a circular disc attached to help with alignment and support of the channel.

Ease of operation

The piston would have to be quite long to extend deep enough in the channel to compress the charcoal. It would be awkward and unwieldy to have to lift this heavy and long piston out of the channel for every impact. Jamming of the piston or dislocation of the channel are possible complications that may arise if the user is to lift the piston for every strike.

5.2. Hammering Experiment with Cylindrical Briquettes

The hammer experiment is expected to more closely simulate the results of a pile driver because the piston is hit with metal weight that has been given some initial velocity and allowed to travel a certain distance. It is theorized that using a hammer to strike the piston will be easier than lifting the piston out of the channel for every strike, especially when the press is scaled up to actual size.

Hammering the piston to form cylindrical briquettes produced the best results out of all the impact loading trials. The average density was 0.29 g/cm^3 and the briquettes were able to withstand a compressive force of about 390 N. These tests showed that impact loading is a feasible and promising concept so subsequent sections describe more tests and design features aimed at exploring options and improving the overall design.

5.2.1. Description of Equipment and Procedures

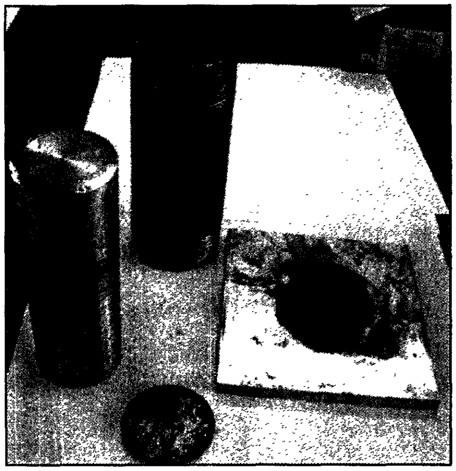


Fig. 5.5a Equipment parts.

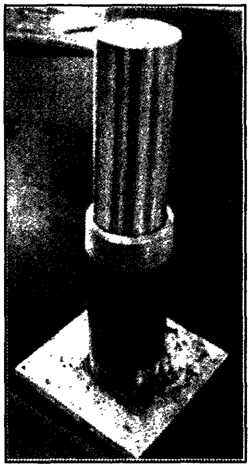


Fig. 5.5b Assembled.

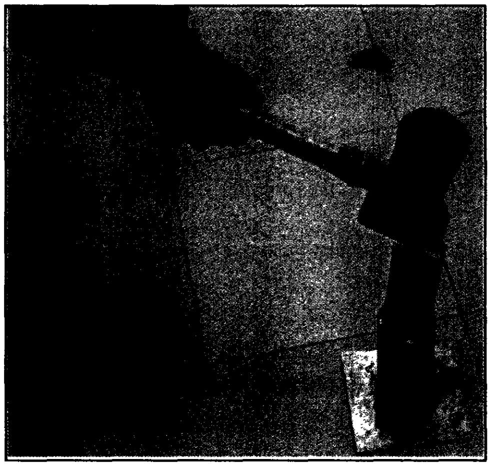


Fig. 5.5c Equipment in use

A 1.788 kg hammer was used to strike a stainless steel piston of the dimensions 1.91"OD x 5.69"H. The same steel pipe from the previous pounding test was used as a channel for the briquette-making die. It was filled loosely with charcoal with a thin disc made out of aluminum sheet metal at the top and in the middle of the channel. The pipe was placed on a wooden disc that was screwed to an aluminum plate set on the floor.

The piston was placed gently upon the charcoal column, allowing it to compress by weight alone. A hammer weighing 1.788 kg was used to strike the piston repeatedly as shown in Fig. 5.5c, until there was no noticeable change in height. After each strike, the depth of the the piston in the channel was marked by drawing a line on the piston along the rim of the channel. The distance between the bottom surface and the lines on the piston were then measured with a pair of calipers and recorded.

Four different trials were recorded. Three were conducted with the same user to determine whether the resulting briquettes were consistently similar or whether there would be an improvement due to practice. One trial was conducted with a different user to determine what role variations in striking technique and force would play.

5.2.2. Observations

During the experiment, several things were noticed about the performance of the equipment and the reaction of the material to this particular manufacturing process. Theories and suggestions for improvements appear below.

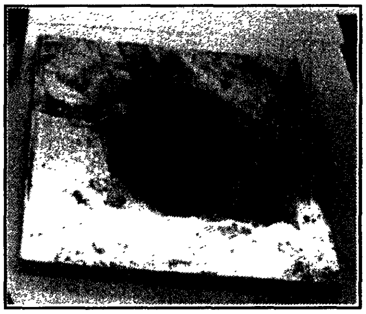


Fig. 5.6a Charcoal on wood

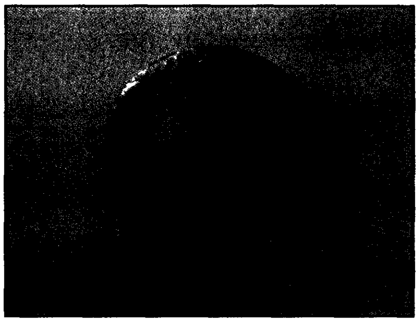


Fig 5.6b Deformed piston top

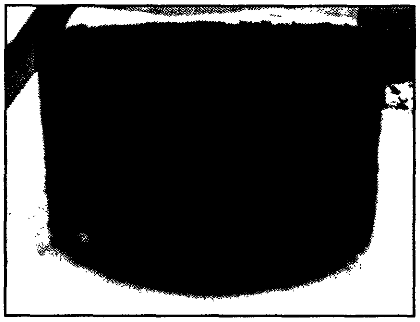


Fig 5.6c Striations in briquette

Adherence to wood

No spacer was used at the bottom of the channel, on top of the wooden disc because high compression forces would cause the screw, which was holding the wooden die to the metal base plate, to form a dent in the spacer. However, the hammer produced forces high enough to make the charcoal stick to wooden disc. This was not observed in the pounding test. More importantly, wood should not be used as the spacer material because the charcoal adheres to it, making the surface in contact more fragile after separation.

Piston deformation

Repetitive strikes form the hammer caused the top of the piston to bulge outward noticeably. The top was measured to be 1.95" in diameter after the completion of the experiment. The bulge is probably due to off-centered or slanted strikes to the piston. Any design in which the entire piston must enter the channel must ensure that a strong enough material is used or that the impact does not occur directly on the piston or that there should be some mechanism for ensuring that all strikes hit center and are directly downward.

Tilting of channel

In this experiment, the users struck the piston with the hammer without holding the channel in place. Since the clearance between the wooden disc and the channel is big enough to allow for as much as 20 degrees of tilt. A slight tilt would also be exacerbated rather than corrected by subsequent strikes. Either a better mounting surface or support structure is needed to ensure that the channel remains vertical during the striking process.

Spacer misalignment

A few briquettes had noticeably unparallel top and bottom surfaces. The alignment of the spacer is crucial to ensuring parallel surfaces for testing, but the spacers do not align themselves in the column as previously hoped. Parallel briquette surfaces are not important to the end users unless the spacers fail to separate the briquettes successfully or if the spacers jam, impeding the compaction of the charcoal underneath. Either thicker spacers or a different loading method is needed to avoid these possible complications.

Striations from extraction process

The extraction process was producing striations, which may serve in as lines of weakness, in the curved surfaces of the briquettes.

Tolerances of parts

Out of the four steel pipes considered for use as a channel for the briquette-making die, only one allowed the piston to pass easily through it. The interior diameter of the pipes vary slightly and are quite rough so each piston may have to be made specifically to match each channel or the clearance would have to be quite high at the cost of allowing for more tilting of the piston in the channel.

5.2.3. Analysis

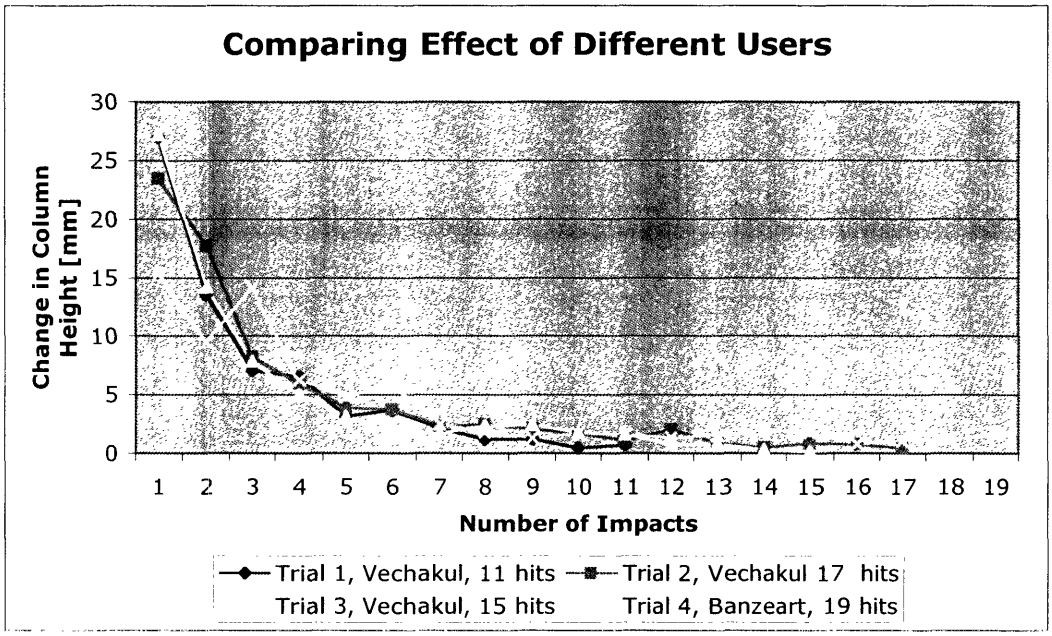


Fig.5.7 Effect of different users in hammering experiment to form cylindrical briquettes.

Optimal number of impacts

It seems as though after about six impacts, the charcoal is no longer compacted significantly, regardless of whether the strikes were consistently the same force. To account for variability of the force applied due to difference in users and inconsistencies in each strike, a mechanical stop is needed to ensure that the same compaction ratio by each cycle. Weaker strikes may require more impacts, but the user would continue to impact load the piston until the mechanical stop is engaged. Less effort would be expended if the user were to press the piston down with body weight as much as possible before beginning to impact load the piston. This change may reduce the number of required hits to four or five.

