DEVELOPMENT OF SHREDDING AND WASHING MACHINE FOR POLYETHYLENE TEREPHTHALATE (PET) BOTTLES PELLETIZER

Oluwatobi I. Okunola *, Damilola A. Oyebade‡**, Olawale O. Olanrewaju

* Federal University of Technology, School of Engineering and Engineering Technology, waleolanrewaju166@yahoo.com

**Federal University of Technology, School of Engineering and Engineering Technology

‡ Damilola A. Oyebade, Federal University of Technology, PMB 704, Akure, Ondo State, Nigeria.

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Abstract- Plastics, owing to its widespread use in almost all sectors, has become a foremost important environmental threat facing humankind and recycling is considered the best and viable option to tackle this peril. The purpose of this research was to develop and evaluate PET bottles shredding and washing machine for waste management and recycling. The research was aimed at shredding PET bottles into required sizes with an area of 0.001m^2 (10mm x 10mm) for a plastic pelletizer. The machine developed performs washing, cleaning and shredding of PET bottles using rotating blades are arranged in auger-like manner, other features of the machine includes hopper, washing chamber, adjustable screen and centrifugal pump. The machine was designed with high consideration for safety, easy operation, efficiency and cost. The machine has the capacity to shred 50-75kg of PET bottles per hour. The recycling efficiency, shredding efficiency and percentage retention are the parameters used to evaluate the performance of the machine at variable operation speeds (187.5rpm, 273.8rpm and 350.2rpm) and feeding rates (1.0kg/hr, 1.8kg/hr and 2.4 kg/hr). Tests results showed higher ratio of the shredded plastic of the desired size at 1.8kg/hr and 350.2rpm, accounting for 60.01% shredding efficiency. The recycling efficiency of the shredding and washing machine is 93.73% at 273.8rpm and 1.8kg/hr feeding rate, with the highest retention of 17.9% at 2.4kg/hr feeding rate and 185.7rpm. The shredding and washing machine will be used in combination with plastic pelletizing machine in a waste recycling plant.

Keywords: Plastic, Waste Recycling, Polyethylene Terephthalate, Shredding

1. Introduction

Production of plastics has increased globally, as it surfaces across almost all aspect of the economy. With its flourishing applications, the use of plastics is of more benefits for society (Okiy et al,. 2018), which include making packaged food lasts longer, reducing wastage, the use of plastic in pipes promotes clean drinking water supplies, while plastic enables life-saving medical devices such as surgical equipment, drips and blister packs for pills (Andrady & Neal, 2009). Nevertheless, the increase in the use of plastic has an effect on the environment associated with its manufacture and disposal (Ayo et al., 2018). Waste management has become a global predicament, requiring adequate attention in order to solve the world's resource and energy challenges. No doubt, 2018 world environmental day was centered on beating plastic pollution (UN Environment, 2018.

Presently, plastic is one of the most useful and important materials in the world (Dutta and Choudhury, 2018). Over the past 50 years, there have been a global increase in the production of plastic, from 2 x106 metric tonnes (Mt) in 1950 to 381 x106 Mt in 2015, and is anticipated to double in the next 20 years. The total global production of plastics to date is estimated at 8,300 x 106Mt (Royer et al, 2018). Globally, plastic waste constitutes more than 60% of the total global municipal solid waste (MSW) of which 22% were recovered and 78% disposed of. Plastic bottles make up approximately 11% of the content landfills, causing serious environmental consequences (Ayo et al., 2018).

Plastics are synthetic organic materials produced by polymerization. They are of high molecular mass and can be molded or extruded into desired shapes. Several substances, as well as polymers, are an addition in the production of plastics to improve performance and or reduce cost (Ikpe et al., 2017).

