Chapter

Conceptualization and Design of a Small Pyrolysis Plant for the Sustainable Production of Flexible Bricks and Bituminous Concrete from Polyethylene Terephthalate Waste

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Abstract

Polyethylene terephthalate is majorly used for packaging of various products because of its resistance to chemical attack and environmental degradation, but the proper disposal of this non-biodegradable material has been a major challenge. Pyrolysis is the melting of plastic in the absence of oxygen. Currently pyrolysis of polyethylene terephthalate is considered as a viable recycling method since it only requires 5% of the calorific value of polyethylene terephthalate. This research was aimed at designing a pyrolysis plant for the production of construction materials with acceptable mechanical properties such as compressive strength and water absorption. Sustainable, eco-friendly road construction from bituminous concrete with waste polyethylene terephthalate has the capability of reducing carbon emissions. The polyethylene terephthalate bituminous composite has the flexibility of plastic but strength of concrete. The bricks have a maximum compressive strength of 10 N/mm^2 which is within the standard range and have less water absorbing tendencies hence have a longer lifespan. Value addition is equally important in the pyrolysis plant so as to contribute to sustainable development. This book chapter reviews the different products such as polyethylene terephthalate composite bricks and flexible pavements which can effectively use polyethylene terephthalate waste as a raw material.

Keywords: pyrolysis, bricks, waste, polyethylene terephthalate, recycling, bituminous

1. Introduction

The word plastic refers to any material which is made of synthetic or organic compound which has malleable properties. Polyethylene Terephthalate (PET) is being used for beverage and food packages all over the world, but the problem with the disposal of this non-biodegradable hydrocarbon materials has been a major challenge to the world. The major features which play a big role in the usage of plastic are malleable, light weight, impervious to water and low cost [1]. Recycling of plastic into construction materials can help in providing a cleaner environment. Much of the waste generated from this PET has ended up in water drains and eventually into the ocean. It is the belief of some school of thoughts that by 2050, there will be more plastics than fish in the ocean of the world if this trend is not quickly addressed [2]. Concrete bricks are a type of brick that is commonly used in low and medium cost housing development in developing countries since it is cheap and easy to produce. The conversion of the solid residue remaining after pyrolysis to bricks will add to sustainable value addition recycling of waste PET.

During pyrolysis the hydrocarbon bonds are broken down due to the heat applied. **Figure 1** shows the most common but crude way in which people have been disposing of plastic waste in Zimbabwe.

Table 1 shows the different types of plastics and their symbols. The different plastic types have different uses affected by their chemical structure.

Waste utilization has become an attractive alternative to disposal given the scarcity of space for landfilling and its ever increasing cost; utilization of waste PET in concrete bricks is viable. The use of waste products in concrete not only makes it economical, but also helps in reducing disposal problems [3]. The three types of pyrolysis namely conventional/slow pyrolysis, fast pyrolysis and flash pyrolysis differ majorly in terms of temperature, residence time and products made. **Table 2** summarizes the differences in order to understand the process.

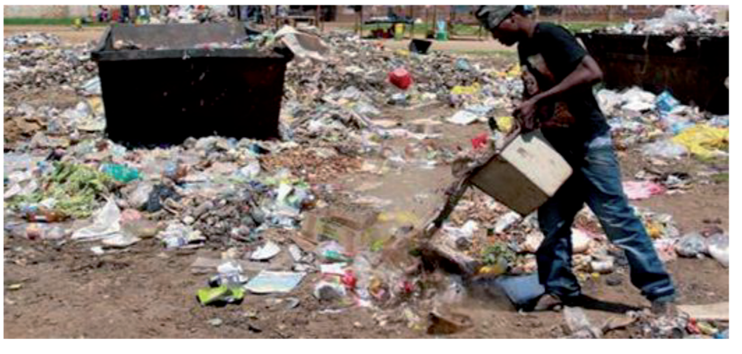

Figure 1.
Disposal of waste in Harare, Zimbabwe.

