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Paper Briquetting: an Appropriate Technology?

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Part II Individual Project Final Report

Summary
The following is a report into the viability of introducing paper briquetting technology in Poipet, Cambodia. The device would be used to encourage income generation for the local poor.
The key aims of the device have been identified: the device must be appropriate technology, be environmentally friendly and produce briquettes that can compete with existing fuels.
Research has been undertaken into existing briquetting techniques and devices. One such device, a hand operated press produced in the UK, has been purchased and investigations carried out into the characteristics of the briquettes it produced. It has been found that combustion can be optimised by using newspaper or cardboard, and the more compact and homogeneous the briquette, the longer the burn time. Models have been put forward to predict the drying behaviour of the briquettes and work done to identify changes in structure as the paper is soaked in water.
Research has shown that replacing traditional fuels with paper briquettes will not have any net detrimental affects to the environment. Existing briquetting schemes have been identified and guidelines drawn up for introducing a scheme in Poipet. Any technology used must be appropriate to the situation - the device should be labour intensive and made locally using readily available (ideally reused) materials.
With the information available it appears that paper briquetting is a viable option and it is hoped that this report can be used as a basis for such a scheme.

Contents

1. Introduction

The initial idea for the project came from a project manager working for ZOA refugee care in Poipet, Cambodia (original email shown in appendix A). ZOA are trying to identify alternative sources of income for the poor in the area – many of whom are currently employed as day labours, earning just enough to survive.
Poipet is situated on the border with Thailand and every day tonnes of waste material is shipped across the border to be processed in Thailand. This material includes cardboard, paper, waste plastics and even car batteries.
One way in which the local people could recycle some of this material themselves is by making some of this waste cardboard or paper into briquettes that could then be burnt as fuel. To be successful the briquettes would need to be competitive with charcoal/wood (currently the fuel of choice in the area) – in price and in the way they burn. If a device could be designed that did this, and that could be made and used by the local population, then there would be many benefits both to the environment and the economy.
In section 2 existing devices already on market have been identified. Tests have been carried out on one of these devices and detailed in section 3. Aspects of briquette drying, structure and combustion have been focused on and conclusions as to optimum structure along with drying models have been suggested. Practical aspects of implementing paper briquetting in Poipet are identified in section 5 and finally suggestions for further work put forward in 7.

Objectives

- To investigate the viability of introducing paper briquetting technology in Poipet.
- Propose guidelines for implementation of such a scheme. Environmental and social implications should be considered.
- To research existing paper briquetting technology and design a device that can be made and used by the local population in Poipet.

2. Existing Products

At a very basic level attempts have been made to create fuel from newspaper simply by rolling them up into 'logs'. Although a nice idea these do not burn well. One possible reason is that the surfaces of newsprint can contain a clay based coating. This retards full combustion [1]. These logs have been found to burn better if soaked first with water and then dried.

Existing presses can be divided into 2 categories: high pressure (HP ~ above 1 tonne/sq. cm) and low pressure (LP ~ below 1 tonne/sq. cm) The HP presses are large automated machines where dry paper or cardboard is compressed into briquettes without a binder. (manufacturers of these presses are given in references [2-4]) One common design uses a mechanical screw or piston to force the paper through a die, shown below in figure 2.1. Piston types can produce up to 500 kg/hr [5].

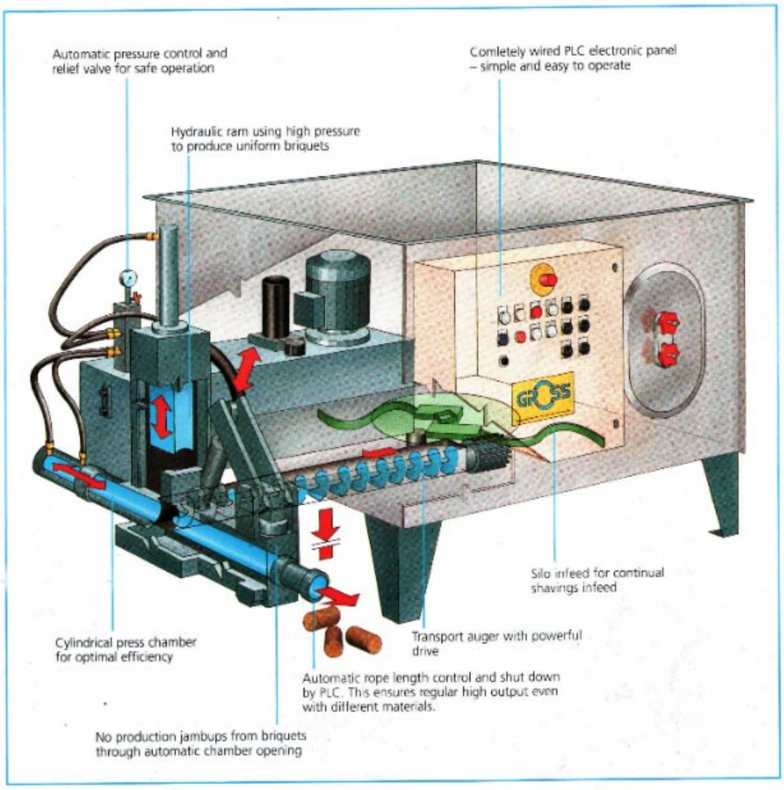


Figure 2.1. Schematic diagram of HP piston press

Because of their scale and cost they are generally used by big companies who have to large amounts of waste paper or packaging to dispose of. I found several examples of companies using briquetting machines to fuel heating boilers. The briquettes were usually mixed with coal before being burnt. One example is given in appendix B.

The LP presses tend to be on a smaller scale and can be designed to be hand operated. In developed countries only a minority of people still use wood/charcoal stoves and because fuel is relatively cheap there is simply not the incentive to recycle in this way. The only device I found that was available in the UK was made by a company called the Centre for Alternative Technology (CAT) [6]. They were making a small press (shown in figure 2.2) to compress wet newspaper into bricks. The newspaper itself binds together well when wet so no binder needs to be added. They also suggested that the bricks should be burnt alongside wood or coal.

In developing countries where wood or charcoal stoves are the norm there is much more scope for this sort of technology. Paper is generally not considered to be a low-cost resource and subsequently there are few cases where paper alone is briquetted. There were many examples where other materials had been used. Parts of Asia and Africa have been briquetting biomass, usually agricultural residues such as bagasse (sugar cane waste) or rice husks [7], for a long time.
LP presses on a cottage industry scale are still relatively under developed although there are 2 distinct types: continuous or discrete (eg. lever press, such as one made by CAT). I have found several examples being used for small scale production in developing countries.
Figure 2.5 is an example of a discrete LP press developed in India. It produces a hollow briquette again using biomass with paper pulp as a binder [8].
The Itermediate Technology Development Group in East Africa [9] (ITDG-EA) have helped with the development of several ‘waste-to-energy’ briquetting schemes. Figure 2.3 shows a LP piston press that make briquettes from organic residues (rice husks, coal dust, wood shavings etc) and uses paper as a binder. The press is similar to the one in figure 2.2 but the wet mix is rammed manually into the cylinder instead of using a screw. Tests carried out have shown that although 100% paper can be used, the briquette will burn with much more cleanly when the paper content does not exceed 30%. Neither type of briquette burns with an open flame but once fully ignited they burn in a similar fashion to charcoal. A picture of the press is shown below in figure 2.3.

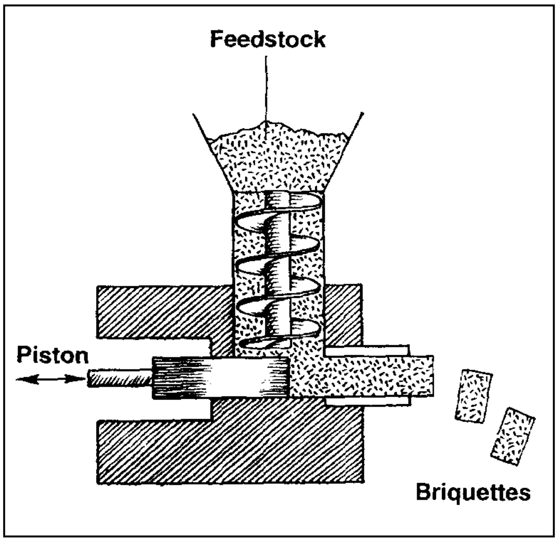
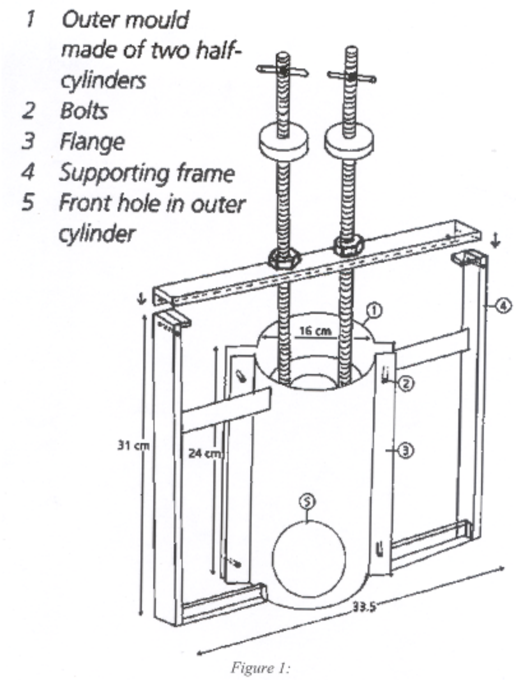


Figure 2.2. Schematic of basic piston press

Another very different device, also from East Africa, is shown in figure 2.4. The device, similar in principle to tongs, is being introduced to several villages in Kenya [16]. The materials being used are mainly waste paper or card mixed with soil (and of course water) to improve combustion and reduce cost.