Plastics are of five major categories, High density polyethylene (HDPE), Polyethylene terephthalate (PET), the polypropylene (PP), Low density polyethylene, the polyvinylchloride (PVC) (Ayo et al., 2018). Polyethylene Terephtalate is a polyester of terephtalic acid and ethylene glycol. It is applied in many fields due to its inert chemical and physical properties. Disposal of waste PET bottles poses a challenge as repetitive recycling of the bottles exhibit a possible danger of being changed into a carcinogenic material and only a small proportion of PET bottles are being recycled. (Jadhav et al., 2018). Plastic bottles are made from a petroleum product known as polyethylene terephthalate (PET), and they require huge amounts of fossil fuels to both make and transport them. Plastic recycling includes taking any type of plastic sorting it into different polymers and then chipping it and then melting it down into pellets after this stage it can then be used to make items of any kind such as plastic chairs and tables (Darshan and Gururaja, 2017). Plastic recycling involves several complex processes; thus, a small volume of the world plastic is recycled as only certain types of plastic bottles can be recycled by certain metropolises (Jadhav et al., 2018). Plastic waste recycling has a great potential for conservation of resources and reduction in the emission of Greenhouse gases, as it could be used in the production of diesel fuel. Plastic waste recycling conserves energy, saves landfill spaces, provides jobs for people and provides alternative materials (Ikpe et al., 2017). This resource conservation goal is very important for most of the national and local governments, where rapid industrialization and economic development is putting a lot of pressure on natural resources (Williams, 2005). Plastics either infiltrate the streets as litter or lies stagnant in landfills, oozing hazardous chemicals into the ground. Non-biodegradability of plastics poses as a major disadvantage to its use (Faaiyyaj et al., 2017).

Plastic recycling in developing countries like Nigeria, is at a minimal rate resulting in the increasing purchase of more plastics, even at higher cost. It is observed in Nigeria that there is no system in place to recover and recycle used PET bottles (Olanrewaju and Ilemobade ,2009; Okiy et al., 2018). Nonetheless, more bottles are produced daily increasing the amount of waste generated. The limited or absence of recycling machines and probably ignorance of recycling technologies in the country has resulted into the non- recycling of littered waste PET bottles compared to other countries of the world (Atadious and Oyejide, 2018).

Plastics recycling in waste management is a collective effort which requires the involvement of every arm of the society which includes large industries, medium scale and at the local level also. Study and field survey showed minimal involvement of local recyclers in PET recycling as manual labour is been used for chopping plastic waste which limits volume of shredding and results in human fatigue, the cost and maintenance of existing machine is very expensive and not affordable for local operators (Ugoamadi and Ihesiulor, 2011). Thus, a need for an indigenous PET shredding and washing machine, which is affordable and of reliable efficiency.

The objective of this research is to develop a PET bottle shredding machine, to crush used plastic bottles into a required size for efficient pelletizing, thereby reducing the cost of transportation and improving waste management. Waste PET shredding and washing machine is a machine that reduces used plastic bottles to smaller particle sizes to enhance its portability, easiness, and readiness for use into another new product.

2. Material and Method

Sonkhaskar (2014) defined shredding as the transfer of a force amplified by mechanical advantage through a material made of molecules that bond together more strongly and resist deformation more than those in the material being crushed, hence, the toughness and strength of the shredding material must be relatively higher than that of the PET bottles.

2.1. Design Principles and Consideration

The special feature in the developed machine includes: auger-like blade, hopper (Trapezoidal in shape) the washing chamber placed beneath the adjustable screen, the centrifugal pump, electric motor (5 hp, Single Phase), portability and low cost of machine components. This machine does not require high skilled technology know-how to operate successfully.

The following factors were considered in the design of plastic waste shredding and washing machine to make it more efficient; safety, compactness, power requirement, easy operation, speed, rigidity, shear strength and cost. The selection of materials was based on durability, ease of fabrication, cost and availability

The plastic waste shredding and washing machine is powered by an electric motor while the washing is subjected to high pressure and recycled by electric centrifugal pump. The machine employs the principle of scissor cutting. Some set of blades are arranged systematically round the rotating drum will others are fixed to the wall of the machine. The rotating blades are arranged in auger-like manner, these blades rotate and shears the plastic against the static blade fixed to the wall of the shredder.

2.2. Design of Machine Components

2.2.1. Design of hopper

The hopper is trapezoidal in shape which serves as the input unit, so it was designed to provide smooth convey of waste plastic into the shredding chamber as shown in Fig 1. The hopper is configured to ease the delivery of the PET bottles into the shredding chamber.