Symbol	Type of plastic	Application
1	Polyethylene terephthalate (PET)	Clear transparent plastic
2	High-density polyethylene (HDPE)	Opaque plastic bottles
3	Polyvinyl chloride (PVC)	Water service pipes, cable insulation, footwear packaging
4	Low density polyethylene (LDPE)	Grocery bags, packaging film
5	Polypropylene (PP)	Margarine tubs, microwaveable meat trays.
6	Polystyrene	Yoghurt pots, fish trays, egg cartons, vending cups, plastic cutlery and toys
7	Other	Plastics that do not fall into any of the above categories. e.g., melamine.

Table 1.
Types of plastics and typical uses.

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Method	Temperature (°C)	Residence time	Heating rate (°C/s)	Major products
Conventional pyrolysis	400–500	5–30 min	Low 10	Gases, char, bio-oil (tar)
Fast pyrolysis	400–650	0.5–2 s	High 100	Bio-oil (thinner), gases, char
Flash pyrolysis	700–100	< 0.5 s	Very high >500	Gases, bio oil

Table 2.
Differences between types of pyrolysis [4].

Heating rate	Time	Temperature (°C)	Char	Liquid	Gas
Slow (<10^3 W/m^2)	1000s	~500°C	25%	35%	40%
Medium (>10^4 W/m^2)	100s	~500°C	17%	58%	35%
Fast (>10^5 W/m^2)	1s	~500°C	15%	65%	20%
Flash (>10^6 W/m^2)	0.01s	~500°C	10%	70%	20%
Slow (<10^3 W/m^2)	1000s	~1000°C	40%	35%	25%
Medium (>10^4 W/m^2)	100s	~1000°C	20%	37%	43%
Fast (>10^5 W/m^2)	1s	~1000°C	15%	20%	65%
Flash (>10^6 W/m^2)	0.01s	~1000°C	0%	15%	95%

Figure 2.
Illustration of pyrolysis properties on end products [4].

Hence from the table, as the temperature increases, the residence time decreases and the solid products become less. The amount of solid residue produced is determined by the type of pyrolysis and mainly affected by the heating rate. **Figure 2** clearly outlines the effect of heating rate and other pyrolysis factors on the products.

Hence from the figure it can be deduced that in order to obtain a higher yield of the solid residue or char, the heating rate should be slow.

2. Background and literature

Plastic pyrolysis is a tertiary recycling method for disposing of waste and repurposing it in a sustainable manner [5]. Incineration and landfilling are two traditional methods for disposing of plastic waste in developing countries, both of which have shown to be unsustainable. Plastic waste is primarily disposed of in landfills or incinerated. Utilization of PET in bricks and flexible pavements has gained momentum over the past decade. The general failures linked with basic bituminous asphaltic concrete (BAC), which are commonly used in surfacing courses in bricks and flexible pavements include rutting, bleeding, polish, cracking and potholes. Repurposing of the waste PET plastic in raw BAC used in bricks and pavements will be a more sustainable waste management option since flexible pavements constitute over 90% of paved roads around the world [6]. Due to various environmental issues such as air pollution and soil contamination, as well as economic resistance due to space waste and disposal costs, these approaches are encountering significant popular resistance [7]. The conversion of PET to bricks would be a more sustainable method of recycling plastic waste.

2.1 Incineration and landfilling (pyrolysis processes waste disposal)

Incineration is a waste treatment process which includes the combustion of waste for recovering energy [8]. Landfills occupy space and are therefore unsustainable. Pyrolysis is a tertiary recycling technology because chemical degradation results in the creation of products with a higher added value than the raw material that undergoes pyrolysis. Pyrolysis is defined as the cracking process in the absence or in poor content of oxygen. By mass, 67 percent of plastic waste may be converted into fuel, gasoline oil, or diesel [8].

2.2 Advantages of plastic pyrolysis over other recycling methods

Pyrolysis of waste PET plastic is a more sustainable way of waste management as it creates value. The residue from the tertiary recycling method can be further treated to produce secondary raw material. The advantages of pyrolysis are:

- It is an inexpensive method of processing waste and can be used with a variety of feedstock.

- Minimizes the amount of non-biodegradable waste that goes to landfills and incinerators, thereby reducing greenhouse gas emission.

- Reduced risk of water pollution.