Increased strength of hammered briquettes

The hammered briquettes produced much better results than briquettes formed at 1000N although they had comparable densities. One possibility is that impact loading created a hard protective surface on hammered briquettes that protected it from being crushed under compression. Another possibility is that changing the ratio of milliliters of binder to grams of charcoal from 1:1 to 2:1 increased the strength of the briquette. It may be necessary to experiment with the binding mixture, reducing the water so that it is enough to dissolve the cassava, but does not interfere with compaction.

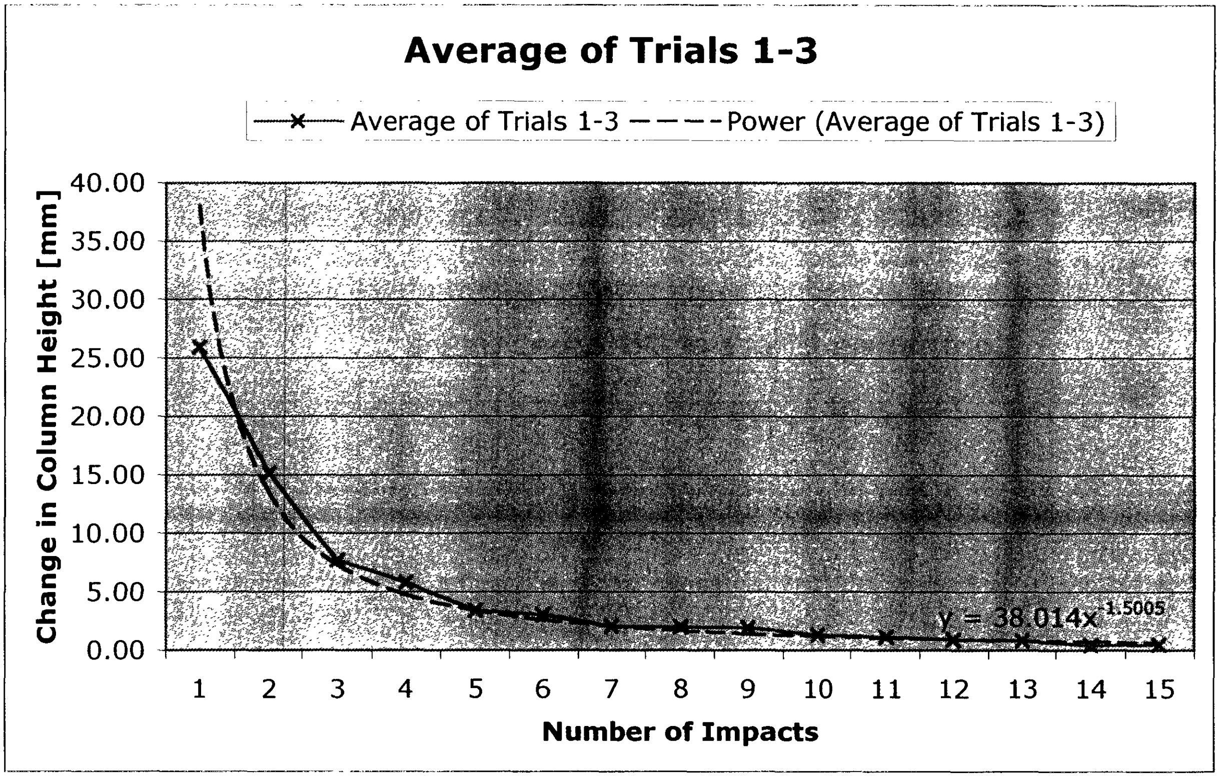


Fig.5.8. Average change in charcoal column height for trials 1-3 with each impact.

Table 5.2 Percentage of height reduction for average of trials 1-3

Number of Impacts	Briquette Height [mm]	Percentage of Start Height
0	52	100%
0 (weight of piston)	43	82%
1	30	58%
2	23	43%
3	19	36%
4	16	30%
5	14	27%
6	13	24%
7	12	22%
8	11	20%
9	10	18%
10	9	17%
11	8	16%
12	8	15%
13	8	14%
14	7	14%
15	7	14%

5.2.4. Comparison with Pounded Briquette

<ins>Compaction ratio</ins>

The ratio between initial and final height of the charcoal column increased from about 2:1 with the clover and pounded briquettes to about 4:1 after only six impacts and 7:1 after thirteen impacts with the hammer. Figures.5.9a and b also shows that the hammered briquette has significantly smaller grains than the pounded briquette.

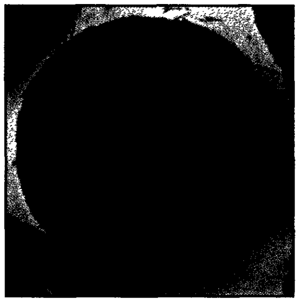


Fig. 5.9a. Pounded.

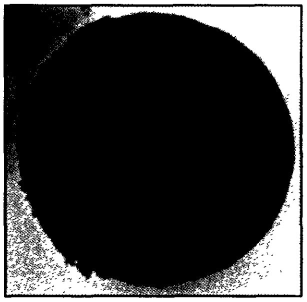


Fig.5.9b. Hammered.

5.3. Side-Loading Pile Driver with Central Shaft

The hammer test was a sufficient proof-of-concept that impact loading from a separate heavy weight striking the piston could produce enough force to form adequately strong briquettes. This marks the beginning of the detailed design of a prototype to further analyze the feasibility and factors associated with impact loading.

Several tests will be performed to experiment with the press design and possible features. Changing directions from a cylindrical channel to a rectangular box would facilitate experimentation with side-loading and a central shaft that would allow for making briquettes with holes. It was hoped that multiple features could be tested through modification of the same prototype. Although any final press design would be adapted to have multiple channels so many columns of briquettes could be formed in parallel, only one column was tested for prototyping purposes.

Having a central shaft makes it necessary to have a matching hole in the piston or a hollow piston that would not be impeded from entering the channel by the rod. Adding a hole increases the surface area of burning, which would release more energy more quickly. This may have detrimental effects if it weakens the structural integrity of the briquette, causing it to disintegrate more quickly while burning and crumble instead of burning completely. A positive consequence of increased surface area is the increased rate of heat released, which would produce higher temperatures. Burning tests must be conducted to investigate the influence of adding a hole, but it is not within the scope of this thesis to do so.

The following sections provide an explanation of how the design for the impact loading prototype was conceived, a description of the components of that prototype, the general procedures by which it is used, and an analysis of the advantages and disadvantages of this particular embodiment of the impact loading concept.

5.3.1. Motivation for Box Channel

Although a more drastic change in design would have less correlation with previous tests, more could be learned by switching from a cylindrical channel to a box-shaped channel. The channel was designed to have a square cross-section because it was conducive to side-loading and tight arrangement of multiple channels. Box-shaped briquettes may also be packed more carefully together so they may not degrade as much during transportation.

Ease of splitting and closing channel
An experiment was conducted to test an alternative loading method from pouring charcoal in at the top and forcing it out of the bottom of the channel. This change in loading and unloading procedures has the potential to expedite the briquette-making process and improve briquette quality by reducing the tendency to create lines of weakness during briquette extraction.

Switching to a box would facilitate experimentation with side-loading. It is not as easy to test this concept with a cylinder because it is inherently harder to align two halves of a cylinder than to close one side of a box. It is necessary to be able to remove a side of the channel easily and seal it well before standing the charcoal column upright because charcoal fines would spill out from any significant gaps or openings in the channel.

Multiple channels
All prototypes were tried with a single column, but the potential for extending the design to multiple channels was always kept in mind. Square channels are easier to group together because they can be placed directly next to one another and can even share the same walls. This is not possible with cylindrical channels.

Packing and transportation
Box-shaped briquettes can also be packed more tightly, and can be shipped in boxes rather than bags to reduce the tendency for abrasion from rubbing against one another. However this packing process would take more time, and boxes may not be readily available.

5.3.2. Hypotheses

Loading
The cross section of the channel must be small (approximately 2 inches in the critical dimension, be it diameter for a circle or side length for a square) because the greater the area, the lower the compression pressure that can be achieved with the same force. However, it is difficult and time-consuming to pour the charcoal mixture into a small opening. Loading the channel may be optimized without affecting the achievable compression pressure if the direction of filling is perpendicular to the direction of compression.

Inserting spacers
Unless the spacers have some thickness, they tend to misalign when dropping. Since they do not fall on a flat surface, but rather a mound of charcoal, they do not become level once in position. It may be easier to insert and align the spacers if they can be pushed into the filled trough rather than dropped down a long channel.

Spacer alignment
Spacer alignment is important because the spacer will not divide the briquettes or may jam if not properly placed. It was unknown whether the central shaft would cause the spacers to jam or to keep them more aligned. It was also hard to predict whether the spacers had to start on the shaft

or whether the shaft would be able to locate the hole in the spacers as the spacers were forced down by the piston.

Unloading

When briquettes are forced through the end of the channel, friction from the walls of the channel elongate the briquette causing striations or gaps. The striations created by forcing the briquettes through the end of the channel form lines of weakness, along which the briquette fractures when compressed.

Square briquettes with a circular hole in its center were found to be weaker from such striations and would fracture perpendicular to the cylindrical axis more often than cylindrical briquettes [Bateman & Harrison & Ljubicic, 2005]. If the briquette could be removed from the channel without being allowed to uncompress, it is presumed that their strength would be increased due to a lack of striations or obvious lines of weakness. It was hoped that it would be easier to remove the briquettes if the user could pull the central shaft, which would engage the spacers and not the briquettes directly.