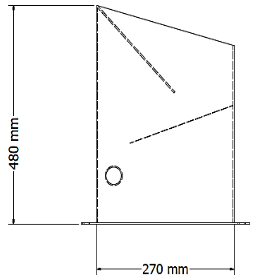

Figure 1: Hopper

To calculate the coefficient of friction, μ as stated by Khurmi & Gupta (2004)

$$\mu \ = \ tan\,\alpha \qquad (1)$$

Where μ = Coefficient of friction of plastic=0.54 (Engineering ToolBox, 2004)

$$A \ = \ Repose\ angle\ of\ plastic$$

From equation 1, $\alpha \ = \ tan\,\mu$

Note: This type of hopper used is a gravity discharge one and the recommended angle of inclination (ϕ) of hopper for gravity discharge of Agricultural material must be greater than the repose (α).

Hence, the angle of inclination of the hopper (φ) =38.37°

(ii) *Determination of the cross-sectional area of the hopper*

The cross-sectional area of the hopper = area of trapezium.

Using the equation, Area of cross-section of hopper, (Tata, 2011)

$$A_h = \frac{1}{2}(a+b)h \qquad (2)$$

Cross-sectional area of hopper = 0.0246 m^2

(iii) *Determination of the volume of the hopper*

Volume of the hopper = Area of cross-section of the hopper x width of hopper,

The volume of the hopper is 1.155x10-2 m^3

(iv) *Determination of the weight of the PET bottle that the hopper can accommodate*

Volume of PET bottle (coca cola) in the shredding chamber

Given the volume of PET bottle (Coca-Cola bottle) is 7.7 x 10-4 m3 (Faiyyaj et al., 2017) No of bottle to fill the hopper = volume of hopper/ volume of PET Bottle = 1.155x10-2 m^3/ 7.7 x 10-4 m^3 = 15bottles.

Weight of the PET bottle inside hopper, Wb = mass of PET x gravity x density = 3.04 N.

2.2.2. Cutter Design

Determination of the weight of the auger cylinder

The machine is required to produce 75kg/h (0.02083kg/s) of shredded plastic. This capacity in terms of shredded output depends on the amount of waste plastic fed into the machine and the average weight to be shredded as experimented by Ikpe et al., (2017)

Diameter of the outer cylinder, d1 = 0.1m, diameter of the inner cylinder, d2 = 0.088 m,

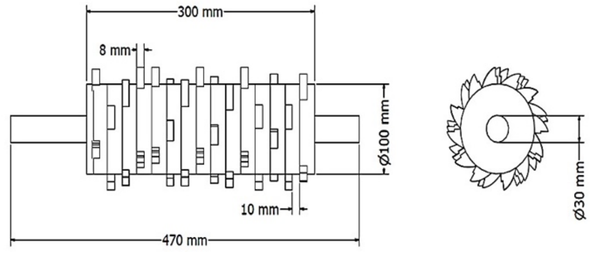

Figure 2:

Figure 2: Cutter

Using equation as used by Tata (2011),

$$A_c = \frac{\pi d_1^2}{4} \qquad (3)$$

The area of the outer cylinder is 7.86x10-3 m2 and the area of the inner cylinder as 6.08x10- 3 m^2

Area of the solid portion, which is the difference in the area of the outer and inner cylinder is 1.78x10-3 m2, Density of mild steel = 7850 kg/m^3

Volume of solid portion = area of the solid portion x length = 4.45x10-4 m3 Using equation 3, the area of the cylinder cover is 7.86x10-3 m^2

Determination of speed of belt

The belt speed is determined using equation 4 below as used by Tata (2011)

$$N_1 D_1 = N_2 D_2 \qquad (4)$$

Where Angular speed of driving pulley, N1 = 500 rpm, Diameter of driving pulley, D1= 60 mm, Angular speed of driven pulley, N2 (rpm), Diameter of driven pulley, D2 = 110 mm

Determination of tension acting on the driven pulley T1 & T2

From Figure 3; equation 5, 6 and 7 is to determine belt tension as stated by Khurmi & Gupta (2004)

$$\frac{T_1}{T_2} = e^{\mu\theta} \qquad (5)$$

Where T1 = Tension at the tight side, T2 = Tension at the slack side, μ = coefficient of friction between leather belt and metal pulley, θ = wrap angle

$$P \ = \ (T_1 \ - T_1)\,V \qquad (6)$$

Where V = Linear velocity in meter per sec, P = Power of the electric motor, T1 = Tension on the tight side, T2 = Tension on the slack side (Khurmi & Gupta, 2004)

$$V = \frac{\pi d N}{60} \qquad (7)$$

Using equation 6, the Linear velocity of the electric motor, V is 15.7 m/s, the power required to drive the cylinder is 3700W = 3.7KW.