Figure 2.1. LP piston press developed by ITDG EA.

Figure 2.4. Briquetting 'tongs' being used in Kenya.



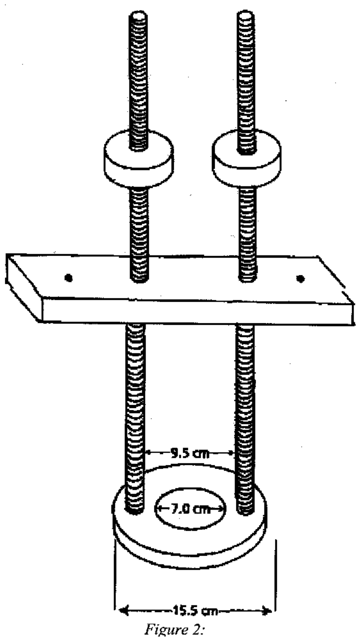


Figure 2.5. LP press developed in India

3. Experimental Work

I have undertaken experimental work looking at different types of briquettes produced by a press made by CAT [6] (see fig. 3.1). In order to produce the briquette the paper has to be ripped up and soaked in water – if the paper were dry it would not bind together. The press then squeezes the paper together, removing excess water and compacting it into a briquette. The briquette then has to be dried before being burnt. The main characteristics, important to manufacture, are the way in which the briquettes dry and subsequently burn. Also of importance is their robustness – how easy they are to handle.

Fig. 3.1. Hand operated lever press from CAT. Figure on right shows compacted briquette in position

3.1 Drying Characteristics

Briquettes drying under varying conditions have been monitored and attempts made to fit models to their drying characteristics. This will give us insight into how the briquettes dry and help to predict drying times in conditions different to those already experienced.

3.1.1 The Drying Process

As a material dries its moisture content falls to an equilibrium value determined by the relative humidity (RH) of the air around it. The lower the desired moisture content of the material, the lower the RH of the drying air should be. This relationship between equilibrium moisture content and RH is often shown in the form of a sorption isotherm [11].

Assuming that RH is sufficiently low, moisture will evaporate from the material surface. The energy for this evaporation is provided by the air, which means that the temperature of the drying material ('wet-bulb' temperature) will be lower than that of the air ('dry bulb' temperature). The balance of this heat and energy flow is the basis for evaporation models, one of which is used below.

As the material starts to dry the relative humidity, usually around 1, remains constant for a certain period (shown in fig. 3.2). Under contant air conditions this will lead to a constant drying rate, referred to as the 'constant rate period' (CRP). After a certain time the RH will fall below a critical level. As this happens the drying rate starts to decrease. This is called the 'falling rate period' (FRP) and the internal resistance to moisture transport starts to play a more important factor in the drying process. Further substages in the FRP have been identified and these as well as a more in depth overview of the drying process are included in Coumans paper on drying kinetics [12].

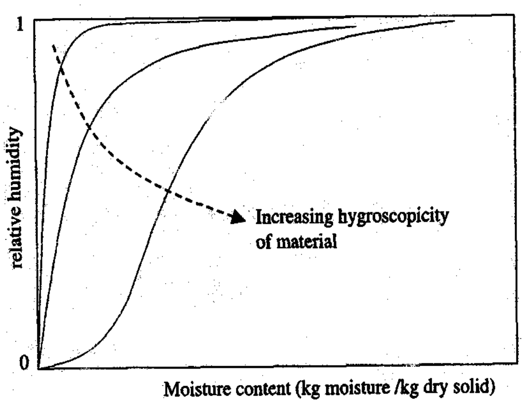


Figure 3.2. Typical sorption isotherms for materials with different degrees of hygroscopicity.

3.1.2 Mathematical Models

Equilibrium Drying Models

At sufficiently low drying rates the material will be close to equilibrium with the drying air. Moisture content will be similar throughout the material and drying will not be limited by internal transport.

A practical model published by J. Holman [13] models a 'standard pan' (a volume from which evaporation occurs) in the atmosphere. The model is as follows:

$$E_{lp} = (3.212 + 0.02224u)(p_s + p_w)^{0.88}$$

where E_{lp} = land-pan evaporation, mm/day

u = daily wind movement measured 152mm above pan rim, km/day

p_s = actual vapour pressure of air under temperature and humidity conditions 1.524m above ground surface, kPa

NOTE: To convert the pan measurements to those for a natural surface, the above equation should be multiplied 0.7.

The model does take into account air temperature, humidity and airflow and is designed to model evaporation outdoors. However it assumes relatively low drying rates and does not take into account the material properties or different drying phases.

Diffusion Models

It has been accepted that the drying of biological products during the FRP is controlled by the mechanism of liquid and vapour diffusion [11]. Here, the effects of different moisture transport mechanisms are characterised by a moisture diffusion coefficient *D*.

A form of Ficks diffusion equation, given in 'numerical recipes for C' [14], models diffusion:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(D \frac{\partial u}{\partial x} \right)$$

where u = moisture content
t = time
x = space co-ordinate

This model assumes constant resistance to moisture (i.e. homogeneous material) and volume shrinkage is negligible. However the main assumption is that diffusion occurs in one plane only (note the space co-ordinate in 1 dimension only).

3.1.3 Experimental Procedure

Experiments were performed to determine the effect of certain variables on the drying characteristics. The variables considered were material, air temperature, soak time of the paper prior to pressing, compaction pressure and surface area.

Four different types of material were investigated: newspaper, corrugated board (cardboard), office paper and glossy paper. The paper was ripped into pieces of roughly 100 cm^2 and submerged in water for a recorded amount of time. Apart from an occasional stir the paper was left untouched. Prior to pressing the paper was weighed out to ensure similar sized briquettes – of surface area/volume ratio ~0.07. The compaction force was measured simply by placing a certain mass on the levers. Briquettes were dried on a flat surface in laboratory conditions[1]. Temperature and humidity were monitored and the mass of the briquettes was measured at regular intervals. Experiments were done with soak times of 0 – 470 hours, temperatures at 40ºC and 20ºC, compaction pressures of 0 – 200kPa and surface area /volume ratio ranging from 0.51 - 1.11.

The non-dimensional moisture content was calculated using the following formula:

$$M = \frac{X - X_f}{X}$$

[1] Humidity 35%, Temperature 20ºC, wind speed 0.

where M = moisture content
X = sample mass
X_f = final mass

This assumes that the final mass is the dry mass. In practice the final mass will always be slightly above dry mass because of water vapour in the air.

3.1.4 Results and discussion

Effect of drying variables

Figure 3.2 shows the relationship between the pressure exerted and subsequent initial moisture content of the briquette for four different briquettes. Pressure was maintained for 20 sec in each interval and all four materials were soaked for 70 hours prior to pressing.

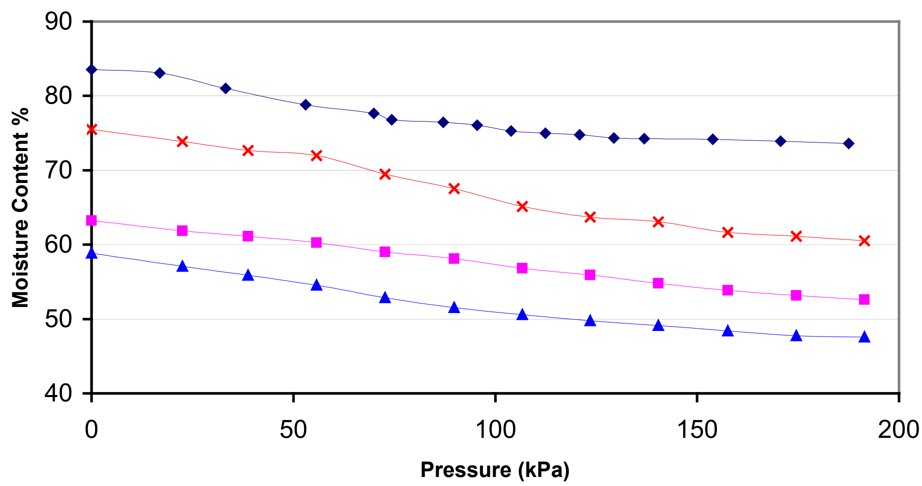


Figure 3.2. Moisture content of briquette vs pressure applied by press. (♦) newspaper, (×) cardboard, (▲) office paper, (■) glossy paper.

The relationship between pressure and moisture content appears to be fairly linear for all samples. Theory would suggest that this trend would level off as the paper fibres became so compacted that permeability (or lack of it) would prevent moisture from escaping. Unfortunately upper limit for the CAT press was around 190kPa so further tests to determine at what pressure this occurs could not be carried out.

The amount of water absorbed prior to pressing will depend on the material properties – how easily it absorbs water, and the amount of time it is allowed to soak. Figure 3.2 and 3.3 give similar results on the propensity of the different materials to soak up water. They would indicate that newspaper was the most absorbent and glossy and office paper the least.