5.3.3. Description of Equipment

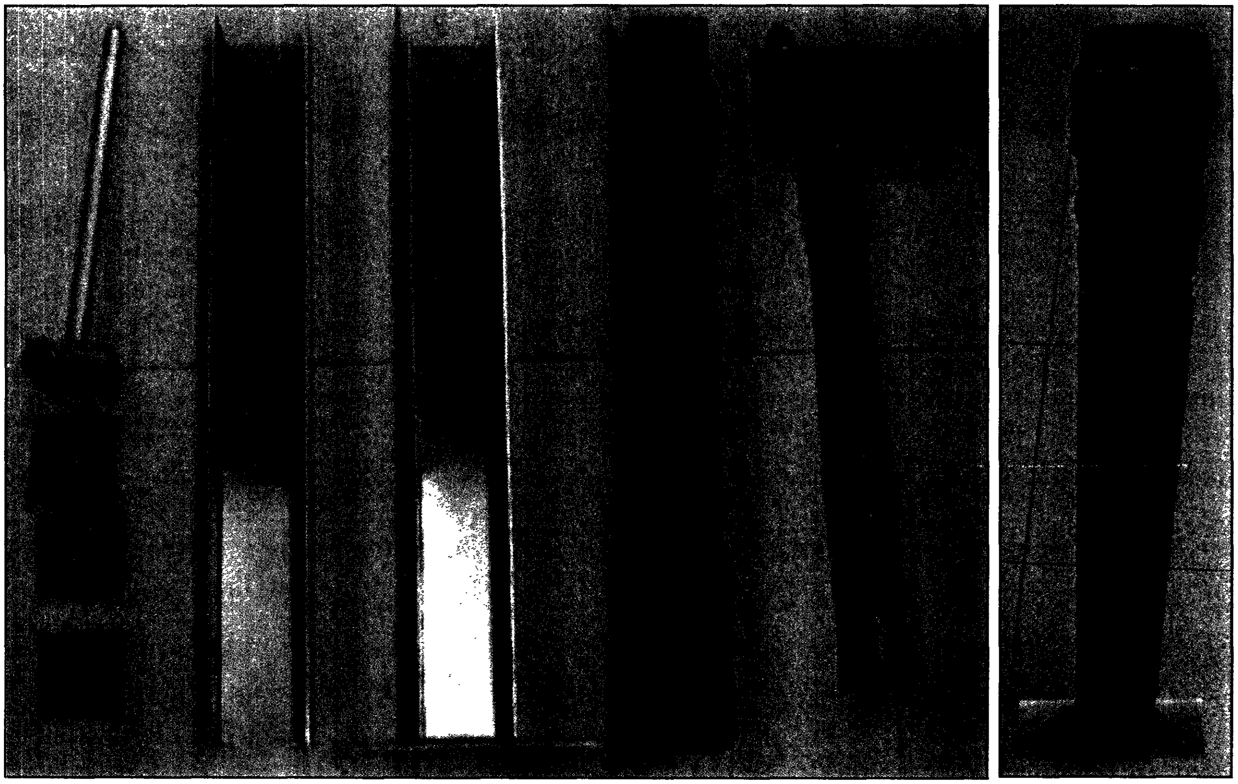


Fig.5.10a. Final prototype: central shaft, channel halves, piston, hammer. b. Assembled press.

Channel

Two 18" long 2"x2" U-channels were formed out of 1/16" aluminum sheet metal. Thicker aluminum sheet could not be bent into a U on the bending break, and cracked after even a small bend was made. One of the U channels was made from a 20" long sheet so that a bottom plate could be bent up to close one end of the U, and make it easier for filling. The extra material also left a 2" protruding tab on each side of the U for foot plates to stabilize the column once it was upright. This channel is meant to be the loading trough for which the other channel could serve as a cover.

Piston

A 2"x2" hollow square extrusion was used as a piston. The piston is 18" long, which allows for enough room for a handhold between the striking surface and the mechanical stop where the piston is prevented from going further into the channel. The handhold is meant to increase stability and ease of lifting the piston when switching between channels in later models. A hollow piston is desirable because it allows for experimenting with punching holes in the briquettes.

Central shaft

The central shaft is meant to be used with the side-loading U-channels. A 0.5" OD x 9" long central shaft with a 0.25"x 20 tapped hole screwed to a 2"x2"x0.75" wooden square. The screw was countersunk into the square to allow the square to sit flat at the bottom of the channel, holding the central shaft vertical to punch holes in the briquettes. The central shaft was filed down on a lathe to give it a rounded, slightly pointed top to allow it to pass more easily through the briquettes. Holes measuring 0.5" in diameter were drilled into the center of four 2" square 1/16" thick aluminum spacers and filed out slightly to allow the central shaft to pass free through.

Mechanical stop

A mechanical stop was made to stop the piston from going further into the channel once it was 4 inches from the bottom of the channel. This would ensure that the four briquettes produced would each be about an inch tall. If the 18" channel was filled entirely to the top, the maximum compaction ratio would be 4.5:1. Since the assumed ideal compaction ratio is about 4:1, this allows for a slight error in filling. To serve as a mechanical stop, a 1/16" thick sheet of aluminum was bent into a U-channel with three 2" sides that are 4 inches long, and bolted to the top of the piston. In order to ensure that repetitive impacts from the mechanical stop would not damage the channel to the extent that it would no longer allow the piston to enter or the cover to close, a bicycle tire inner tube was wrapped around the bottom edge of the mechanical stop. It was wrapped around the entire handhold area as well, to provide better gripping surface and protection from the bolts holding the aluminum part of the mechanical stop to the piston.

Spacers

The spacers are 2" x 2" squares that were cut on a band saw from 1/16" thick aluminum sheets. Four spacers were made without any holes, and four were made with 0.5" circular holes drilled in their centers to allow room for the central shaft.

Hammer

A 16" long steel sledge hammer weighing 1.788kg was used to strike the piston. It was held with one hand about 2 inches from the head and the other equally far from the end of the handle. More force could have been generated if the hammer was held at the end, but this technique was used in an attempt to minimize the effects of a lever arm and to approximate the hammer as an accelerated mass.

5.3.4. Procedures

Without Central shaft

The loading trough was filled loosely with charcoal and the spacers were inserted into the charcoal. The cover was put over the loading trough, and C-clamped at the top and bottom. The piston was allowed to rest on the charcoal, compressing it with its weight alone. The user then compressed the charcoal further with body weight, and then proceeded to hit the piston with the hammer until the mechanical stop was reached or until more impacts seemed unreasonable because increases in displacement were minimal.

With central shaft

Three spacers were inserted on the central shaft, and the central shaft was placed in the channel with the wood base flush against the bottom panel. The spacers were then arranged at equal distances from each other on the central shaft, with the last one being flush against the wood. The last spacer must be placed next to the wooden base to protect the bottom briquette when the stack is being removed from the central shaft.

Once the spacers were aligned, the trough was filled with charcoal. This method was easier than inserting spacers into a charcoal-filled trough because it does not require an extra step to fill the gap created by the insertion of the spacers.

Another spacer was inserted into the trough above the central shaft to determine whether the spacer would slide onto the central shaft during compression or whether all spacers must be placed along the central shaft beforehand. The cover was then clamped over the trough, and the same impact procedures as described above for using the side-loading box without the central shaft.

5.3.5. Observations Without Central Shaft

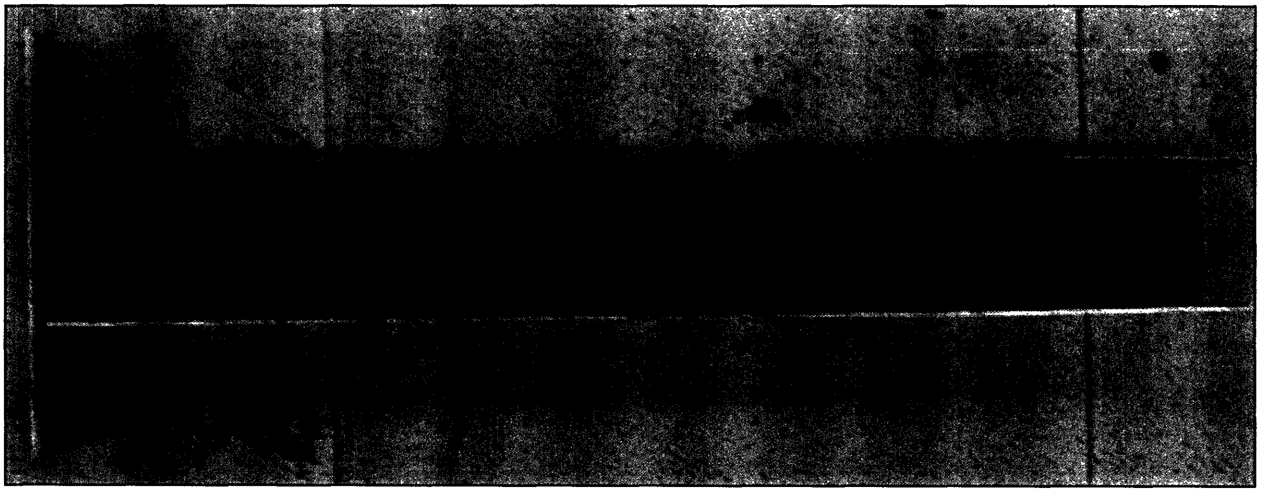


Fig. 5.11. Charcoal-filled trough with spacers inserted at equal intervals.

Loading

Filling the trough was not noticeably easier than pouring charcoal through a funnel into the top of the channel. Since the trough was so narrow, it was still a bit of a meticulous task to ensure that the charcoal filled the entire length of the trough evenly without leaving gaps or overflowing. It is presumed that the benefits of side loading will not be significant until the loading area is increased in both directions.

For one channel, the loading area increases by a multiple of 8:1 when converting from top-loading to side-loading. However, since the one side is still only 2 inches long, it requires precision in that direction. If four channels were side-loaded instead of top-loaded, the increase in area would be 8:1, but it is much easier to fill four troughs that have a combined cross sectional area of a 8" x 16" rectangle rather than a row of four channels that have the equivalent area of a 2"x 8" rectangle. Also, for top-loading, it matters how much charcoal enters each channel because a spacer must be inserted at discrete intervals. For side-loading, the channels are entirely filled at the same time and all spacers are inserted afterwards.

Inserting spacers

It was harder to insert the spacers in the charcoal-filled troughs than initially expected. If the charcoal were packed tightly, forcing the spacer into the trough would take more force, but the charcoal would hold the spacer in place once it was inserted. In order to place the spacers in the trough, it was necessary to wiggle them in between fibres of charcoal that could not be easily broken by pressing down on the spacer. Wiggling the spacers created a gap in the charcoal right next to the spacer, making it easier to insert but less likely to stay aligned. If the charcoal was not shifted to fill the gaps and pack in the spacers, the spacers would tilt once the channel was placed upright. Tilted spacers can sometimes become jammed against the sides of the channels, inhibiting the briquettes below it from being adequately compressed. The grain stucture in the briquettes below the misaligned spacer is noticeably larger than the ones above it, suggesting a large difference in density and compaction.