2.2.3. Shaft Design

Determination of Shaft Diameter

To calculate the diameter of the shafts, the weight of the auger is 41.46 N, the sum total of weight of cutter blade to be used is 10.44 N, the weight of the pulley that will be acting on the shaft is 60.5 N, the weight of 16 bottles is 3.04 N as illustrated in Figure 3 and 4.

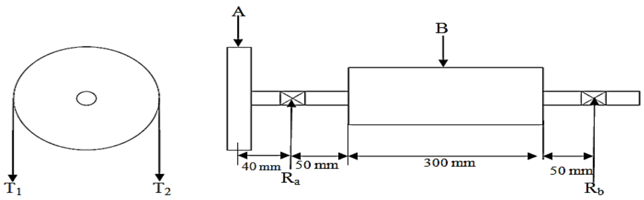

Figure 3: Schematic diagram for shaft

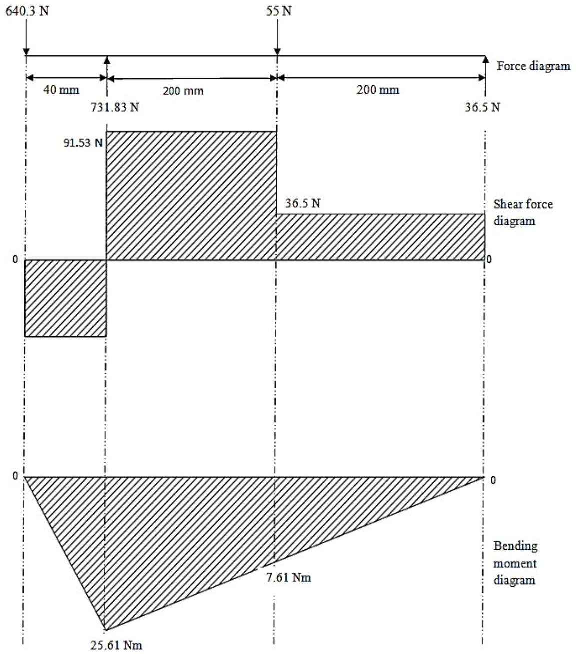

Figure 4: Forces acting on shaft

Where A = weight of pulley + sum of forces of the belt (since the tension of the belt is acting downward), B = weight of auger + total weight of the cutting blade + weight of plastic bottle on the puerperal of the shaft.

$$d^3 = \frac{16}{\pi\tau}(\sqrt{(k_b m_b)^2 + (k_t m_t)^2}\,) \quad (8)$$

Where, τ = allowable shear stress of metal with key way = 40 x 106N/m2 mb = maximum bending moment = 25.61Nm

mt = torsion moment = 22.3N

Kb = combined shock and fatigue factor applied to bending moment = 2.0 (sudden loading) Kt = combined shock and fatigue factor applied to torsional moment = 2.0 (sudden loading) (Khurmi & Gupta, 2004)

$$d^3 = \frac{16}{3.142(40\times10^6)}(\sqrt{(2\times25.61)^2+(2\times22.3)^2}) \quad (9)$$

$$d = \sqrt[3]{8.652 \times 10^{-6}}$$

d = 20.5 mm

Using the factor of safety = 1.4, 30mm shaft is selected.

2.2.4. 2.2.4. Machine Fabrication

The different parts of the machine that were discussed above were assembled together by welding while the detachable parts were bolted. Also, an isometric view of the machine is shown in Figure 5 and Figure 6 shows the shredding and washing machine.