Figure 3.3 shows the relationship between soak time and initial water content for newspaper.

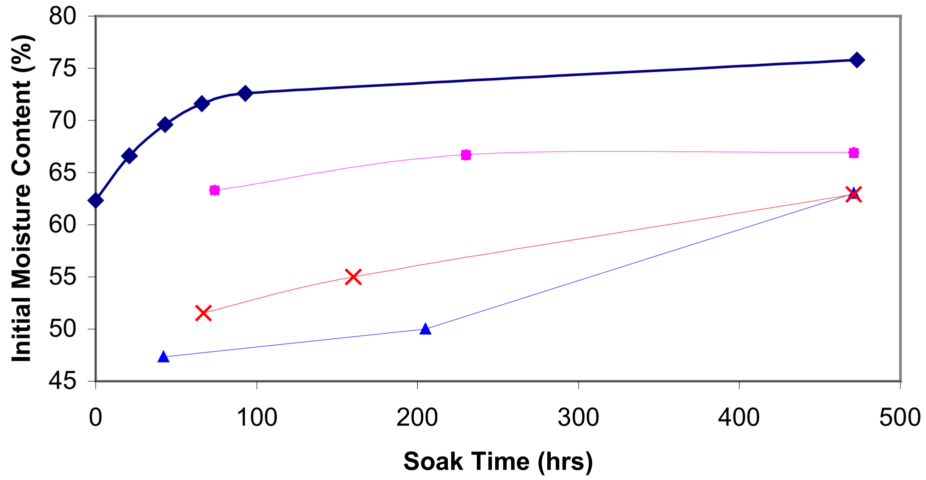


Figure 3.3. Moisture content after pressing vs length of soak time for newspaper. (♦) newspaper, (×) office paper, (▲) glossy paper, (■) cardboard.

The initial moisture content increases the longer the paper has been soaked. i.e. exerting the same pressure on samples which have been soaked for differing amounts of time does not leave them with the same moisture content. The longer the paper is soaked for, the more water it absorbs and the higher the moisture content will be after pressing.
However the changes are small compared with the large variation in soak time and have no significant impact on the overall drying time. Soak time did have much more of an impact on structure and this is discussed in section 3.3.
The effect that the material has over drying profile is shown below in figure 3.4.

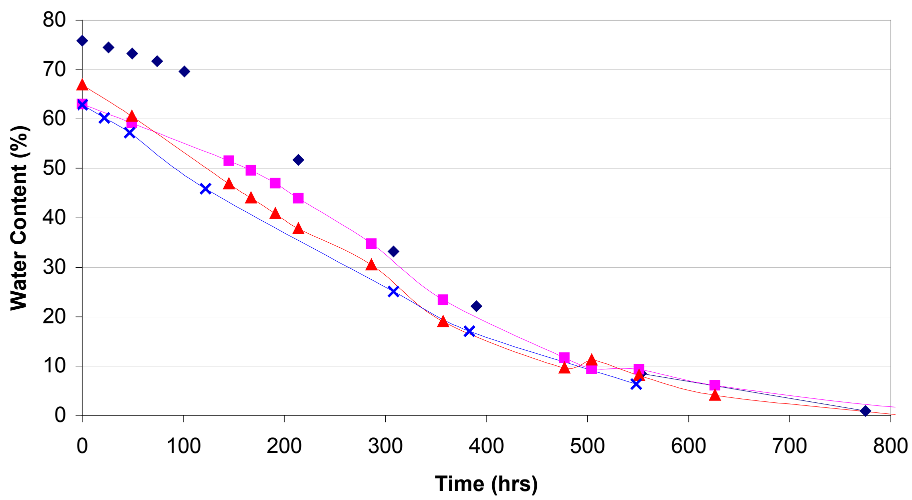


Figure 3.4. Drying curves for different materials at 20°C, soak time 470hrs. (♦) newspaper, (×) office paper, (▲) cardboard, (■) glossy paper.

The type of material seems to have little affect over the actual drying times.
Figure 3.5. shows the influence of temperature on the drying curve from 2 briquettes, both of the same size and material and compressed under the same pressure, but allowed to dry at different ambient temperatures. The increase in temperature leads to an increase in drying rate and the figure shows as expected.

One problem with this experiment was that I was unable to control the humidity which varied between 35% –55%. This will have distorted the results.

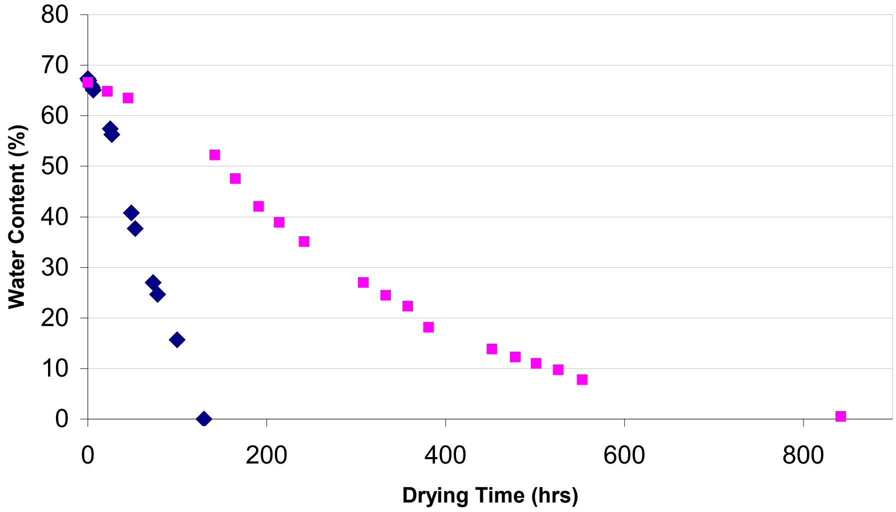


Figure 3.5. Drying curve for briquettes at different temperatures. (▲) 40°C, (■) 20°C.

The influence of surface area on the drying curves for 3 newspaper briquettes is shown in figure 3.6. As expected the briquette with the higher surface area to volume ratio dried at a faster rate than the others.

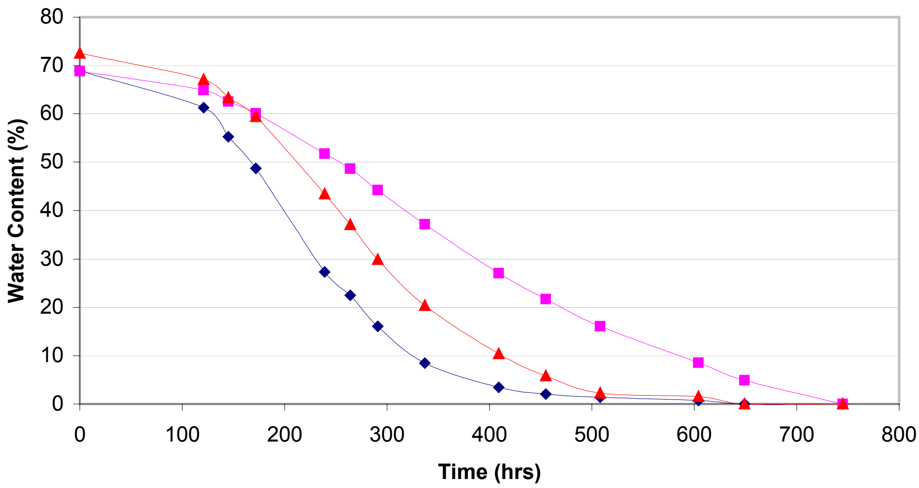


Figure 3.6. Drying curves for newspaper briquettes. Surface area to volume ratio: (■) 0.51, (▲) 0.81, (♦) 1.11

Evaporation Model

The drying rate was calculated (an example calculation is given in appendix C) and plotted against actual data. When the value for surface area is taken as the top area of the briquette the model provides a reasonable forecast.

The model only predicts a constant drying rate and so was never likely to fit a real curve. I does however, seem to be able to predict the time for the moisture content in the block to reach ~15%. The model seems to work for all the different scenarios I created. Fig. 3.7-9 show 3 different scenarios.