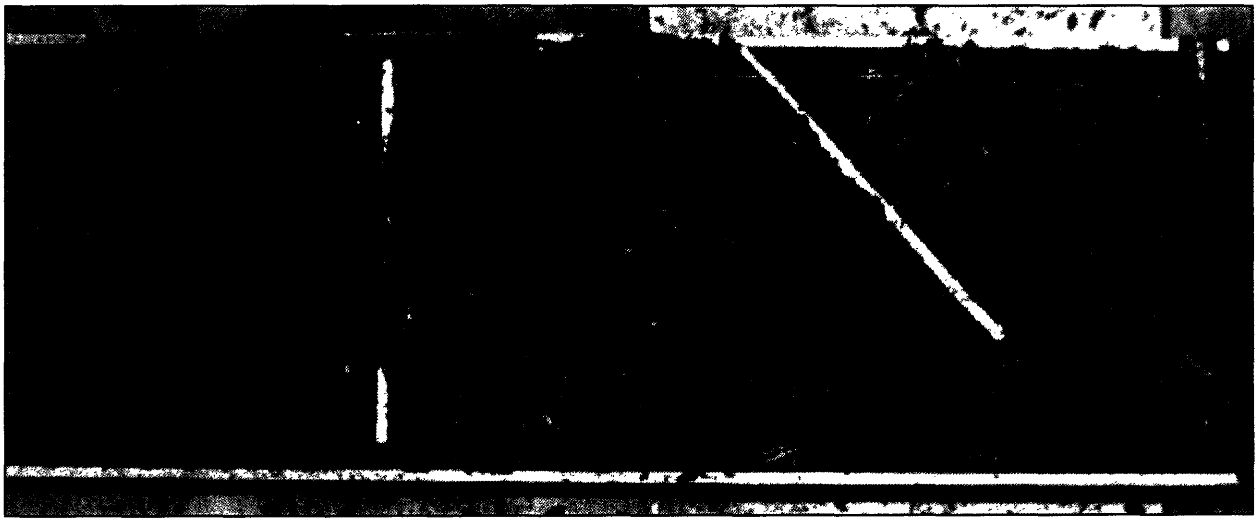


Fig. 5.12. Misaligned spacer prevents charcoal below it in the channel from being compressed.

The technique of filling the spacer gaps with additional charcoal rather than rearranging the charcoal already in the trough, proved to be the most effective. However, the attention that this operation requires raises doubts about whether it is indeed the most efficient.

Unloading

The briquettes would not fall out of the channel even when turned upside-down because the walls were bent outward during the compression stage, and acted like a spring clamp as they tried to return to their original shape.

It was difficult to remove the briquettes from the U-channel without having access to the bottom. The bottom spacer was pressed firmly against the bottom panel and the briquettes were squeezed between the side walls, so there was no way to grip the briquette from two opposite sides. Only the top was accessible, so the only way to remove the briquettes without damaging them was to pry apart the channel walls, which allowed them to slide out quite easily. Trying to pry the briquettes out directly caused the edges to crumble.

The foot plate became detached after aluminum became weak and cracked from repetitive bending due to the tilting of the channel. It was possible to load the channel by holding the foot plate over the channel outlet while filling. Moreover, it was easy to grasp the briquettes and pull them out of the channel because the bottom was removable and would not inhibit access to the briquettes. No striations were visible on any surface of the briquettes, suggesting that extraction from the sides causes less damage than pushing the briquette through the channel.

5.3.6. Observations with Central Shaft

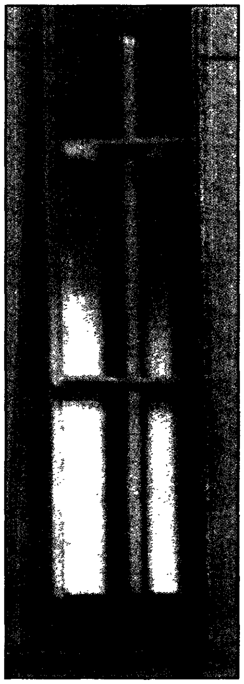


Fig. 5.13b. Inside view after compression with central shaft.

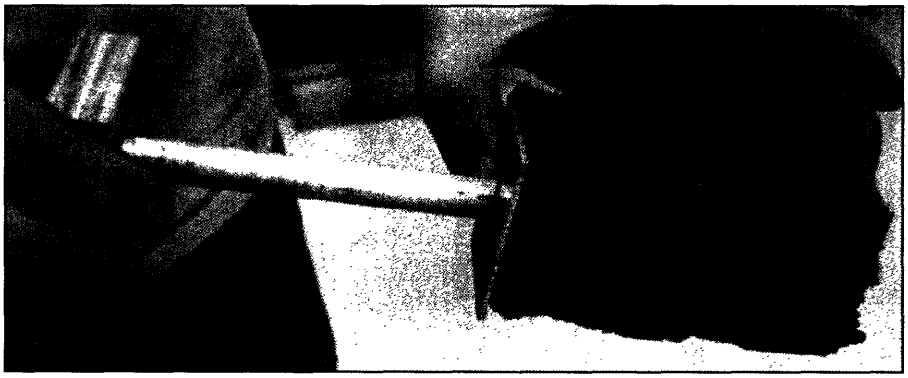


Fig. 5.13a. Central shaft and spacers in channel before filling. c. Extracting briquettes from shaft.

Spacer alignment

The rod did help to keep the spacers aligned. The central shaft limits the degree to which the spacers can tilt with the amount of clearance that is left between the central shaft and the hole in the spacer. Although the contact between the central shaft and the spacers adds to the friction resisting compaction, this frictional force is mostly negligible since most of the force is causing the spacer to slide along the central shaft rather than directly against it.

Unloading

Since the central shaft has a bottom plate, there is no need for a for a removable bottom panel, which makes the construction of the press body easier. The central shaft did help as expected by allowing the user to pull the briquettes out while the spacers sandwiched and protected them. This behavior probably applies up to a certain limit of briquette cross sectional area to hole diameter. Once the hole size increases to the point where the remaining briquette walls are not strong enough to remain intact even when sandwiched between spacers, the briquette will become damaged.

Decreased cross sectional area

Adding the 0.5"OD hole decreased the cross sectional area of the 2" square briquette from 4 in^2 to 3.8 in^2, increasing the compression pressure achievable for a certain applied force.

Rough edges

By twisting slightly and pulling on the bottom spacer, the briquettes could be pulled off of the central shaft with no noticeable damage. The spacer next to the wooden base protected the bottom surface of the bottom briquette. Although the edges next to the spacers were rougher and more fragile than the edges formed by compression into the inner edges of the channel, the edges of the hole did not crumble when brushed with a finger. The edges were sharp and well-compacted because there was a tight fitting spacer at the top and bottom of every briquette to keep the hole from widening or causing cracks in the surface as the central shaft was pulled out.

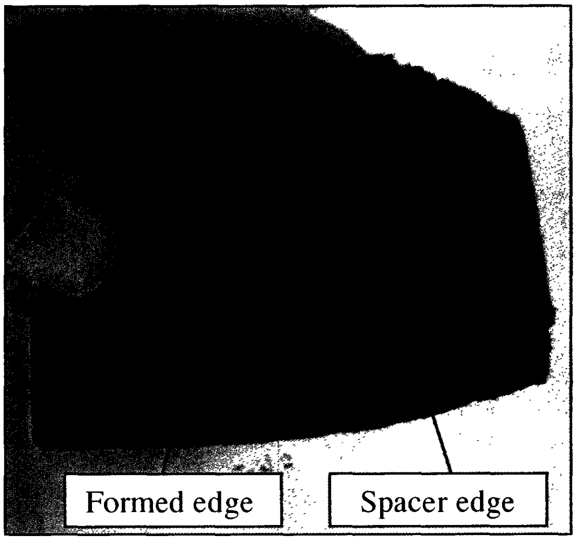


Fig.5.14a. Edges of solid square briquette.

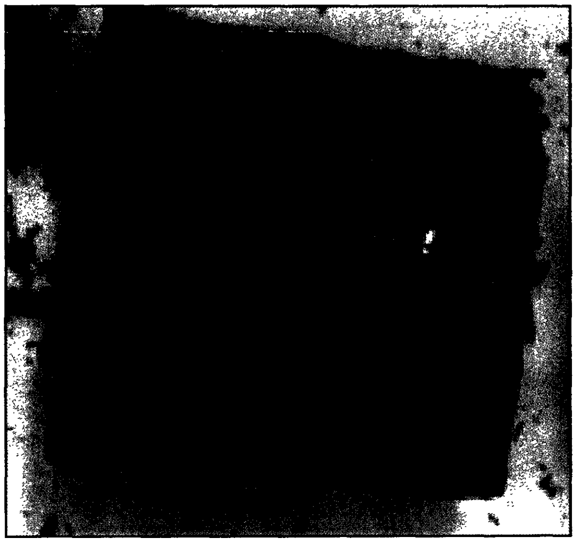


Fig.5.14b. Edges of square with hole.

5.3.7. Analysis

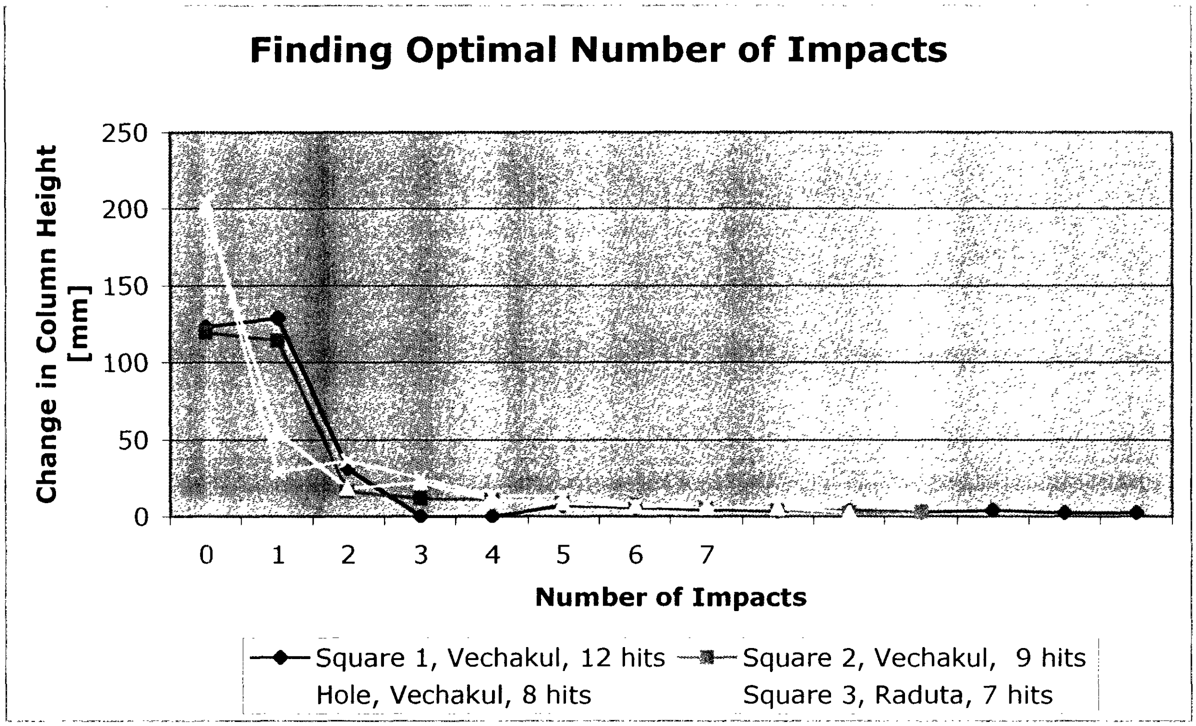


Fig. 5.15. Effect of different users in hammering experiment to form square briquettes.