- Creates jobs for low income earners in developing countries based on the waste generated, they collect the waste for recycling.

- In comparison with combustion it has lower process temperatures and has a lower emission of pollutants.

- Hence pyrolysis of waste PET plastics will be a more sustainable method of waste management rather than the traditional methods.

Figure 3 shows the different stages in the chemical degradation process. It starts with the initiation step which involves homolytic breaking down of the carbon to carbon bonds either by random or end chain scission. The result is two radicals and it leads to propagation which is the hydrogen transfer reaction either by intra or intermolecular forming and unzipping leading to unstable free radicals. Then the final step termination of the free radicals forming unreactive materials.

3. Methodology

A sustainable alternative was essential in the design due to the issues with non-biodegradable plastic waste. In the last few decades, the recycling of PET as building material has been gaining ground, the properties of the plastic make it most suitable [5]. The goal of the study was to simplify existing technologies for value addition pyrolysis. Three different options were considered. Careful consideration and analysis were conducted in order to determine which of the three concepts provided the best solution to the Product Design Specification (PDS). The plant's primary selection criteria were the heat exchanger and the source of heat. Use of the binary dominance matrix was essential because it allowed for simultaneous analysis of all concepts. SolidWorks was used to model three design possibilities, as illustrated

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in **Figure 3**. The heat exchanger in Concept (a), the Double Pipe, was laminar for fluid flow hence the rate of heat flow was lower than in the other concepts. Since Liquefied Petroleum Gas (LPG) is used as a heat source in Concept (b), the Shell and Tube, the target market without electricity may choose LPG. Furthermore, a Shell and Tube heat exchanger could be more expensive than a helical coil heat exchanger. Due to its helical coiled heat exchanger and coiled heater on the reactor, Concept (c), the Helical Pipe Heat Exchanger, dominated the weighted objectives. The selection was heavily influenced by the ease of assembly and fabrication. The different concepts are shown in **Figure 4**.

Due to its great strength, formability, and corrosion resistance, stainless steel was chosen over mild steel. **Table 3** shows the binary dominance matrix that was used to choose the most optimal concept based on functionality, efficiency, ease of maintenance, reliability, simplicity, cost, quality, and ergonomics. Concept (c) was chosen as a result.

Due to the helical heater on the pyrolysis tank there is even heating and the molten PET is then combined with the bituminous asphaltic concrete (BAC). This mixture is then put into casting bricks and also used in making concrete [8]. Recycling of PET and using it in construction will be a great stride since the PET is non-biodegradable and its chemical properties will further make the BAC durable.

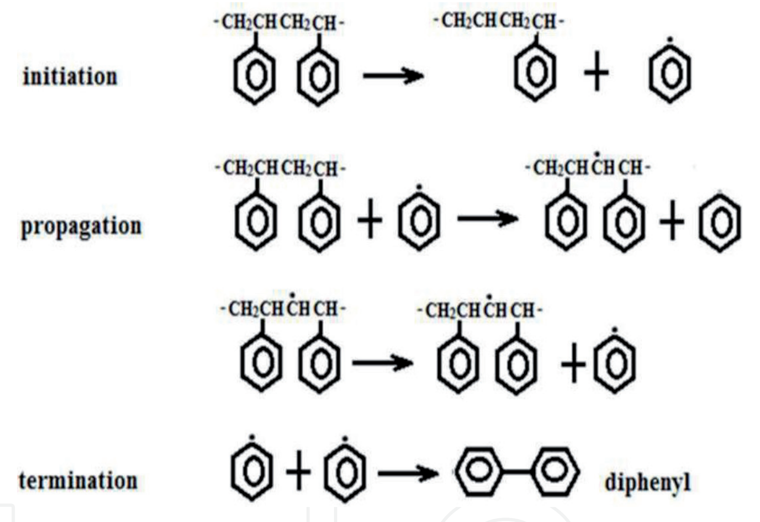


Figure 3.
Stages of radical degradation reaction.