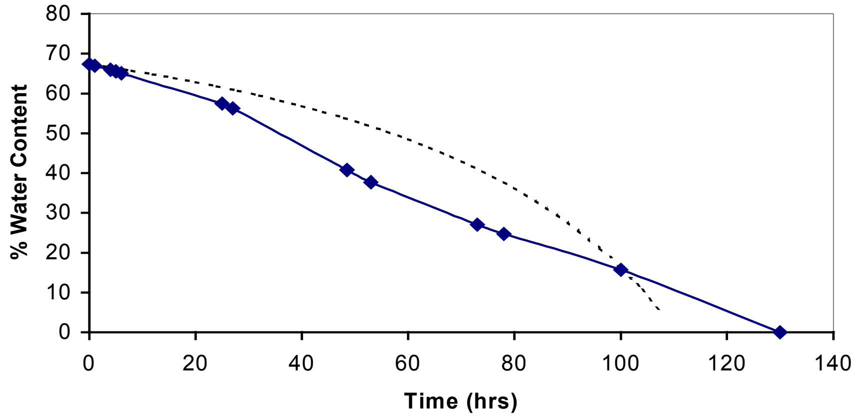


Figure 3.7. Graph showing actual drying curve from newspaper sample, soak time 20 hrs, dried at 40 ℃. (♦) actual data, (---) model

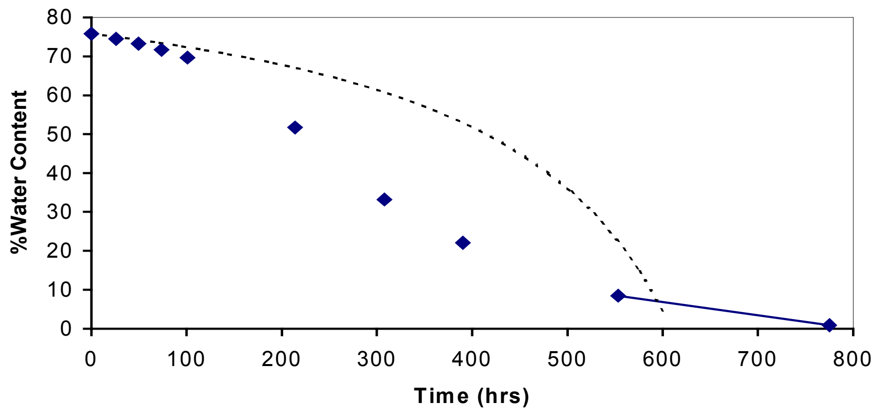


Figure 3.8. Graph showing actual drying curve from newspaper sample, soak time 473 hrs, dried at 19℃. (♦) actual data, (---) model.

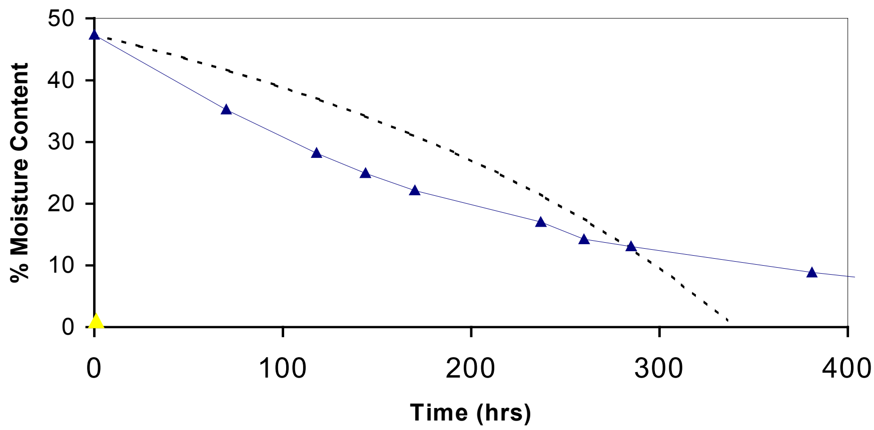


Figure 3.9. Graph showing actual drying curve from glossy paper sample, soak time 42 hrs, dried at 19℃. (♦) actual data, (---) model.

Diffusion Model

Ficks diffusion equation given in 3.1.2 is an initial value problem and was solved numerically using a finite element approach. A copy of the C-program is given in appendix D.

The program was run for several different scenarios that had been tested experimentally. Results of the model were compared with several sets if data (see figure 3.10) and a diffusion constant calculated by fitting the model curve to the actual drying curve. The model worked for some but not all scenarios using a diffusion coefficient of 10^{-10}. The model may not work because of the assumptions made (see 3.1.2.) Also it is likely that the diffusion coefficient will not be constant but change with moisture content, temperature and wind speed. Existing research [12] has shown that this relationship is likely to be an Arrhenius-type one.

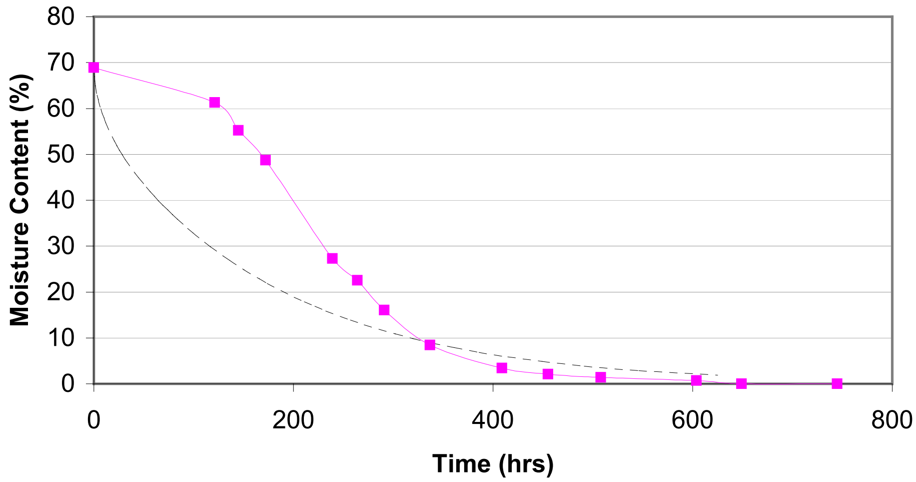


Figure 3.10. Drying curve for newspaper sample, soak time 70hrs, temperature 20ºC, SA-vol 0.051, diffusion coefficient 10^{-10}. (♦) actual data, (---) model.

3.1.5 Conclusion

The average time for a briquette dried at 20°C, 35% humidity, 0 wind speed and SA volume ratio 0.07 to reach 10% moisture content is around 450-500 hours. It should be noted that increasing temperature and surface area will decrease the drying time of the briquettes but material and soak time have little effect.

The evaporation model fits the data badly but seems to be able to reliably predict the time required for a sample to reach 15% moisture content. The diffusion model more closely fits the actual mass transfer taking place but proves unreliable in its current form.

3.2 Combustion

Probably the most important characteristic of any briquette is the way in which it burns. These tests help to show how the briquette structure, influenced primarily by the soak time, affects this.

Ideally the briquettes should burn in a similar way to wood and charcoal. Properties of the different materials are in table 3.1.

Material	**HHV – dry basis (MJ/kg)**	**Ash Content (%)**
Newspaper	18.9	5.4
Corrugated board	17.3	4.8
Office paper	15.1	8.8
Glossy paper	12.3	22.8
Charcoal	34.8	1.0 [25]
Wood (pine)	22.4	1.3

Table 1. Higher Heating Value (HHV) and ash content for different materials. (taken from a paper by Liu and Li [24])

These values indicate that newspaper and cardboard are comparable to wood in the energy they release. This also assumes that the materials are completely dry and in practice would be lower due to moisture content (green wood has a moisture content of ~50%).

The first stage of combustion involves the devolatilization. Here the volatile components present in the paper or cardboard are burnt and gas is produced. What is left is char, a solid residue mainly composed of carbon, which degrades to ash with continued heating. The devolatilization step corresponds to pyrolysis since it can occur without oxygen and is the subject of a paper by S. Salvador *et al* [15]

In further ongoing work by S. Salvador [16] the effects of density on the combustion of cardboard briquettes are investigated. Early findings point to increased burn time for briquettes of higher density.

Some problems with the combustion of newspaper were identified in a report by M. Sud [17] which looked at the development of a newspaper fuelled boiler. In this case the newspaper was not compacted but simply shredded and fed in via a hopper. The volatiles in the paper burnt off very quickly leaving char. The char tended to go out and did not degrade further unless more paper was fed in.

3.2.1 Burn Tests - using barbecue

Figure 1 shows a newspaper briquette after sitting on a disposable barbecue for 30 minutes. Along the bottom the paper had degraded to char but had not burnt completely. No flames had been visible. The highest temperature reached was ~500°C on the surface between the charcoal and the paper. This temperature was very localised and soon dropped away around the edges of the briquette.

Figure 3.11. Newspaper briquette after 30mins on barbecue

3.2.2 Burn Tests - using wood burning stove

Figure 3.12. Wood burning stove used for combustion tests.

Clearly the temperatures reached using the barbecue were too low for complete combustion to occur. For further tests a wood burning stove was used where much higher temperatures could be achieved.
Although the stove burns the briquettes in an environment that is very similar to their intended destination, it is not ideal for controlled combustion. The flow of air through the stove could not be regulated from briquette to briquette. Also the briquettes need an existing fire in order to burn properly (as do ordinary logs) and this was difficult to control. Efforts were made to get the existing fire to a similar state and temperature before adding each briquette.
Temperature measurements were taken around the briquettes at different stages of burning but other than that the results are qualitative. Photos of the briquettes at similar time intervals have been included for comparison.
Two types of newspaper briquette were tested; one where the paper had been soaked for 473 hours and one that had been soaked for only a few minutes. Briquettes made from office paper, cardboard and glossy paper were also tested.

Newspaper briquettes
Figures 13, 14 and 15, 16 show the newspaper briquettes after 1 minute and 10 minutes respectively in the stove. As the pictures show, the briquette that was soaked for a short time combusted faster. Temperatures reached 900°C along the bottom edge and around 550°C around the other sides. Flame extinction occurred around at 20 mins and by 25 mins the briquette started to disintegrate.
The briquette soaked for 473 hours burned more slowly and as the pictures show maintained its shape for longer. Temperatures around the outside were similar at 550°C but less along the bottom ~ 750°C. The briquette stopped producing flames at around 30 mins but still maintained its shape for a long time after forming compact glowing embers.