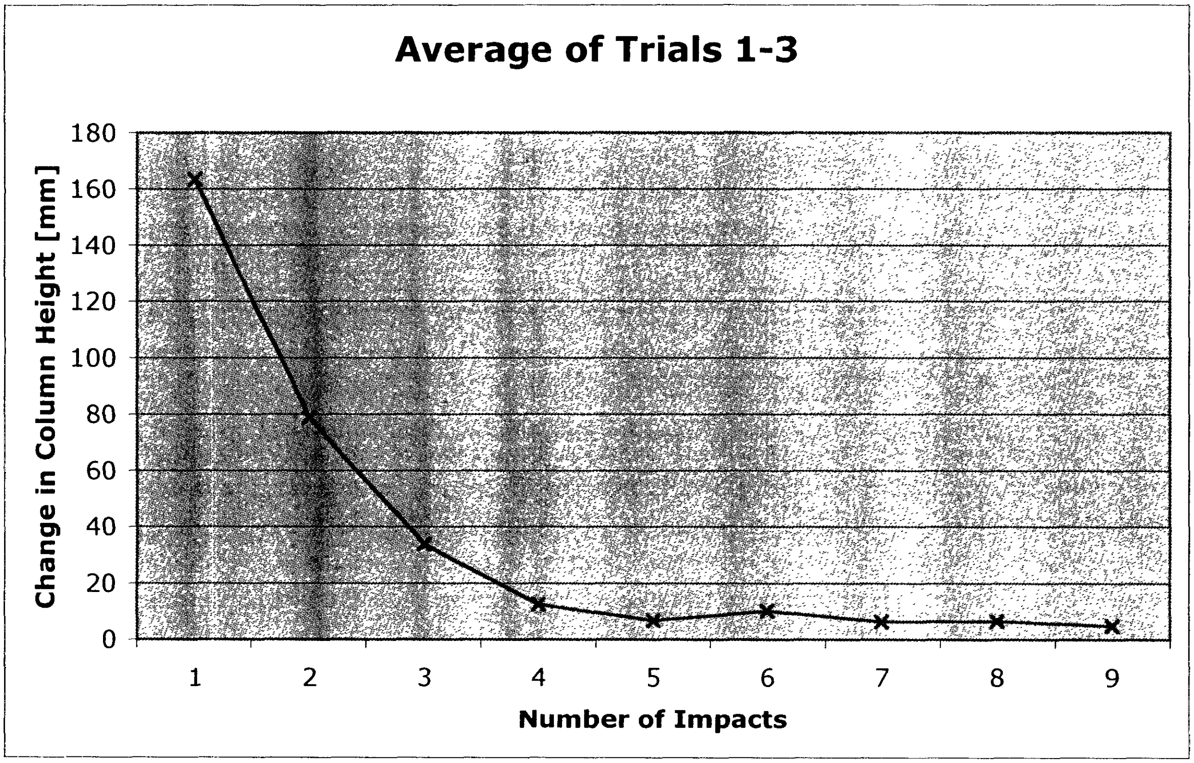
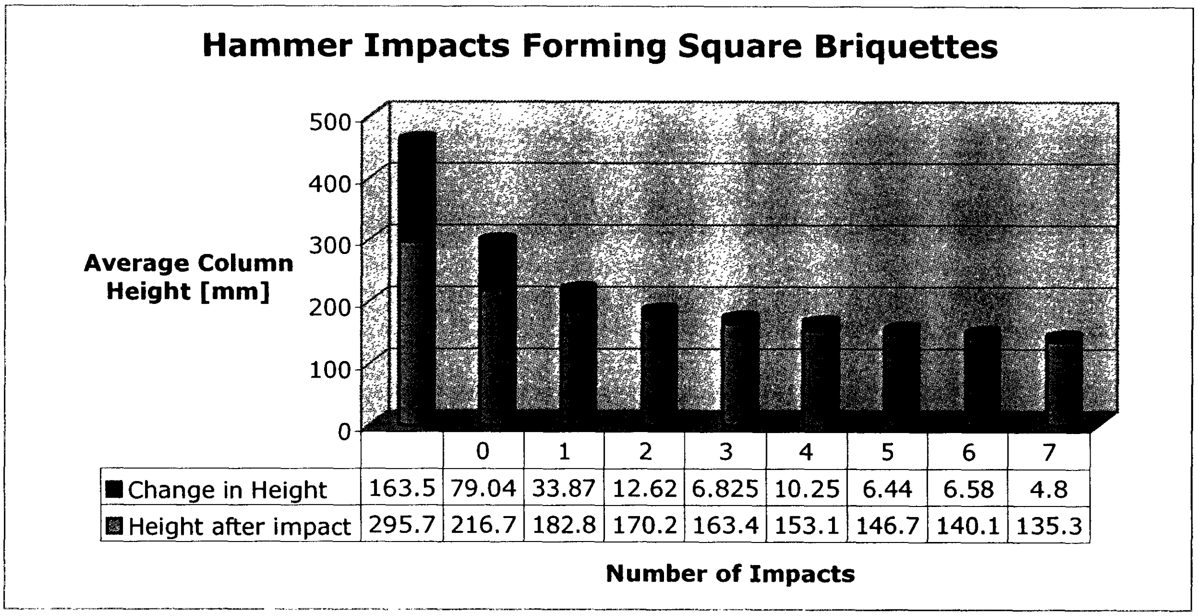


Fig. 5.16. Average change in height with number of impacts



		0	1	2	3	4	5	6	7
■ Change in Height	163.5	79.04	33.87	12.62	6.825	10.25	6.44	6.58	4.8
▨ Height after impact	295.7	216.7	182.8	170.2	163.4	153.1	146.7	140.1	135.3

Fig.5.17. Visual representation of change in charcoal column with number of impacts.

5.3.8. Advantages and Disadvantages

Bottom panel

It was useful that the loading trough had a bottom in addition to the walls that formed the U. When filling the channel, it was easier to pack the charcoal when it was constrained in 4 directions by a combination of walls and spacers. The mouth had to remain open to leave an opening for the piston.

The top was a bit more difficult to fill because there was nothing to keep the charcoal from falling towards the mouth of the channel. After the trough was filled and covered with the other U-channel and stood straight up, a spacer could be dropped into the mouth and pressed against the charcoal to make the top level. This technique seemed to work well because the top briquettes consistently had a flat and level top surface. However, the same technique could not be used for the bottom of the channel so the channel needs a fixed bottom cover at least for the loading stage.

Foot plate

The user could step on the protruding bottom panel to keep the channel upright since it was inherently unstable and tended to tip especially after each impact. However, the bottom panel must be fixed to the U-channel walls either by welds or latching mechanisms because the folded metal weakened and eventually broke off due to the tilting of the U-channel. A foot plate may not be necessary if several channels were connected together, giving the whole structure a wider base for support.

Bent U-channel walls

The bent aluminum sheet was not strong enough to adequately confine the charcoal in the horizontal direction. The pressure on the charcoal forced the walls outward, but once the compression force was relieved, the walls wanted to return to their original orientation and acted as a sort of spring clamp, holding the briquettes in the channel during the unloading stage. If U-channels were to be used, the walls would have to be rigid or fixed to prevent this spring clamping action.

It is possible that some of the impact force was lost to bending the U-channel walls outward. If the walls were rigid, energy would not have been dissipated into deforming the walls.

Spacer alignment

There is a small gap between the charcoal and the U-channel cover because the loading trough cannot be filled to the brim without a significant amount of spill. When the channel is placed upright, the charcoal slides to fill this gap, and causes the spaces to tilt downward towards the cover. The tilting of the spacers not only produces slanted briquettes, it also prevents lower briquettes from being compressed as much because the spacers become an obstruction when jammed against the channel walls.

Misalignment of the spacers also leads to rougher edges because as the spacer tilts, it allows more contact between the two briquettes it was meant to separate. The two briquettes are joined along these lines of contact so when they are separated, the lines become rough edges which are weaker than formed edges.

Perhaps the best spacer material would be a sturdy but flexible material, like plastic. A thin piece of plastic could probably be inserted into the charcoal. It could be oversized to not allow any charcoal to touch even if it were misaligned slightly. However, it must remain flexible enough to conform to the walls and not prevent the charcoal underneath from being compressed.

Protection of briquette surfaces

Enough spacers must be made so that there can be one at the top and bottom of every briquette. For example, if four briquettes are to be formed, five spacers are required so that there can be a spacer between each briquette, and one on the top and one on the bottom of the entire stack. This allows the user to hold or push against the briquette stack without damaging any surfaces.

Charcoal column height

The top briquettes were noticeably more compressed than lower briquettes. Not only were the top briquettes shorter and less fragile, the grain structure was visibly finer. This suggests that most of the force is going into compressing the uppermost briquettes, and only a portion of the force is actually being transmitted to the lower levels. This correlation was not seen with the 2" diameter cylindrical briquettes, which were formed with two briquettes per column.

Friction

The side surface area actually remains the same at 6.28 in^2 for a 2"OD x 1"H cylinder and a 2"L x 2"W x 0.78"H square, which are briquettes of the same volume. This suggests that squares and briquettes would experience roughly the same amount of friction if the normal force were the same. However, it is difficult to speculate about the lateral force distribution and direction for square or cylindrical briquettes.