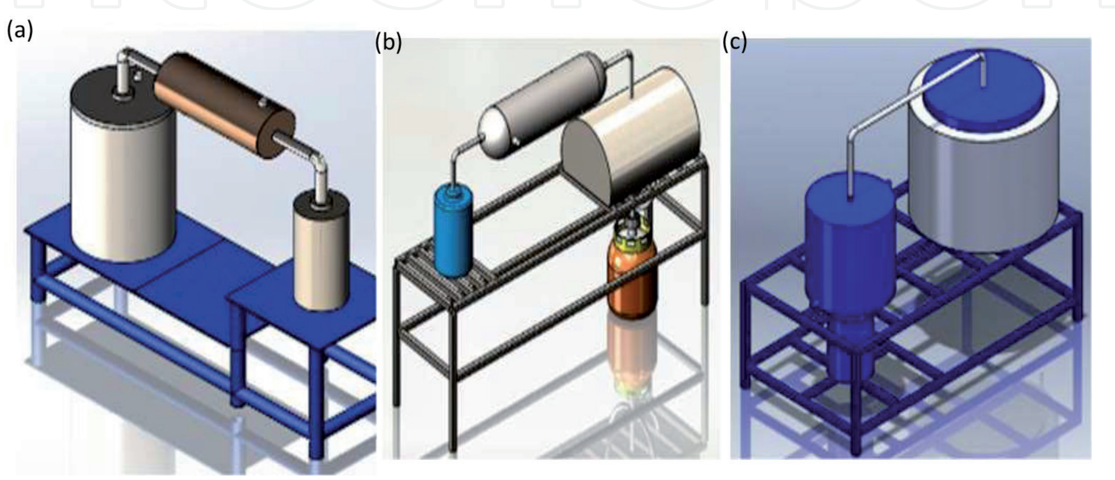


Figure 4.
Concepts (a) double pipe; (b) shell and tube; (c) helical pipe heat exchanger.

Criteria	Weight	Concept rating/10			Concept weighting/100%		
		(a)	(b)	(c)	(a)	(b)	(c)
Function	10	7	5	9	70	50	90
Efficiency	9	6	6	8	54	54	72
Cost	8	4	6	8	32	48	64
Ease of maintenance	6	7	7	9	42	42	54
Reliability	6	5	5	8	30	30	48
Ease of manufacture	4	6	7	9	24	28	36
Lifespan	4	7	8	9	28	32	36
Simplicity of layout	2	5	7	8	10	14	16
Quality	1	8	6	9	8	6	9
Weight	1	8	5	9	8	5	9
Ergonomics	1	6	6	8	6	6	8
Total score					312	315	443

Table 3.
Concept selection using the binary dominance matrix.

3.1 Experimental design development

The pulverized plastic wastes used in this work were collected from disposed plastic waste used for packaging water and fruit juices at Petreco Zimbabwe. The PET waste (**Figure 5**) was collected and cleaned with tap water to remove any form of contaminants and deleterious materials before sun drying for a minimum of three days.

The waste PET was added into the pyrolysis tank with a helical heating coil for even heat distribution. Oxygen was eliminated from the chamber by use of oxygen scavengers. Weight batching was used to be able to eliminate errors due to size and void in the material. Whilst molten the PET was tapped out of the pyrolysis tank into the brick cast mold. Mechanical tests were key to ascertain the properties of the brick. Hence compression test, water absorption test and flexural strength test were carried out. The different mechanical tests are described below.

3.1.1 Compressive strength test

Compressive strength is a mechanical test that measures the amount of compressive load a material can sustain before failure. It is the most accurate indicator for measuring the engineering properties of a building material because a higher compressive strength indicates a good and strong material. Compressive strength in bricks and flexible pavements greatly depends on the amount of compaction, heat treatment and the concrete mix ratio.

3.1.2 Water absorption test

Absorption of water is a critical factor for the durability of bricks and flexible pavements. When water penetrates brick, it decreases the strength of bricks. Hence the brick internal structure must be adequately dense to avoid the leaking of water. To increase density and decrease water absorption of clay bricks, the firing temperature must be raised [7]. Generally, the water absorption values decreased with

Figure 5.
Sample pulverized PET.

increasing temperature, and decreased with increasing amounts of waste plastic in the mixtures. Hence PET plastic would reduce the water absorption of the pavements and bricks.