Cardboard
The cardboard burnt easily and extremely quickly. Within seconds large yellow flames were produced and continued until about 16 – 18 mins. Around the surface temperatures were ~650°C and up to 900°C along the bottom. After 15 minutes the briquette had disintegrated into different pieces and was completely burnt by 25 mins.

Glossy Paper

This proved the most difficult to burn. As shown in figure 5 large areas of the surface were unaffected after 1 minute. After 10 minutes most of the surface had burnt and turned to ash but the inside was still intact. The flames had died down and the briquette would have gone out without building up the fire around it.
Temperatures reached were high – up to 1000°C on the bottom and 600°C around the outside. Blue green flames were observed.
After 20 minutes parts of the core were still intact and the briquette wasn't completely burnt until 40 minutes. A large amount of ash was produced – much more than other materials.

Office Paper
The office paper burnt in a similar fashion to the newspaper soaked for 473 hours. Temperatures reached were similar and the briquette stayed in one piece until 30 minutes. Flame propagation was worse however and the briquette needed turning and the fire stoking in order for it to burn completely.

3.3.3 Conclusions
Minimum temperature needed for combustion of the paper was in the order 550 - 600°C. This is easily achieved in a wood burning stove.
On the whole the cardboard and newspaper briquettes burnt better than the others – the important factor being that once alight they burnt completely without needing to be supported by the existing fire. This is probably due in part to their higher calorific values.
In line with the data from table 3.1, the amount of ash produced was more than would be expected for wooden logs, the glossy paper producing an unusually large amount. This could be a problem in cramped stoves that lack a grate system to remove ash.
Obviously the structure of the briquettes affects greatly the burning characteristics. Both the newspaper soaked for a short time and both cardboard samples had a similar structure. The paper was bound loosely together and disintegrated much faster. This can be seen clearly in figure 22 where the cardboard briquette has almost fallen apart after 10 mins. This loose structure seems to help the flames propagate through the briquette and leads to a faster combustion.
The briquette soaked for a long time, although of similar density, has a much more homogenous structure. It produced lower temperatures than the others but held together and burnt for longer, producing compact embers at the end – something more similar to a wooden log.

Figure 3.13. Newspaper (473 hrs) after 1 min.

Figure 3.14. Newspaper (0 hrs) after1 min.

Figure 3.15. Office paper after 1 min.

Figure 3.16. Glossy paper after 1 min.

Figure 3.17. Cardboard after 1 min.

Figure 3.18. Newspaper (473 hrs) after 10 mins.

Figure 3.19. Newspaper (0 hrs) after10 mins.

Figure 3.20. Office paper after 10 mins.

Figure 3.21. Glossy paper after 10 mins.

Figure 3.22. Cardboard after 10 mins.

3.3 Physical Characteristics

The structure of the briquettes is an important characteristic. It will determine the way they can be handled and affect the way in which they burn. The nature of the paper prior to soaking, the length of time it is soaked for, the pressure used for compaction, and the treatment of the mixture while soaking will all have an effect on structure.
In this study the effect of varying soak time was investigated for newspaper, cardboard, glossy and office paper samples. Briquettes were made after 0 (2-3mins), 65 and 470 hours of soaking. All other variables were kept constant; the compaction pressure was kept at ~145kPa, all the paper was ripped into pieces roughly 100 cm^2 prior to soaking, and during soaking the paper was, apart from an occasional stir, left untouched. A scanning electron microscope (SEM) was used for comparison of newspaper samples.

The greatest change occurred in the newspaper and glossy samples. The longer the paper was soaked the more consistent and pulp-like the mixture became and the better it bound together when pressed. Figure 1 shows 2 newspaper briquettes side by side, clearly highlighting the differences. It was noted, especially for the glossy sample, that at higher soak times the briquettes were harder to press and less water was removed.

Fig. 3.23: Briquette structure when soaked for 0 and 473 hours. (0 hours on right)

Cardboard and office paper were least affected by the soak time. They both failed to bind (the briquettes disintegrated after being removed from the press) when soaked for less than 65 hours. Briquettes soaked for 65 and 470 hours were similar in appearance – the material returning to a state similar to that prior to soaking. The cardboard briquettes were loosely bound together making them very fragile. The office paper briquettes were stronger, bounding together better the longer they were soaked.
Dry newspaper samples from briquettes soaked for 2-3 minutes (S0) and 470 (S470) hours were studied using SEM. Individual sheets were still visible in both samples but their structure, although similar had key differences.
Figures 24, 25 and 26 show top views of both samples. The structure seems to be made up of thick fibres or fibre bundles joined together by a different substance, probably lignin[2], and much thinner fibres (this is shown clearly in figure 26). The thick fibres appear more visible and detached in S470. Also the surface seems to be more porous.
Ink was not obvious on S470 but clearly visible on the surface of S0 (see figure 27).
Figures 28 and 29 show end-on views of both samples at different magnifications. S0 has much more compact sheets (similar width to unsoaked newspaper) but the gaps between them are large. Conversely the gaps between the sheets in S470 are only just visible but the fibres within each sheet are more spread out. Both S0 and S470 had similar average densities.

[2] Lignin, a naturally occurring substance that binds together the wood fibres. This is removed in chemical pulping processes (for most office paper and paper board products) but is present in newspaper [27].

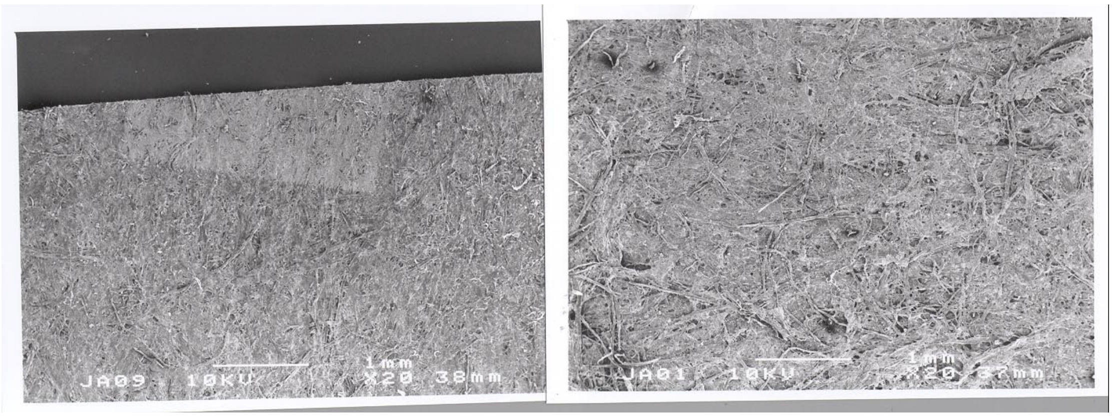


Figure 24. Top down view on S0 (on left) and S470. Mag ×20.

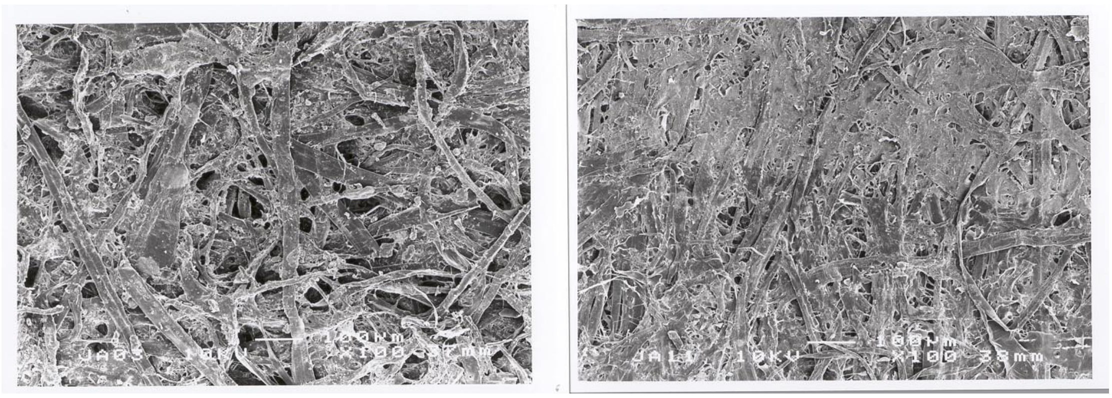


Figure 25. Top down view on S0 (on right) and S470. Mag ×100.

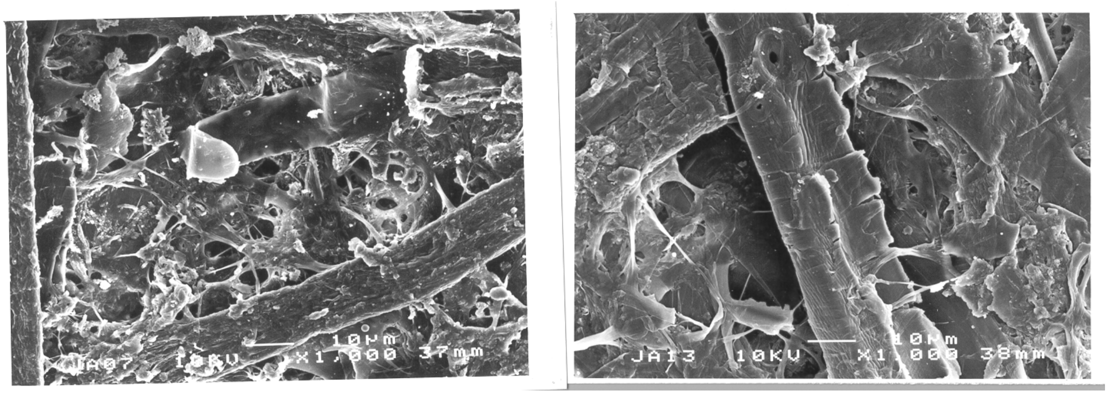


Figure 26. Top down view on S0 (on right) and S470. Mag ×1000.