Cross-sectional area

It was significantly harder to compact the charcoal, even though the increase in cross-sectional area was only 21.5% from an area of 3.14 in^2 for a 2" diameter circle to 4.00 in^2 for a 2" square. Experimenting with a 1.75" square with a cross sectional area of 3.06 in^2 may produce more comparable results to the 2" diameter circle.

Possible misuse

Since the driving mechanism relies upon the use of a hammer, the process is not standardized. With variations in type and characteristics of available hammers, the effect on the press and the quality of briquettes may also vary. It was hoped that the mechanical stop would ensure standard compression ratios, but striking with different hammers may result in longer batch times, multiple impacts, or other variations. Indirect or slanted hits from the hammer could also deform the piston or channel. As an alternative to using hammers, rocks could be used as a replacement, but with some decrease in safety, applicable force, and user friendliness.

Central shaft

Incorporating a hole punching mechanism makes the design of the press slightly more complex and increases the cost due to that complexity and the need for more material. However, it helps to keep the spacers aligned and greatly increases the ease with which the briquettes can be removed so it is worthwhile as an additional design feature.

Briquettes with holes

A hole in the center of briquette would increase the surface area, thereby increasing the amount of heat released during burning. However, a hole weakens the structural integrity of the briquette and causes it to fracture more easily.

5.4. Compression Testing

Briquettes formed in the prototypes described above were tested to determine their relative compressive strengths. It was found that the compressive strengths correlated more with material density than briquette geometry or production method as shown in Figure 5.20.

The compressive strength of the briquette is assumed to correlate directly with its durability during transportation. Compressive strength is defined to be the maximum load a briquette can withstand before cracking or crumbling (Richards, 1990).

5.4.1. Description of Equipment

The Zwick machine will serve as an instrumented compressing device, allowing parameters, such as height displacement and applied force to be recorded. It is a single column, screw actuated, universal testing machine with a 2.5 kN load cell which records the applied force as it gradually increases. The preload was set to 0.5 N, below which no force will be recorded. The test speed was set to be 25 mm/min with a maximum extension of 12 mm. Two parallel platens with facial areas greater than that of the briquette were attached to the Zwick to provide smooth and level compressing surfaces.

5.4.2. Procedures

To determine compressive strength, the suggested procedures in Richards' *Physical Testing of Fuel Briquettes* were followed (1990). For each test, a cured briquette is placed in between the horizontal parallel platens of the Zwick. In general it is tested in its weakest orientation if it is practically achievable. Although the weakest orientation for a cylindrical briquette may be on its curved edges between its flat and curved surfaces, it is not feasible to hold it in this unstable orientation for testing. Thus, most briquettes were compressed radially, along their the curved surfaces. The platens theoretically make a line contacts with the curved surfaces of the briquette, and failure occurs as a result of tensile forces along a plane connecting the lines of contact between the briquette surfaces and platens.

5.4.3. Observations

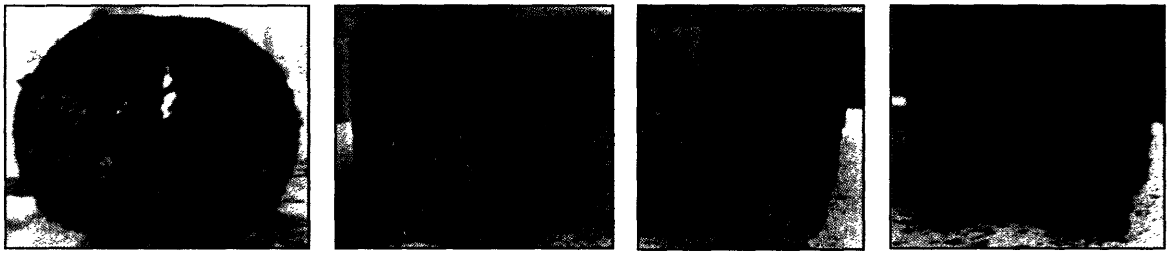


Fig. 5.18. a. Hammered cylinder front-fracture. b. Hammered square front-fracture. c. Hammered square side-fractured. d. Hammered square with hole multi-fracture.

Hammered cylinders: variable fracture

The hammered cylindrical briquettes fractured either along its front face (Fig. 5.18a) as expected or along its side following striation lines. The denser briquettes tended to fracture along its front face rather than on its side, suggesting that forcing the briquettes through the channel to extract them formed fewer striations in denser briquettes.

Hammered square: variable-fracture

Some square briquettes fractured on the front face (Fig. 5.18b) and some fractured on the side face (Fig. 5.18b), indicating that there was no preferential direction for fracture. In the cylindrical briquettes, geometric factors resulted in dominant tensile force along a central plane causing the briquettes to typically fracture on its front face.

Hammered square with hole: multi-fracture

The squares with holes tended to fracture along several lines in its front and side faces. It was difficult to determine where fracture initiated because several lines would appear almost simultaneously. This suggests that the hole changes the fracture mode from a single clean fracture to a multi-fracture.

Interestingly, the hole does not decrease the compressive strength of the squares, as shown in Table 5.4. Density seems not to be the dominant factor either since solid squares with a density of 0.23 g/cm^3 broke at 166 N while squares with holes with a density of 0.21 g/cm^3 broke at 207 N. It is possible that by changing the fracture mechanics of the briquette, the hole increases the compressive strength for a given density. More tests must be conducted to verify this hypothesis.

Overall, these observations suggest that the fracture mechanics of the briquettes vary with formation method, density, and geometry. Although this is interesting to note from a materials point of view, the compressive strength regardless of fracture mode is the parameter of most importance to the end user. Thus, the following section details the compressive strength data.

5.4.4. Analysis

Loading was allowed to continue past the point of failure until a height displacement of 12 mm was reached. Sometimes the force would increase once the platens had come into contact with another portion of the briquette. These false peaks were ignored, and the force at the first maximum as taken to be the compressive strength of the briquette.

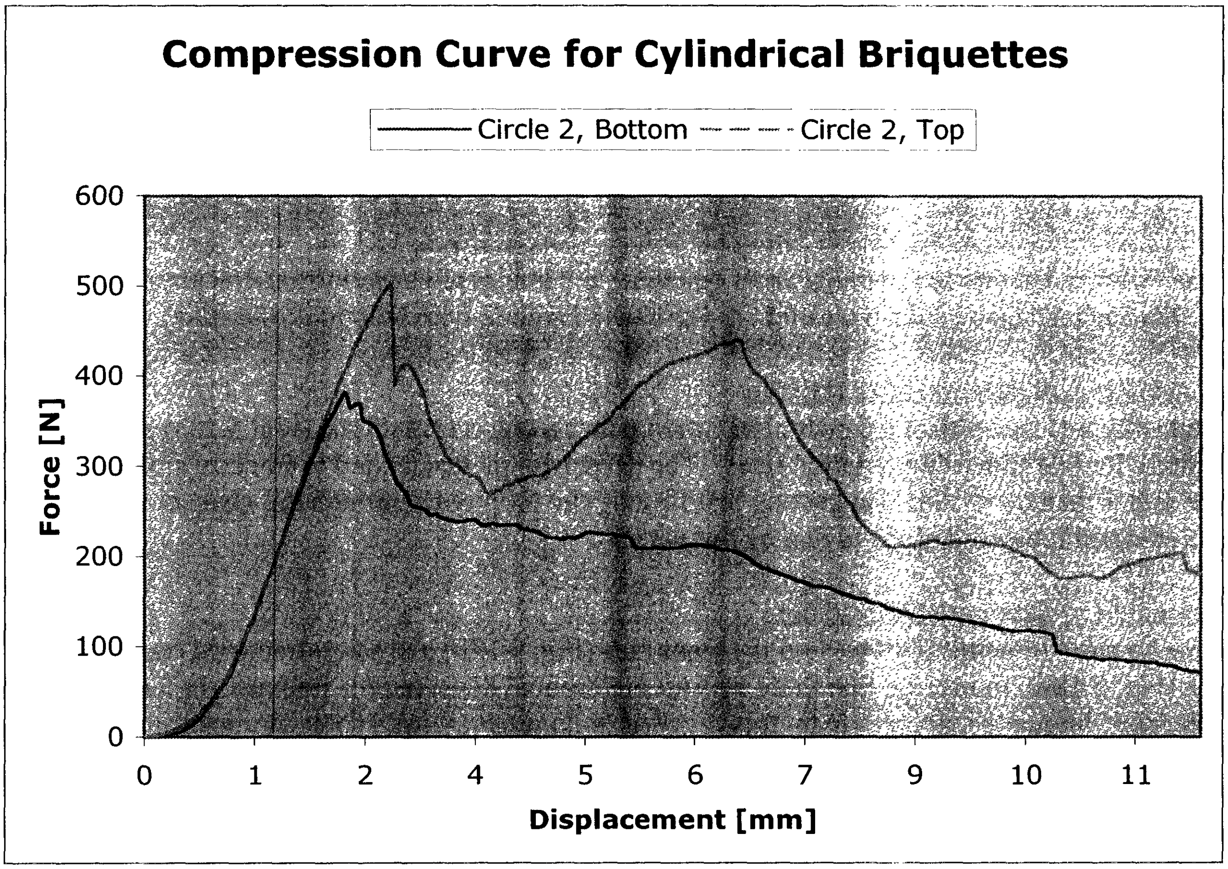


Fig. 5.19. Example of compression testing of hammered cylindrical briquettes formed in series.

Consistent slope

The two curves in the figure had about the same slope, which was true for most of the trials. Since these tests are relatively repeatable, the Young's modulus could be calculated from the slope. It seems that the Young's modulus increases with briquette density and compression strength.

Variation in density with level in column

Two cylindrical briquettes that were formed in series with the same number of impacts, were compression tested individually to produce the curves shown above. Since the briquettes had different densities, they broke under different loads. The briquette on top was denser and had a higher compression strength. The variation in density for briquettes formed in series can be seen more clearly in the table below. In most cases, the topmost briquette was the densest. However, more tests need to be conducted to prove that this trend is not due to errors in density due to nonuniform briquette geometry.