3.1.3 Flexural strength

The flexural strength of brick is its ability to resist bending through internal stresses generated within the brick or flexible pavement. Elastic stresses are developed within the brick and pavement material to resist the external load. Resistant tensile stress that develop, keep the bricks in shape until the failure of the structure. Whenever the material is overloaded the structure will rupture, and flexural cracks are developed at the point of highest tensile stress on the brick or flexible pavement [5]. It's an integral test in determining properties of the brick.

4. Results and discussion

The model of choice was the Helical Heat Exchanger. In order to enhance mobility and temperature monitoring, wheels and a thermometer also included in the frame as shown in **Figure 6**. In this model electrical energy is used to melt the plastic making use of an oxygen scavenger to remove oxygen from the reactor. In order to optimize the intended operation, the heat exchanger's dimension was to be calculated. Using Eq. (1) below to calculate the required length of wire, ten turns of the helical copper pipe were chosen.

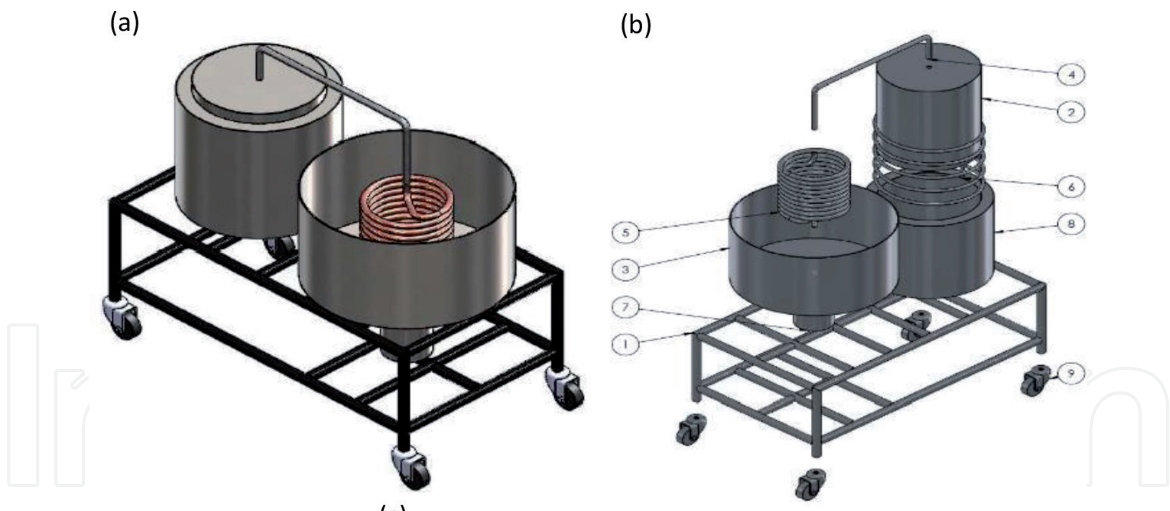
$$L = N\sqrt{(2\pi r)^2 + p^2} \tag{1}$$

$$\mathrm{L} = 10\sqrt{2\pi(7.5)^2 + 20^2}$$

Using Eq. (2), the helical pipe volume was found.

$$V_e = \frac{\pi}{4}(d_o)^2 L \tag{2}$$

$$V_e = \frac{\pi}{4}(15)^2 \times 512 = 90.4 / \mathrm{mm}^3$$



(c)

9	ROULETTE 3,8	4
8	reactor casing	1
7	Collector	1
6	heater	1
5	Helix heat exchanger	1
4	Pipe	1
3	Heat exchanger tank	1
2	Tank	1
1	Stand	1
ITEM NO.	PART NUMBER	QTY.

Figure 6.
SolidWorks model of the heat exchanger (a) assembled heat exchanger (b) exploded view (c) parts list.

4.1 Flexible pavements and bricks experimental results

The pulverized PET was melted in the pyrolysis chamber in the absence of oxygen Different amounts of PET were used in the mixture with bituminous asphaltic concrete to optimize the best properties from the materials. After testing the compressive strength of the bricks at different percentages of PET the results in **Figure** 7 were obtained.