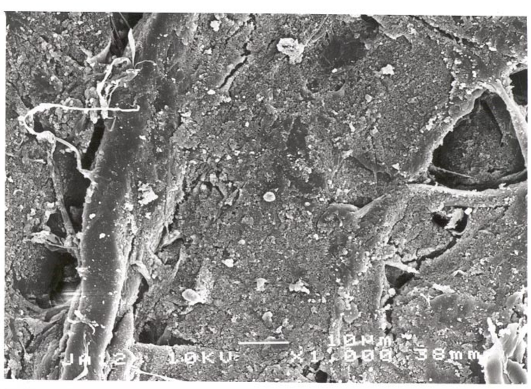


Figure 27. Top down view of S0. Mag ×1000. Ink visible on surface.

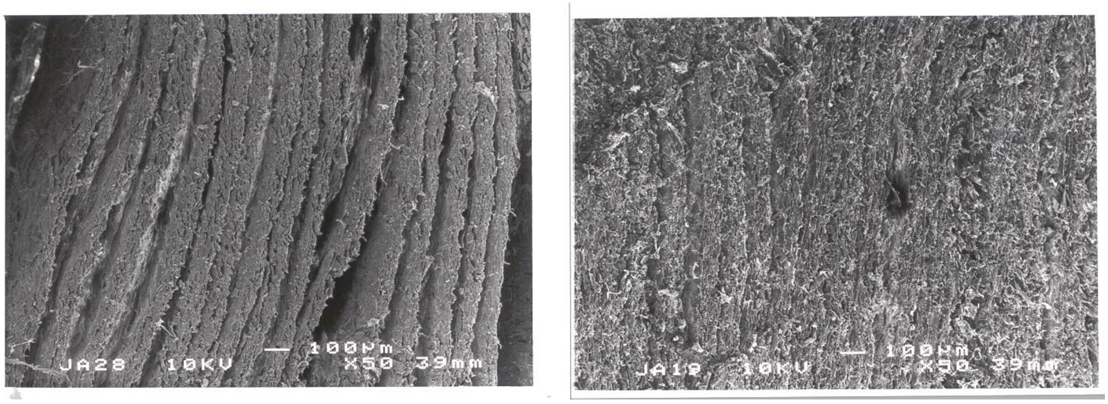


Figure 28. End-on view of SO (on left) and S470. Mag ×50.

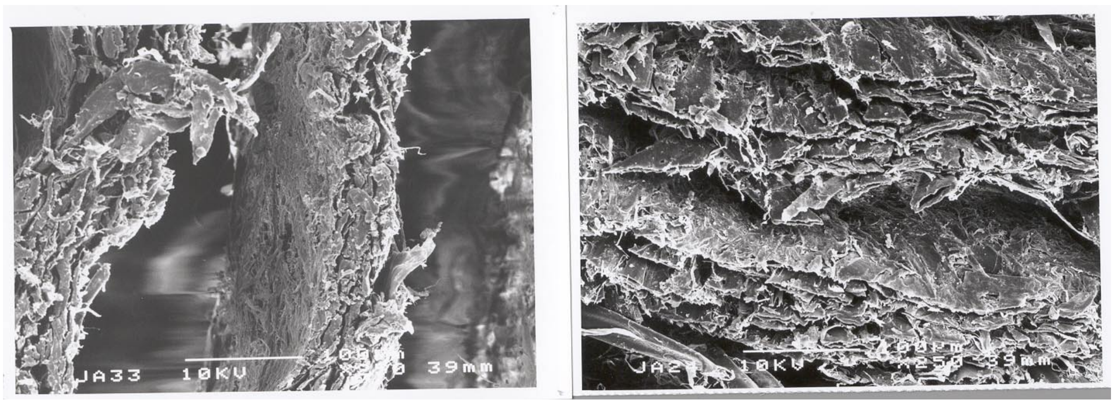


Figure 29. End-on view of SO (on left) and S470. Mag ×250.

Conclusion

When the paper is soaked the fibres will absorb water, expanding as they do, until reaching a saturation point. As the fibres expand the gaps between them will become smaller the structure less permeable – making it harder to remove water by pressing.

The longer the paper is soaked for the looser and less dense the fibre structure becomes. It is these loose fibres that seem to help create stronger sheet to sheet bonds and produce a stronger briquette. Eventually the structure of each sheet will start to disintegrate and the mixture become more homogenous. This process can be accelerated by mashing the paper while it is soaking.

In the context of my experiments, although some materials will bind with very little soaking, much longer is needed to achieve a strong durable briquette. In briquettes soaked for a short time the material returned to its original state with many gaps present between the sheets.

Cardboard and office paper were extremely resistant to extended soaking and their structures remained similar to their original state. Newspaper and glossy paper degraded considerably with extended soaking and produced strong, durable briquettes.

4. Environmental Aspects

Burn or Recycle?

Since the 1980's recycling and reuse have been key issues around the globe. There has been a trend across various industries of increased recycling driven by the demands of consumers and government policy. Generally recycling saves energy and reduces the use of a finite resource, however this does not hold true for paper.

The raw material, cellulose, is not a finite resource. As long as the wood used comes from well managed forests, those where planting rates equal felling, then it can be treated as a form of renewable energy.

When virgin fibre is pulped there are leftover residues (eg. bark) and, depending on the type of pulping, chemical residues. This biomass is always burnt to supply energy for the pulping process. When waste paper is pulped there are none of these residues and the entire energy requirement has to come from traditional sources - often fossil fuel based. Further more, instead of recycling the waste paper, it can be used in co-fired (burnt with another fuel, usually coal [18]) power stations to produce electricity. This displaces fossil fuels.

Much research has been undertaken into the relative merits of the two options, whether it is better to recycle paper or to burn in waste-to-energy (WTE) schemes [19-21]. Life cycle analysis, which looks at the impacts of a strategy in all areas, is a common approach. In a paper on the subject, L. Gaines [19] concludes that the best course of action depends on the objectives. If the goal is to save fossil fuel energy and reduce landfill volume WTE is the best option. If conserving trees is the priority the waste paper should be recycled. The general consensus seems to be that, depending on the type of paper, combustion in WTE schemes is more beneficial than recycling.

In the context of this problem, the paper would simply be replacing existing fuels (wood and charcoal) and not being used for energy recovery. The deciding environmental factor would be the nature of the source of wood in Poipet. It is likely that the wood and charcoal used does not come from well managed forests but is simply taken from near by sources. Using paper briquettes would reduce the demand for wood and reduce local deforestation – making it more beneficial to burn rather than recycle.

There are many other factors to take in account - such as knock on effects to the local recycling industry, and no clear right or wrong answer.

Emissions

Basic stoves used in poor communities in Poipet are likely to be badly ventilated. It is therefore highly important that emissions from the briquettes contain no harmful emissions.

Extensive research has found no studies directly relating to this subject. However there are many examples (some are given in [10, 26-28]) where waste paper is being burnt in similar situation with no apparent side effects.

A paper by Yasuhara *et al* [30], finds that dioxin emissions from newspaper are comparable to that of wood. In terms of greenhouse gases, research by L. Gaines [19] has shown that combustion of briquettes for energy recovery is preferable to recycling. The same report also finds that sulphur oxides are actually reduced by co-combustion of paper.

5. Guidelines for Implementation

Even when briquetting is considered to be a viable option many factors must be considered in order for the scheme to be successful. One of these key factors is the need for the briquetting device to be appropriate technology.
The original definition of this comes from Dr EF Schumacher. “A technology tailored to fit the psychosocial and biophysical context prevailing in a particular location and period.”[22] In other words appropriate technology should employ local skills, use local material and financial resources. It should be compatible with local culture and practices and satisfy local wishes and needs [23].

Case studies and reports from existing projects [10, 26-28] have been used to identify key factors for the success of a briquetting project in Poipet. Most points simply build on the above statement but are helpful in bringing a practical sense to the theory.

- Local involvement from the beginning.

In the case studies above local involvement has been essential to the acceptance of briquetting technology. A successful approach seems to be introducing the technology to specific local groups, with cheap fuel production and income generation (from selling the briquettes) as the key selling points. The users should be involved as much as possible - from the design process through to early ownership and control.
Involvement of local government can be very important. In some cases the control of local deforestation (eg. by introducing licences) has made briquetting more competitive.

- Made and maintained locally.

This is crucial for any briquetting device. High capital projects, which use high-tech western technology, often do not have the necessary infrastructure to support them. This can lead to high levels of down time when problems arise.
If it is designed in another location, efforts must be made to ensure that suitable facilities and materials for manufacture are available locally. Basic metal working shops are available in Poipet.

- Appropriate size

The device should be designed with the target market in mind. Are the briquettes going to be produced for personal use or to sell? If the latter, how many? There is a large amount of cheap unskilled labour in Poipet and this can be utilised – the briquetting process should be labour intensive. These factors will determine the size and type of the device.