Table. 5.3. Density variation with placement in column

Trial Number	Location	Density [g/cm^3]
Cylindrical # 1	Top	0.32
	Bottom	0.27
Cylindrical # 2	Top	0.3
	Bottom	0.31
Cylindrical # 3	Top	0.28
	Bottom	0.30
Cylindrical # 4	Top	0.28
	Bottom	0.26
Square # 1	Top	0.27
	Middle	0.23
	Bottom	0.19
Square # 2 (with holes)	Top	0.24
	Middle	0.17
	Bottom	0.24
Square # 3	Top	0.24
	2nd from Top	0.24
	3rd from Top	0.22
	Bottom	0.19

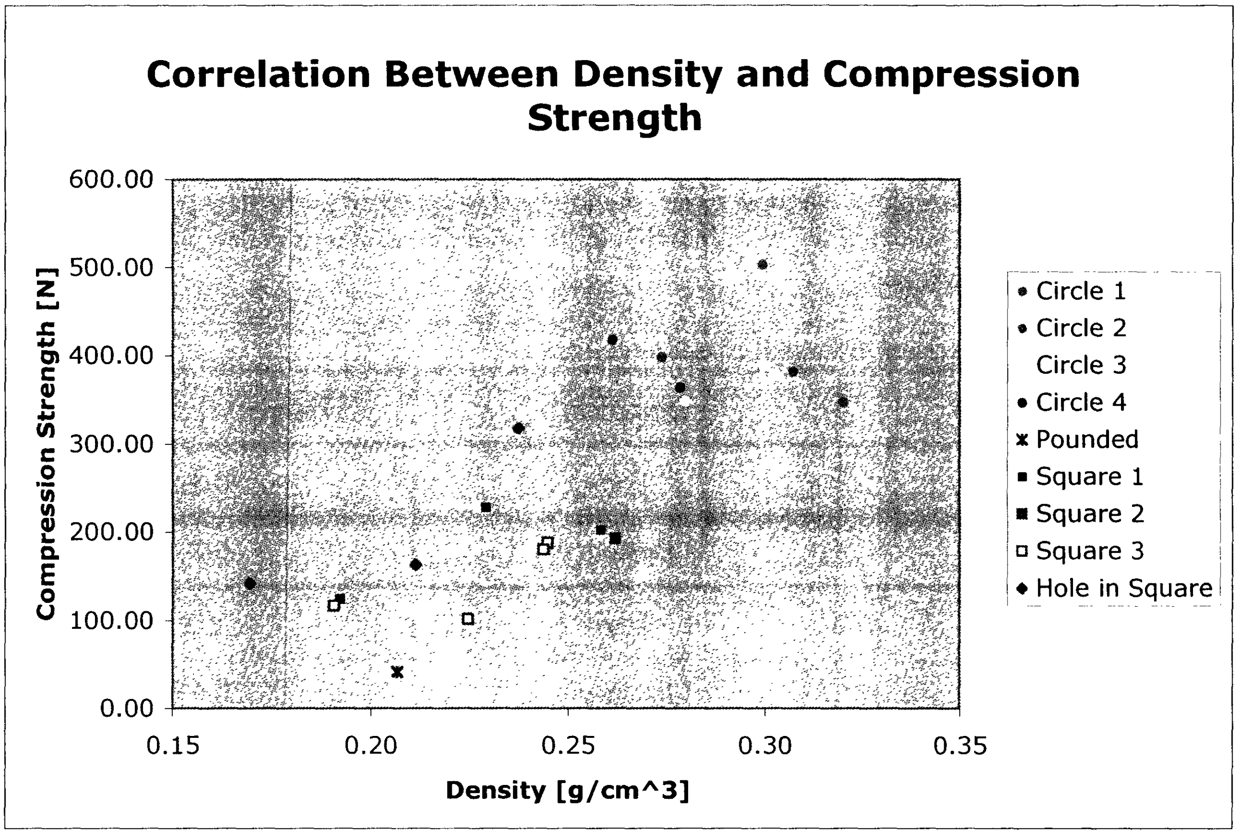


Fig.5.20. Correlation density and compression strength for briquettes formed in prototypes.

Strength increases with density

There is a trend indicating that the compression strength increases with material density. However more tests should be conducted for a wider range of densities to confirm this trend. The graph in Fig. 5.20 shows a noisy scatter plot because there were errors in the calculation of density since the briquettes were non-uniform shapes with some slanted surfaces and irregularities.

Table 5.4 Effect of cross-sectional area and column height on density and compressive strength.

Trial Type	Cross-Sectional Area [cm^2]	Average Column Height [mm]	Average Density [g/cm^3]	Average Compressive Strength [N]
Pounded Cylinder	20.3	104	0.21	41
Hammered Cylinders	20.3	104	0.29	393
Hammered Squares	25.8	453	0.23	166
Hammered Squares with Holes	24.5	464	0.21	207

Effectiveness of Pounding or Hammering

Although the average densities of the pounded briquettes and square briquettes with holes were about the same at 0.21 g/cm^3, the pounded briquette was only able to withstand a fifth of the compressive force. This may suggest that hammering is a much more effective production method than pounding.

Shape factor

Although the 2"OD cylindrical briquettes appear to be of higher density than the 2" square briquettes, this was due to a difference in column height and cross-sectional area, not shape factor. The squares tested had a cross-sectional area about 27% larger than the cylindrical briquettes and were formed in stacks of four rather than two per column. This may have contributed to the compressive strength of the squares being about 42% less than that of the cylindrical. However, if the square and cylindrical briquettes were formed with a comparable cross-sectional area and column height, it is presumed that they would have similar compressive strengths.

Effect of holes

It seems that holes do not weaken the square briquettes because the square briquettes with holes were stronger than those without holes even though the briquettes without holes were denser.

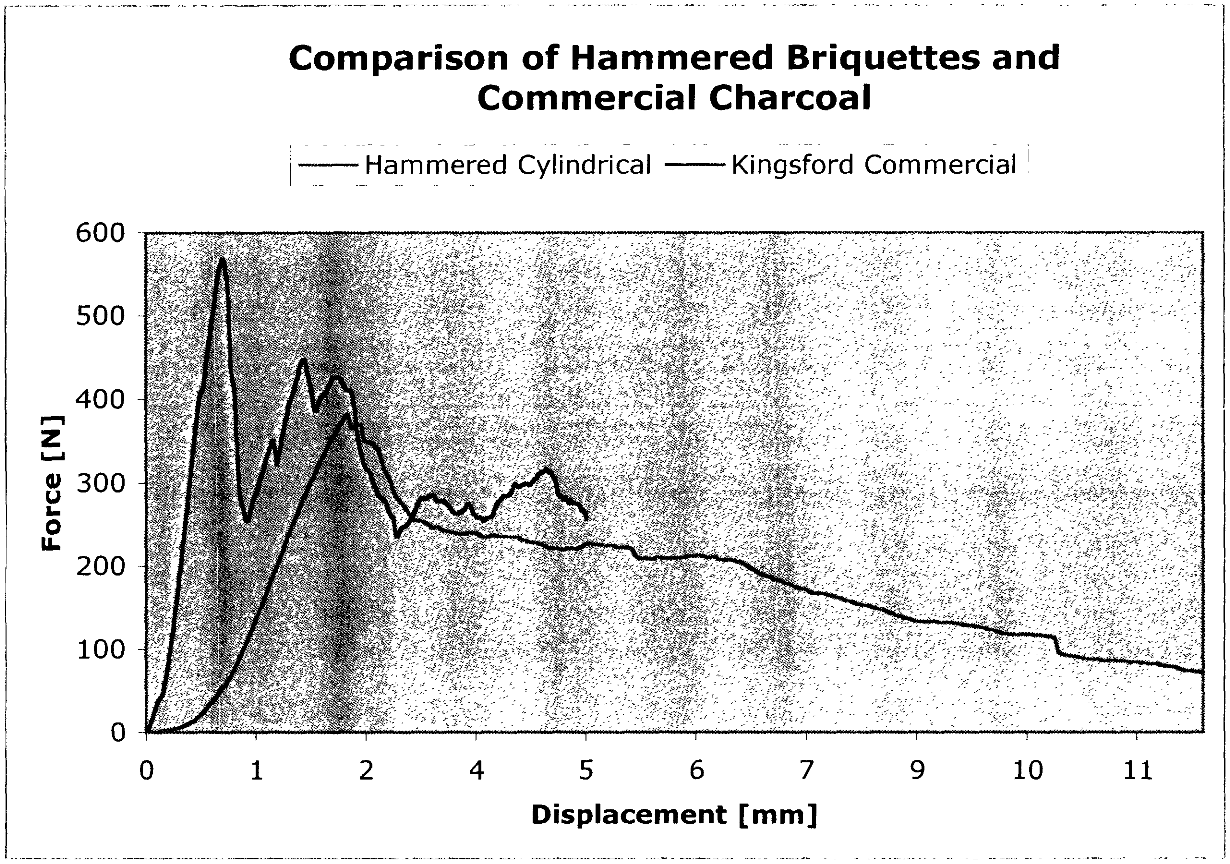


Fig. 5.21 Compression curves for hammered briquettes and commercial charcoal.

The hammered cylindrical briquettes performed better under compression than the briquettes formed in other trials. The cylindrical briquettes were able to withstand an average of 390N which is equivalent to 40 kg or 88 lbs of weight in their weakest orientation (radial). Comparatively, commercial Kingsford charcoal that had been machined into 3cm OD x 2 cm H cylinders were able to withstand an average of 590N of force. The compression curves in Fig. 5.21 also show that the Kingsford charcoal has a steeper force versus displacement slope, indicating that its Young's modulus is higher than that of the hammered briquettes. Since the press briquettes are meant to only perform better than hand-formed briquettes, it is expected that they should not perform as well as commericial charcoal.

The average density of the cylindrical briquettes is about 0.29 g/cm^3, which is 36% of the density of commercial Kingsford charcoal which is 0.80 g/cm^3. Commercial charcoal has additives such as clay, which increases the density of the briquettes. Also, since no correlation has yet been proven concerning material density and burning properties, the hammered briquettes are still considered a promising product.

5.4.5. Implications for Final Design

The square side-loading box with a central shaft performed functionally in terms of operational ease during testing. Since the central shaft improved spacer alignment and facilitated filling and unloading the channel without damaging briquettes, it will be included in the final design as an optional feature. The holes do not seem to significantly reduce the briquette strength, but more burn tests need to be conducted to determine whether it will improve or be detrimental to burning characteristics.

The performance of the hammered cylindrical briquettes suggests that impact loading is a promising method of forming adequate briquettes. They were able to withstand about 390 N of compressive force radially, which is their weakest orientation. Furthermore, the briquettes are likely to be lying on their flat surfaces rather than their curved surfaces, so compressive forces will be primarily axial, not radial. Thus, the briquettes are likely to be able to withstand even higher forces in their usual orientation. This suggests that the briquettes will be able to be stacked for transportation without risk of damage due to the weight of other briquettes resting upon them.