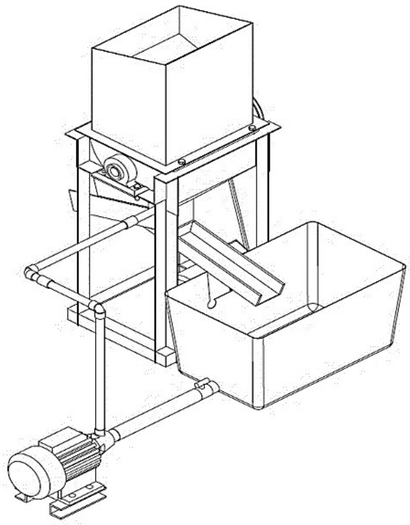

Figure 5: Isometric view of the plastic waste shredding and washing machine

Figure 6: Shredding ans washing machine

3. Performance Evaluation of the Machine

The developed model of a shredding and washing machine for PET bottles is subjected to performance test using a 5 Hp three phase electric motor as the prime mover. PET bottles were shredded at varied motor speed of 187.5rpm, 273.8rpm and 350.2rpm and the bottles are fed into the machine at 1.0 kg/hr, 1.8kg/hr and 2.4kg/hr. Ordinarily, testing the machine started without a sieve to see what size of shreds it would produce. As expected, the process was very quick and produced a wide range of shred sizes. As the teeth of the knives are relatively long and there is little chance of cross-cutting, the pieces tended to be in the shape of long strands when shredding products with a lower material thickness. The wide spread of sizes makes it unsuitable for re-melting in subsequent machines, hence the need for the use of screens, the washing machine washes the shredded plastic with pressure from the pump before it falls out under gravity through the outlet. For each experiment, initial mass, MI of 1.2 kg is fed into the machine, the mass of the shredded plastic, Ms was measured, then sieved with a 10mm screen, the mass of shredded plastic with sizes smaller than and equal to 10mm, Ms1 is measured and the mass of shredded plastic larger than 10mm, Ms2. The experiment was carried out in three replicates and the results were analyzed for an average of five minutes for each experiment. The mass of plastic retained, Msr in the shredding chamber is calculated as the difference between the mass input and the machine output.

$$Msr = MI - Ms \tag{9}$$

Retention (%) is the percentage ratio of the retained mass to the initial input mass of the PET bottles.

$$Retention(\%) = \frac{M_{sr}}{M_I} \times 100\% \tag{10}$$

The Shredding Efficiency is the measure of the percentage of reusable shredded plastic, the percentage of the shredded plastic with area size less than or equal to 10mm2 x 10mm2 relative to the total shredded plastic as used by Ikpe et al., (2017).

$$\text{Shredding Efficiency } (\%) = \frac{M_{S1}}{M_S} \times 100\% \tag{11}$$

The Recycling efficiency is the measure of the useful plastic after shredding, the percentage of the shredded plastic with size less than or equal to 10mm relative to the initial mass of plastic as used by Ayo et al., (2018)

$$\text{Recycling Efficiency } (\%) = \frac{M_O}{M_I} \times 100\% \tag{12}$$

4. Results and Discussion

The PET bottles shredding and washing machine was designed, developed and subjected to performance test in the department of Agricultural and Environmental Engineering, FUT, Akure and powered by a 5Hp, 1440 rpm electric motor. The machine has the capacity to shred 50-75kg of PET bottles per hour. The performance test was conducted on the PET bottles shredding and washing machine developed to ascertain its effectiveness and function ability. Table 1 shows the experimental results, indicating the average output mass, the retained mass, percentage retention, shredding and recycling efficiency for each feeding rate at the various machine speed.

Table 1: Summary of shredding and washing machine test performance with three speeds and feed rate

Speed	Feed rate	Input mass (kg)	Output mass(kg)	Retained mass (kg)	Output <=10mm^2	Output >10mm^2	Retention %	Shredding Efficiency	Recycling Efficiency
187.5rpm	1.0kg/hr	1.2	1.04	0.16	0.59	0.45	13.7	56.77	86.35
	1.8kg/hr	1.2	1.10	0.10	0.65	0.45	8.5	57.97	92.56
	2.4kg/hr	1.2	0.99	0.21	0.51	0.48	17.9	53.01	88.98
273.8rpm	1.0kg/hr	1.2	1.11	0.09	0.69	0.42	7.4	57.05	91.54
	1.8kg/hr	1.2	1.14	0.06	0.69	0.45	5.1	59.78	94.89
	2.4kg/hr	1.2	1.10	0.10	0.59	0.51	8.5	53.30	93.73
350.2rpm	1.0kg/hr	1.2	1.07	0.13	0.62	0.45	11.0	51.60	82.13
	1.8kg/hr	1.2	1.12	0.08	0.69	0.44	6.3	52.94	91.51
	2.4kg/hr	1.2	1.01	0.19	0.60	0.41	15.5	53.35	84.49