- Competitive on price.

This is one of the most important factors determining the success of a project. If briquettes work out more expensive than alternative fuels then they are unlikely to make an impact. Despite any environmental benefits they may bring.
In Poipet scrap paper is, by weight, 10 times cheaper than charcoal with only half the calorific content (for original cost data, correct on 14th October 2002, see appendix E). Production costs still need to be taken into account but it is likely that paper can provide a cheaper source of fuel.

- Flexible

Briquettes are unlikely to completely replace wood or charcoal and so must burn well alongside these existing fuels producing similar results. They should be of a shape that is compatible with existing stoves used by the target group. This means that the briquettes should be no more than 5cm in width or diameter, ideally around 4cm. Length is less important. A common type of stove is shown in appendix F along with original data from Mike Fenemma on existing fuel size.

- Marketing strategy

This is important and has often been neglected in other schemes. Briquetting is likely to be a new concept and so will need publicity, as would any new product. They should be produced with a specific market in mind, eg. consumer, commercial, industrial, non-fuel. Media channels can be used. In one case study the 'novelty' of the briquettes was highlighted as a selling point. In others the briquettes were introduced alongside a new stove design.

- Production strategy.

Production is likely to be on a small scale but despite this production problems should be accounted for. Supply of the raw material needs consistent and sufficient to keep up with anticipated production rates.

6. Conclusion

Paper briquetting does seem to be a viable technology to introduce in Poipet. Waste paper is a low cost fuel source and diverting it from recycling is likely to have no serious environmental implications.

Care must be taken when designing a briquetting device - above all it must be appropriate technology. It should be made locally using readily available materials. It should be a hand operated labour intensive device, on a scale in line with its intended end use. The scheme should involve the local population from the beginning with thorough planning in areas like production levels and marketing.

In terms of combustion, cardboard and newspaper will give best results. When the paper is soaked for a long time they form stronger briquettes which burn for longer. Briquettes of a looser structure tend to disintegrate and burn much faster. The drying process is a diffusion process however a reliable model has been found using evaporation based parameters.

7. Further Work

Although efforts have been made to make this report as comprehensive as possible there is much scope for further investigation.

The experimental work carried out has been over a wide area and was very limited by the facilities available.
For the drying analysis, results over a wider range of temperatures and humidities would give a broader picture and allow further verification of the models identified. Also a basic test to identify to equilibrium moisture content (i.e. not assuming that final mass = dry mass) would make the data more accurate. With this information a relationship for the diffusion coefficient and these variables could be found, giving a more reliable diffusion model. To refine the diffusion model further 2D and 3D diffusion models should be considered. Crank [31] gives analytical solutions for several body geometries including rectangular.
Pressing the paper under higher pressures would hopefully show an upper limit where water removal slows. Combustion of higher pressure briquettes may show longer burn times, as suggested by S. Salvador [16]. It would be interesting to compare combustion of different shaped briquettes eg. cylindrical or hollow but further combustion tests should ideally be carried out in temperature controlled environment as well as in stoves similar to those in Poipet (see appendix F).
SEM work could be extended to other materials. Also, using an environmental SEM, water can be condensed onto the paper whilst under the microscope. This would show how different fibres react to soaking.

Aside from the experimental work the obvious progression would be towards implementation of the scheme in Poipet. In this report more time was allocated for the experimental work at the expense of putting forward a design of a briquetting device. Bearing in mind the guidelines set out in section 5, more detailed work needs to be done on costing, target markets – those who are going to make the briquettes and the people who will buy them, production strategy and a design solution put forward. Ideally this should be done by someone with knowledge of the area.

References

1. http://www.motherearthnews.com/askmother/felicia.shtml
2. KK Bailers Ltd. Victory Park Rd. Addlestone, Weybridge, KT15 2AX, UK. Tel: 01932 852423
3. Alois Pottinger, A-4710 Greiskirchen, Germany. Tel: (0 72 48) 600-262 www.poettinger.co.at
4. Holzmag AG. Florenz Str. 4023 Basel, Switzerland. Tel: +41/61/3379696
5. Louvel, R. 'Briquetting of vegetable residues' ITDG Boiling Point, 14, Dec 1987
6. Centre for Alternative Technology, Machynlleth, Powys, SY20 9AZ, UK. http://www.cat.org.uk
7. Assureira, E. 'Rice husk – an alternative fuel in Peru' ITDG Boiling Point 48 (2002), pp 35-36
8. Marimuthu, K. *et al*, 'A compressing machine for converting biomass waste into usable fuel' ITDG Boiling Point No.43, 1999.
9. ITDG East Africa, PO Box 39493, Nairobi, Kenya. Tel: +254/2/715299 e-mail: itdgEA@itdg.or.ke
10. ITDG DFID- funded 'waste-to-energy' project. In print. Contact Liz Bates lizb@itdg.org.uk
11. Panchariya, P.C. *et al,* 'Thin-layer modelling of black tea drying process', J. of Food Engineering, 52, 2002, pp 349-357.
12. Coumans, W.J. 'Models for drying kinetics based on the drying curves of slabs', Chemical Engineering and Processing, 39, 2000, pp 53-68.
13. Holman, J.R. 'Heat Transfer', 2001, pp 309, McGraw-Hill, New York.
14. Press, W.H. *et al*, 'Numerical Recipes in C', 2nd edition, 1992, Cambridge University Press.
15. Salvador, S. *et al*, 'Determination of a reaction scheme for cardboard thermal degradation using thermal gravimetric analysis', J. Anal. Appl. Pyrolosis 67 (2003) pp 307-323.
16. Salvador, S. salvador@enstimac.fr
17. Sud, M. 'Development of a newspaper fuelled boiler' 2001, Mechanical Engineering Part II individual project, University of Nottingham
18. Saxena, SC. 'Fluidized-bed incineration of solid pellets: Combustion and co-combustion', Energy Conversion and Management, 39 (1-2), Jan 1998, pp 127-141.
19. Gains, L.L. and Stodolsky, F. 'Is recycling the best policy option? Insights from life cycle analysis', Argonne National Laboratory, 1996.
20. Byström, S. and Lönnstedt, L. 'Paper recycling: a discussion of methodological approaches' Resources, Conservation and Recycling, 28 (1-2), Jan 2000, pp 55-65.

21. Johnson, C. ‘A life cycle assessment of incinerating or recycling waste paper’ Imperial College of Science and Technology, 1993.
22. Willoughby, K.W. ‘Technology Choice’, 1990, pp. 15, Intermediate Technology Publications, London.
23. Dunn, T.P. ‘Appropriate Technology: Technology with a human face’, 1978, pp. 5, Macmillan Education.
24. Liu, H. and Li, Y. ‘Compacting municipal solid waste into ‘logs’ for combustion at coal-fired power plants’, Symposium on Energy Engineering in the 21st Century. Jan 2000, pp 1425.
25. http://www.woodgas.com/proximat.htm
26. Louvel, R. ‘Evaluation of briquette acceptability in Niger’ ITDG Boiling Point, 01 special edition, 1989, p 28.
27. McChesney, I. ‘Report on the Sudan briquetting workshop’ ITDG Boiling Point, 01 special edition, 1989, p28.
28. Mabona, M. ‘Ndirande Nkhuni biomass briquette programme’ UNDP Generating Opportunites: case studies of energy and women, 2001, p98.
29. Rogers, G.F. and Mayhew, Y.R. ‘ Thermodynamic and transport properties of fluids’, 1995, pp 2, Blackwell, Oxford UK.
30. Yasuhara, A. *et al*, ‘Formation of dioxins during the combustion of newspapers in the presence of sodium chloride and poly(vinyl chloride)’, Environmental Science and Technology, 35 (7), 2001, pp 1373-1378.
31. Crank, J. ‘The mathematics of diffusion’, 2nd edition, Oxford University Press, 1990.

Appendix A – original email from Mike Fennema

>>> "Mike Fennema" <zoappt@bigpond.com.kh> 08/08/02 05:20am >>>

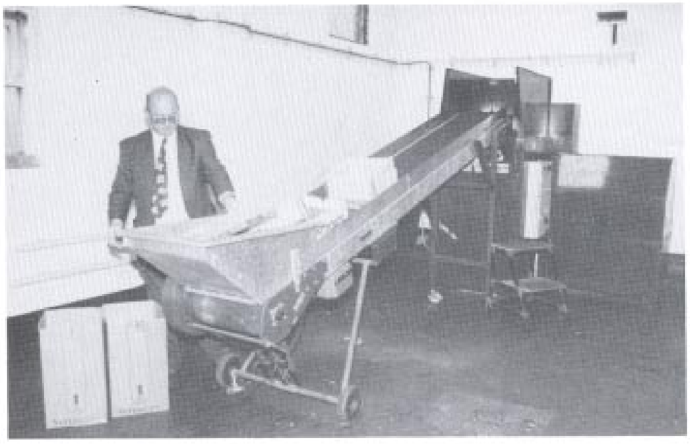
To whom it may concern,
I work with ZOA refugee care in Poipet Cambodia as project manager of an integrated development project covering agriculture, health, education, income generation, water and sanitation, and road construction. I noticed your request for problems and am more than happy to mention a few ideas that come to mind.
Our project focus is in Poipet, which is on the border with Thailand. this is a challenging environment to work in as the value of the land has increased over the past few years, casinos have moved in. The place is a little like the wild west of long ago. The result has been that the rich and powerful end up taking land away from the poor and powerless. The gap between rich and poor grows each year.
Many of the poor survive as day labourers, earning just enough to survive. But always staying dependant on day labor. This work is mostly based at the border, carrying good across by hand, stuck inbetween unscrupulous businessmen and corrupt border officials to whom they must pay bribes.
One focus of our project is to identify alternative sources of income, so that these day laborers can start to depend on different sources of income. So far our efforts are small scale, setting up small businesses. But to make a difference we need to identify a few technologies which can employ much larger number of persons. (Our idea is to build the capacity of local entrepreneurs, not implement businesses ourselves. Although we feel a need to give new options and suggestions at this time).
There are a few areas that seem to have potential to me.
Currently there are a number of resources, raw materials that are exported in great amounts via this border point. They end up being processed in Thailand. These include cardboard paper, recycled plastics, and scrap metal, old batteries. truckloads each day are sent out. Now, Thailand recycles then, adds the value and sells the products back to Cambodia. I have not yet been able to identify some of the potential appropriate technologies that might provide stable income in recycling these products locally.
Do you have any suggestions or experience with this area?
Looking forward to your reply