Although the square briquettes were not as dense or strong as the cylindrical briquettes, it is theorized that this is not due to geometric factors, and that the column height and cross-sectional area were optimized, a box-shaped briquette would perform as well as a cylindrical briquette. Thus, the square channel design has been chosen because of its advantages over cylindrical channels for ease of loading and scalability for multiple channels.

Further testing will be needed to determine the maximum number of briquettes that can be formed per column without resulting in too much friction to allow for compression with a reasonable amount of impacts. The compression pressure would also increase with a decrease in cross-sectional area so the shape of the briquette would have to be optimized.

6. FUTURE WORK

6.1. Preparations for Haiti

Amy Smith will visit Haiti in June 2005. She will bring with her any promising prototypes for the Haitians to replicate or adapt to their locally available materials and tools.

The final design consists of six adjacent square channels arranged in a 2 x 3 grid pattern. A hollow square steel extrusion with one closed end will be used as the piston for all the channels. Two opposite outer walls of the grid will be removable, providing access to all six channels for loading. Once each side of four channels was loaded, the corresponding outside wall panel could be clamped into place to close and seal the grid.

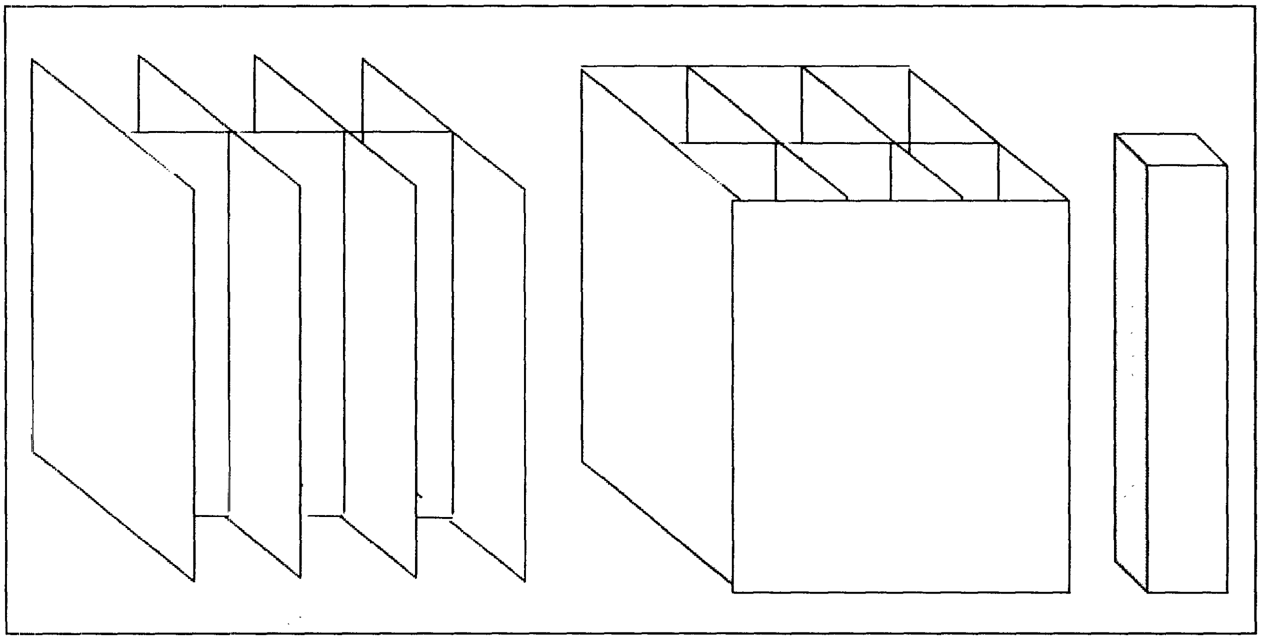


Fig. 6.1. Rough sketch of final design: channels open, channels closed, and the piston.

6.1.1. Adaptations for Side-Loading Box

Rather than attempting to produce the prototype as it would be made in Haiti, it is left to the Haitian metal-workers and technicians to figure out how to adapt the design for production with local materials and tools. Our community partners are inherently more familiar with locally available materials and the local skills and tools so they would be much more able to adapt the prototype design for Haiti. What follows are some suggestions about possible manufacturing processes and materials that may be used in Haiti.

<u>Channels</u>

Since sheet metal bending brakes are not commonly found in Haiti, if they were to bend the channels out of sheet metal, they would have to do so by hand. Although Haitian metal workers are highly skilled, it may be time-consuming and laborious to bend the sheets. An alternative is welding sheets of steel together into a row of channels.

Piston

If hollow steel square extrusions were not available, a 2"OD cylindrical pipe could be used instead. The piston's cross section does not have to match that of the channel because the piston pushes on the top spacer, and if the top spacer is the correct cross section, the charcoal would still be evenly compacted. If pipes were unavailable, a piston could also be made by welding together scrap pieces of steel.

Central shaft

Instead of screwing an aluminum rod onto a wooden square, a steel rod could be welded vertically onto a steel plate.

Mechanical stop

If it is difficult to wrap sheet metal around the top of the piston, pieces of wood could be bolted to the top of the piston to serve as a mechanical stop. The wood would be hard enough to stop the piston from progressing deeper into the channel once sufficient compaction was achieved, but it would not damage the channel from repeated strikes. Designing for failure, it would be preferable and expected that the wooden mechanical stop would fail before the channel, because it is much easier to remake and replace.

Spacers

Sheets of steel rather than aluminum would probably be used for the spacers because steel is more available and less expensive than aluminum in developing countries. Wooden spacers are not recommended because of the scarcity of wood in Haiti, and also because they would not be easily inserted into the charcoal-filled troughs if they were not thin enough. If the spacers were to be dropped into the channel from the top opening, they could be made out of a thicker material such as wood. However, since the charcoal tends to stick considerably to wood, if wooden squares were used, they should be sandwiched in between another materials such as sheet metal or possibly plastic bags.

Hammer

Any sledge hammer could be used, but the efficiency of the method would depend highly upon the technique and strength of the user and the mass of the hammer. If hammers were not available, rocks or metal rods or pipes could be used.

6.2. Alternative designs

Much has been learned about bagasse charcoal and the potential mechanisms by which to form briquettes. Based on the performance of previous prototypes, the following design alternatives are recommended.

6.2.1. Slotted Wall Panels

Another way of manufacturing square channels that would not require any bending would be cutting slots halfway through each panel at its intersections with other panels. The structural integrity of the channels would depend on the thickness of the material and how well the slots were cut to match the thickness of the intersecting side panels. If done successfully, this design has the advantage of not requiring any welding, and being easily assembled and disassembled for portability. Complications could arise if flat pieces of sheet metal were hard to find or produce since it is likely that they may be hammered out of used oil drums. Another possibility would be to use plastic sheets or prefabricated square extrusions, but such materials may not be affordably priced or available in Haiti. Having a design that can be easily disassembled might also make the press susceptible to theft and use for scrap material.

6.2.2. Hammerless Pile Driver

Sometimes when new devices are introduced to developing countries, they fall into disuse or misuse because the devices or their components are found to be more useful for other purposes. If alternative uses for the hammer decreases the ability of the press to make briquettes, it may be necessary to incorporate a driving mechanism that can be used only for the press. The driving mechanism for a pile driver prototype would consist of a heavy mass sliding on a shaft to strike the piston. Having the shaft as a linear guide would also ensure for better alignment of each strike by reducing non-vertical components of force. There would be an end cap on top of the rod to prevent the heavy mass from flying upwards off of the shaft.

6.3. Suggestions for Future Research

There is much more that can be learned about the bagasse charcoal and ways to produce briquettes. However, it is beyond the scope of this thesis to endeavor to perform a complete and comprehensive study of the material and production processes. What follows are suggestions for future researchers about alternative tests.

6.3.1. Burn Testing

The burning properties of the bagasse charcoal are critical to the success of its development as an alternative fuel source for Haiti, but there is very little data compiled thus far. Once a press has been designed to produce briquettes of sufficient compression strength, burn tests should be conducted to determine how long it takes a given mass of charcoal to heat 1 L of water to boiling from room temperature. These values should then be compared to the heating time corresponding to traditional wood and wood charcoal to determine whether the briquettes yield sufficient heat. In addition to standard tests with calorimeters, these tests to directly evaluate the suitability of using these briquettes for cooking are recommended because they would provide a better frame of reference for target users.

6.3.2. Characterization of Material Properties

To determine the relationship between structural strength and material density, it would be useful to form briquettes in an instrumented press with forces ranging from 3 kN to 15N at increments of 3 kN, and test them in compression. This would characterize the compression behavior of the briquettes at a large range of densities, and provide a frame of reference for evaluating the prototypes. The Young's Modulus of the material could also be determined from these tests. Commercial grade barbequeing charcoal can also be machined to be cylinders and so similar compression tests can be conducted to provide a basis of comparison for the bagasse charcoal briquettes. Research is forthcoming on these tests and will be available in June 2005 (Bateman & Harrison & Ljubicic, 2005).

7. CONCLUSION

Much has been learned about bagasse charcoal and potential production processes from trial testing. Several mechanisms for multiplying forces, such as ratchets and pulleys, have been considered and assessed based on their suitability for a briquette-making device. The most important finding was that briquette formation requires more force for compression than previously expected, but prototype trials indicate that impact loading is a promising method of production.

Proof-of-concept for the pile driver design has been established with a single-channel prototype requiring a hammer to strike the piston to compress the charcoal within the channel. Design features such as spacers for making multiple briquette formation in series and a side-loading channel have been shown to increase productivity, reliability, and ease of operation. A central shaft can also be placed in the channel to form briquettes with holes to increase the exposed surface area for burning. Based on initial results, the pile driver press has great potential to eventually be adopted in Haiti as a small-scale briquette-making device.

More tests are required to compare the material properties of the pile driver briquettes to commercial barbeque charcoal, wood charcoal, and bagasse charcoal samples formed at known compression pressures. Burn tests should also be conducted to qualitatively determine how many briquettes are equivalent to wood charcoal pieces because this is likely to be more relevant to Haitian users than calorimetric data. In June 2005, another prototype embodying the pile driver concept with multiple channels to increase productivity will be made and trial tested in Haiti to gain feedback from charcoal producers.

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