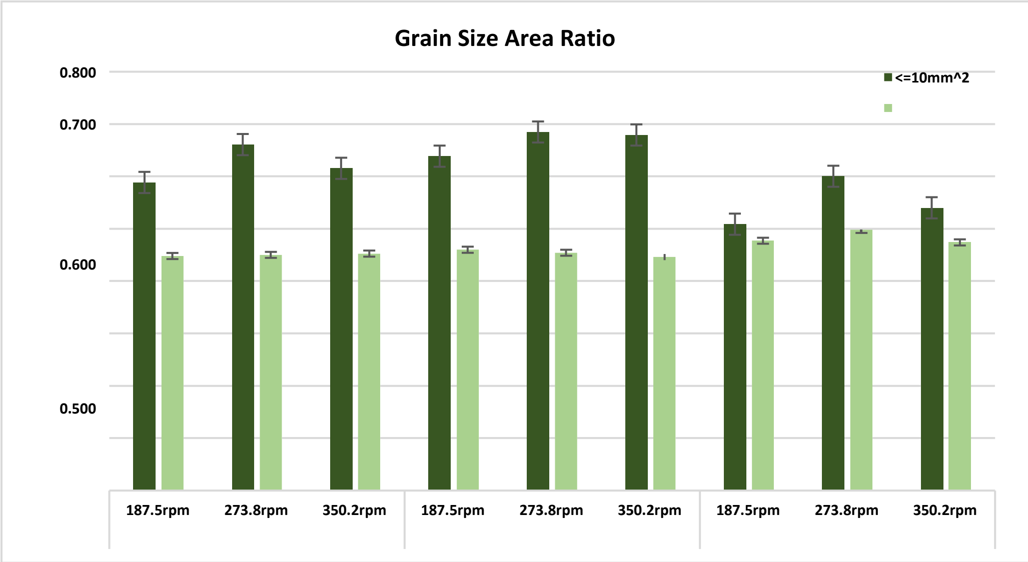

Figure 7: Shredded plastic grain size area ratio

In line, with the purpose of the machine to shred PET bottles into grain sizes of 10mm2 x 10mm2, Figure 7 shows the weight of the grain sizes larger than required area and grains within the required size of the total output of the shredding operation at different speed and feeding rate. The highest output of grain with the required size area of 0.69±0.02kg was observed at 1.8kg/hr feeding rate and 273.8rpm machine speed for every input mass of 1.2kg.

High particle retention in the machine was observed at 2.4kg/hr feeding rate, with the highest value of 17.86±0.36kg at 187.5rpm, this is attributed to the clogging of the shredding chamber due to overloading of the input mass at the feeding rate. Least retention of 5.11±0.59kg was recorded at 273.8rpm machine speed, 1.8kg/hr feeding rate as shown in figure 8. As shown in Figure 9, the shredding efficiency, which describes the shredding machine's functionality to output particles of 0.0001m2 (10mm x 10mm) area, increases as machine speed increases at 1.0kg/hr, 1.8kg/hr and 2.4kg/hr feeding rate, having the highest shredding efficiency of 60.01±0.58% at 1.8kg/hr and 350.2rpm and least shredding efficiency was observed at high feeding rate of 2.4kg/hr.