Mike Fennema
Project Manager
ZOA Refugee Care
Poipet Cambodia

Appendix B – KK balers case study

KK BALERS

Hospital's boilers fuelled by briquetted waste



A conveyor helps ease the loading of dry waste material into the Brickman 300 briquetting press at Leigh Infirmary, maintaining throughput at an optimum level.

A MAJOR proportion of the dry, non-clinical waste produced by Leigh Infirmary, Leigh, Greater Manchester, is now helping to fire the hospital's four steam-generating boilers, reducing fuel bills and the cost of skips which were previously carting much of the loose general waste to landfill.

The ability to convert loose paper, cardboard, plastic, cans and wooden boxes into a valuable and easily handled fuel lies with a Brickman 300 briquetting press, installed by KK Balers Ltd at Leigh Infirmary towards the end of 1992.

Since then the machine has proved 100 per cent reliable in turning more than 700 cu ft (20 cu metres) of dry waste per day into small, tightly compressed briquettes which fill one small wheeled skip of 36 cu ft (1 cu metre) capacity. Compression ratio averages 20 to 1 for all of the dry waste put through the Brickman briquetter which takes about an hour to complete its daily workload.

The briquetted waste helps supplement the coal used to fuel one or two stand-by boilers which are ready to fire into action at any time of the day if there if is a problem with the main unit. All four boilers are rotated and serviced regularly to ensure that heat is always available.

"We would be in real trouble if we lost steam pressure for any reason from the boiler house," explained senior estates officer, Mr Tom Hart. "The boilers not only heat the whole hospital but they provide steam for sterilisation, cooking and humidification. Being able to use briquettes to supplement the coal in the stand-by boilers saves money and provides a most cost-effective way of getting rid of our dry general waste."

Mr Hart commented that, weight for weight, the briquettes produce more heat than coal but, unfortunately, cannot be used in the main on-line boiler because the automated fuel stoking system is suitable for handling only coal. Both the coal and briquettes are shovel-loaded into the stand-by boilers.

"We are onto our fourth and most cost-effective method of dry waste disposal at the hospital," commented Mr Hart. "In the past, paper and cardboard have gone to merchants for recycling but demand has now dried up. Incineration and landfill have also been used but these are wasteful and costly. Briquetting has proved a most satisfactory solution and has created no disruption whatsoever. It gives us free heat and has halved our waste disposal costs."

For the future, Mr Hart is planning to introduce a total segregation system for all of the dry waste produced in the hospital, keeping wet items such as flowers, fruit, vegetables and other foodstuffs separate from the waste destined for the briquetter, ultimately producing more useable briquettes.

Even then, there will still be a demand to be satisfied. "We currently make and burn about 150 briquettes a day," he said. "I reckon this could be increased to 450 without any problem. As a result, we could be looking shortly for additional dry waste from other sources to put through the briquetter. There is no doubt that the machine could handle the additional load, and more."

Before and after. Mr Tom Hart, senior estates officer at Leigh Infirmary, illustrates the compression capabilities of the Brickman 300 briquetting press.

KK BALERS Ltd.
Victory House, Victory Park Road, Addlestone, Weybridge, Surrey KT15 2AX. Telephone: (0932) 852423 Fax: 0932 847170

CASE STUDY

Appendix C - calculation of evaporation rate

Using data from newspaper sample, soak time 473 hours.

ave T = 19 °C
ave humidity = 56 %
$u = 0$
$p_s = 2.196$ kPa (from steam tables [16])
$p_w = 1.23$ kPa
block dimensions (mm):
    length = 215
    width = 85
    height = 55

$E_{lp} = (3.212 + 0)(2.196 + 1.23)^{0.88}$
$= 2.18$ mm/day

now convert this to mass flow (m_w) using value for surface area:

$m_w = 2.18 \,.\, A .\, \rho$

where A = surface area = 0.183 m^3 [3]
    ρ = density of water = 1000 kg/m^3

$m_w = 2.18 \,.\, 0.0198 \,.\, 1$
$= 39.9$ g/day

*the surface area used is the top surface of the briquette, not the entire area.

[3] the surface area used is the top surface of the briquette, not the entire area.

Appendix D – C program listing for diffusion drying curve

```
#include<stdio.h>
#include<math.h>
#include<stdlib.h>

float D = 1E-10; //declares Diffusivity
float dx = 0.06/99; //declares length step, height of block = 60mm
float dt = dx*dx/(20*D); /*declares time step with safety
                        factor 10 - dt must be smaller
                        than dx*/
float TIME; //overall time
float OLD[99], NEW[99]; //moisture content per length step
float TOT[1000000]; //moisture content over total block
float OLDTOT = 66.6; //stores TOT[z] when change in TOT >1
int i, z = 0, zmax; //counters

FILE*ofp;

int main()
{
for (i=0; i<100; i++) //sets initial water content, in this case
66.6%
        {
        OLD[i] = 0.666;
        }

do
        {
        z = z + 1;

        NEW[0] = (((D*dt)*(OLD[1] - (2*OLD[0]) + 0)/(dx*dx))+
OLD[0]);
        NEW[99]= ((D*dt)*(0 - (2*OLD[99]) + OLD[98])/(dx*dx))+
OLD[99];
        TOT[z] = NEW[0] + NEW[99];

        for (i=1; i<99; i++)
                {
                NEW[i] = ((D*dt)*(OLD[i+1] - (2*OLD[i]) + OLD[i-
1])/(dx*dx))+ OLD[i];
                TOT[z] = TOT[z] + NEW[i];
                }

        for (i=1; i<99; i++)
                {
                OLD[i] = NEW[i];//reset values
                }
        OLD[0] = NEW[0];
        OLD[99] = NEW[99];

        zmax = z;

        }
        while (TOT[z] >= 1);

ofp = fopen ("b:dryingcurve1.csv","w"); //creates file
fprintf (ofp, "time step, moisture content\n");
fprintf (ofp, "0,66.6\n");
```

```
for (z=1; z<=zmax; z++) //writes y-values to file
        {
        if ((OLDTOT-TOT[z])>1)
                {
                TIME = (dt*z)/3600; //total time in hours
                fprintf (ofp, "%f,%f\n",TIME,TOT[z]);
                OLDTOT = TOT[z];
                }
        }
fclose(ofp); //closes file

return 0;
}
```

Appendix E – fuel costing data

From : "Mike Fennema" <zoappt@bigpond.com.kh>
Reply-To : "Mike Fennema" <zoappt@bigpond.com.kh>
To : "john arnold" <johnarnold700@hotmail.com>
Subject : AT fuel
Date : Mon, 14 Oct 2002 08:10:08 +0700

```
Dear John

Thanks for your reply and your interest.

I was able to gather some data, I hope it is enough to work
With:

Cost of cardboard:
    cardboard - 1 kg for 2.5 baht
    regular scrap paper - 1 kg for .5 baht
Wood sells for 1 baht per bunch, family consumption is around 6
To 10
bunches per day, or 6 to 10 baht per day.
Charcoal sells for 5 baht per kg, family consumption is around 1
To 2 kg per
day, thus around 5 to 10 baht per day.

1 USD equals around 43 baht at the going rate.
Wood and charcaol are what people use.

One obstacle, even if the economics work out, is whether people
Will like
the taste of the food prepared on cardboard fire!!  I know that
in many
places attempts are made to promote solar cooking, which is
economically
viable, but baked food has a different taste than fried food.
So solar
Cookers are most successful in areas where baking is more
common.
At least with this idea, fire is used, so maybe less affect on
The taste of
the food.

Look forward to your work

Mike
```

Appendix F – original data on existing stoves

From : "zoappt" <zoappt@bigpond.com.kh>
To : "john arnold" <johnarnold700@hotmail.com>
Subject : Re: design of paper briquetting machine
Date : Fri, 28 Mar 2003 08:45:37 +0700

The maximum size that they use for logs is 4 cm in diameter.
Length is not
So crucial as they feed it in bit by bit. Typical lenght is 30
cm.

Size of the stove varies. The bigger one is 20 cm high, with a
33 cm
diameter outer rim, 23 cm diameter inner rim.
The opening were they put the logs in is about 5 cm high, and 13
Cm long.

Hope that makes sense

Mike