Figure 7 shows that the compressive strength of flexible pavements decreased with increase in the percentage of the PET. The results showed a maximum

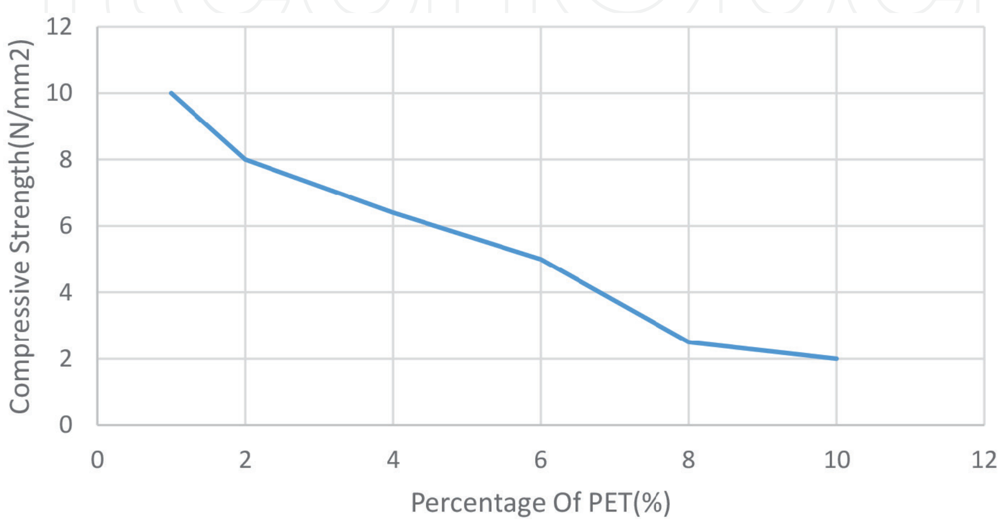


Figure 7.
Compressive strength results.

compressive strength of 10 N/mm^2. However, the water absorption properties decreased with increase in percentage content of PET that is the brick absorbed less water with an increase in the amount of PET.

Since coarse aggregates account for more than 60% of the aggregates, the BAC can be defined as coarse dense-graded and it is suited for all pavement layers and traffic conditions. The PET reduced the flexible pavement and brick compressive strength whilst increasing its fatigue resistance. In addition, it created better mixing between asphalt and the aggregates. During the compressive test the PET bricks had a maximum compressive strength of 10 N/mm^2 which was within the standard range and had less water absorbing tendencies and hence a longer lifespan. Generally bigger aggregate sizes give better mechanical properties, as well as good permeability and traction, and are typically focused at achieving high surface drainage and durability [9]. The flexible pavements with PET as a filler also exhibited increased workability and durability, as well as resistance to irreversible deformation, stress, and low-temperature cracking, and moisture damage [8]. The filler's purpose was to improve stiffness, workability, moisture resistance, and aging properties. The use of waste PET as a flexible pavement is one of the possible uses of the plastic waste.

Globally there is growing demand for high-performance pavement due to increase in traffic and failure of ordinary pavements. In a bid to increase durability of roads especially in developing countries where the roads are deplorable, use of PET waste with BAC and cement as a binder. PET wastes in flexible pavement, brick construction and road rehabilitations would essentially utilize several million metric tons of PET wastes from the waste stream which would have good sustainable effects on the environment such as minimization of pollution and greenhouse gas emissions. It also encourages ecosystem balance by the limiting of non-biodegradable PET wastes from the ecosystem.

5. Conclusion

The concept of employing composite brick and pavement was investigated in this research. PET materials melted during the pyrolysis process due to their low melting point of 250°C. This research brought about the purpose of eco-friendly construction material production in the drive toward achieving sustainable development in the fourth industrial revolution. It enlightens on the concept of eco-friendly road construction by use of flexible pavements and bricks by utilizing waste, non-biodegradable PET plastic. The properties of plastic meant it would not be affected by water absorption which weakens the bricks and flexible pavements. Further research can be done on exploiting the properties of PET in the manufacture of construction materials, especially its light weight and temperature regulation. As a reference for future work the residue char from pyrolysis can be further investigated for use as an activated carbon.

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