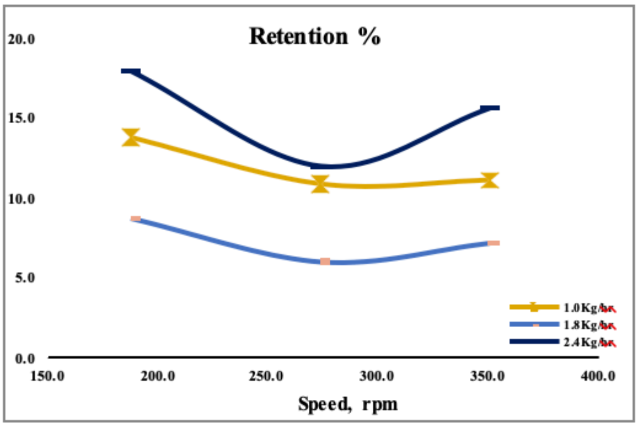

Figure 8: Graph showing the percentage retention of the shredded plastic

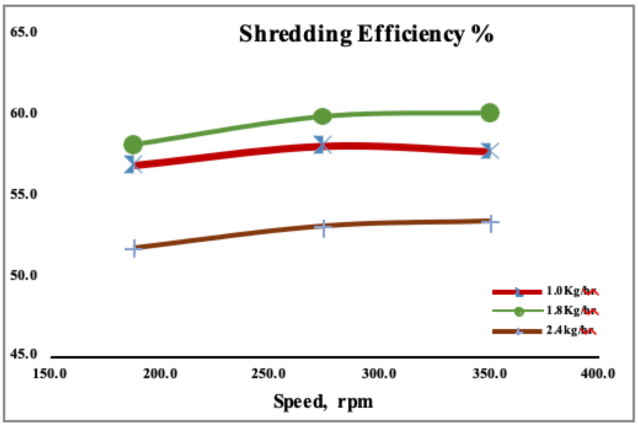

Figure 9: Graph of the shredding efficiency

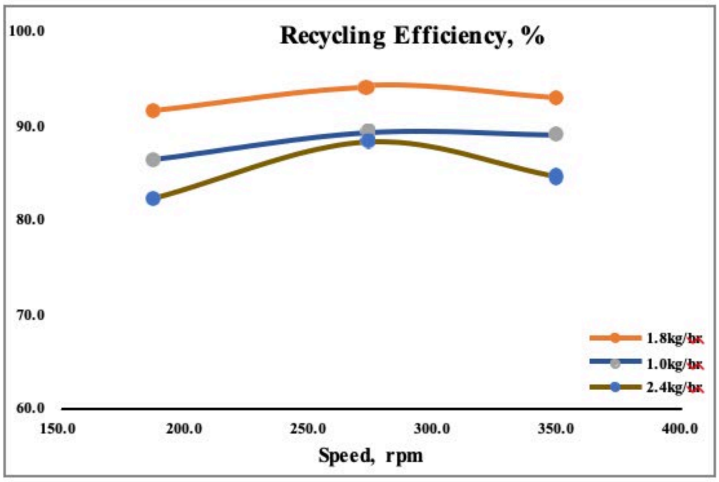

Figure 10: Graph of the recycling efficiency

Figure 11: Shredded plastic grain

It was observed that the machine is highly efficient in the recycling of the PET bottles at the feeding rate of 1.8kg/hr with the highest value of 93.73±0.44% at 273.8rpm machine speed. Consequentially, higher recycling efficiency is observed at the machine speed of 273.8rpm relatively to the feeding rates. Figure 10 shows the PET bottle that was shredded with the fabricated machine, PET bottle shredded are the common table-water bottles, though the plastic were highly ductile (Ugoamadi and Ihesiulor, 2011).

5. Conclusion and Recommendation

Waste management, a global problem requiring immediate attention, could also be resourceful in solving world's resource and energy challenges which is best achieved through recycling. The machine is developed to shred PET bottles into a required grain size for effective functionality of the incorporated pelletizing machine. The waste plastic washing and shredding machine was designed, fabricated and evaluated varying the machine speed and feeding rate, the machine reduced the collected PET bottles into smaller volumes for transportation and pelletizing, reducing human interferences and hazard. The final cost of producing the machine is N70,000 ($191), which is relatively affordable for local recyclers. There was a linear relationship with all the evaluating parameters and the operating speed. The study shows that the shredding and washing machine for PET bottles could achieve a maximum recycling efficiency of 93.73% and a shredding efficiency of 60.01%, producing particles of the desired size (0.001m2). Meanwhile, the maximum particle retention of 17.9% was observed. The shredded plastic obtained will be mildly moist, for this reason, open air drying is advised. The wastewater from cleaning the dirty plastic has considerable low COD value, which is then filter and conveyed into the drainage system without relative impact on the environment. The machine could be very useful in shredding other types of plastics, and efficient in achieving desirable particle sizes.

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