ABUAD Journal of Engineering Research and Development (AJERD)
ISSN: 2645-2685

Volume 3, Issue 2, 105-114

Development of a Low-Cost Polyurethane (Foam) Waste Shredding Machine

Arinola Bola AJAYI*, Samuel Olabode AFOLABI, Tosin Emmanuel FOLARIN, Habeeb Akorede MUSTAPHA, Abiodun Felix POPOOLA

Mechanical Engineering Department, University of Lagos, Akoka, Lagos, Nigeria
abajayi@unilag.edu.ng/a4olabisamuel@gmail.com/Folarin.emmanuelt@gmail.com/
Habeeb_mustapha@yahoo.com/abiodunapaf@gmail.com

*Corresponding Author: abajayi@unilag.edu.ng

Date Submitted: 27/06/2020
Date Accepted: 01/10/2020
Date Published: 31/12/2020

Abstract: *In this paper, a low-cost, small size polyurethane (foam) shredding machine was designed, developed and tested for the purpose of shredding of foam for waste recovery and processing. It has been observed that the wastes generated from various Foam Industries can be recycled. This is to reduce wastages, and encourage clean environment, however, most of the recycling are done on a large scale and only done by large industries that can afford heavy equipment needed for this operation, which does not allow for evaluation of the viability of the process before embarking on such project, and also allow small scale industries venture into this business of recycling of foam materials. For the small-scale industries to be involved so that these polyurethane waste materials from Foam Industries are effectively utilized, there is need for small scale machines that can be used by any industry either large or small and is pocket friendly. Hence, this reason necessitated the need for a small-scale foam shredding machine that can shred foam on a small scale thereby causing a reduction in the operation cost. The shredding machine can be utilized by both small and large business outfits. Standard mechanical design practice was used to design the parts. Factors considered during the selection of materials included: material properties, material cost and availability, processing and environment. The shredder was designed to be operated with one horsepower (single phase) electric motor. The machine has a hopper with a cover, a gear inserted into a roller which has spike rods (6mm thick) made of mild steel, systematically welded on it to shear the fed foam scrap. Screen was fixed into the machine at the bottom side of the hopper to control the size of the shredded materials. Different screen sizes can be fixed depending on the need. During performance test of the machine, 10kg of waste foam of different densities were fed into the machine gradually at different times. It was observed that the average shredding times reduces as densities increases, efficiencies and shredding rates increases with densities. It is concluded from the design, development, testing, evaluation and observation of this machine that this machine will serve the purpose of shredding waste foam on a small scale as intended.*

Keywords: *Foam waste, shredded foam, shredding machine, small scale industries, polyurethane.*

1. INTRODUCTION

There had been several generations of shredders and many different designs as well [1-4]. The first generation of shredders with their transmission mechanism been driven by a belt with low noise level. These belts could slip or deformed after working for long hours or even break [1]. The second-generation shredders were characterized by low accuracy of the gear itself, running at high speed with large noise. It is also prone to broken teeth due to low ductility and strength of gear material. The third-generation shredders were achieved by the introduction of metal sprocket in the design and this resulted in quiet operation, low energy loss, efficient cutting, and perfect coordination of the various components of the system. The fourth generation of shredder machine overcame some of the draw backs of the earlier versions but with friction sounds due to metal gears at high speeds. The fifth generation of shredder machine with rigid motor and installation accuracy reduced the wear and noise and ensure stability of the product [1]. The current sixth generation of shredders has high technology content which can be used to brake harder materials such as CD-ROM, floppy disk, tape, video, and installed with embedded button panel with a protective film to ensure the function of the system [1]. Joseph [3] developed shredding machine with an automatic feeding and has the capability of shredding up to 20 sheets of paper having width of approximately 9 inches. The machine had 3-way switch (Off, Auto and On) switch installed on it. It was also equipped with an AC motor together with a belt drive, the roller and the knife blades that can shear both foams and paper strips. It also has a mechanism for feeding and directing the papers. Chang [2] developed a blade assembly for paper shredder that consisted of long and short partition rings. The single part defect of this machine renders the whole machine assembly useless and this is the major drawback. It had long and short plates casted alongside the blade ring in place of partition rings. It is set up such as to eliminate use of partition rings and minimize cost to enhance efficiency of the assembly. Gu-Ming [5] developed shredder blades with a serrated cutting edges that were made via bending. According to Gu-Ming [5] there are two methods of doing this.

The first technique had a blade body and serrated edge integrally formed and punched from the similar base material. Production cost was high and even high-level material was required. The second technique had serrated cutting edges specially thickened to drop material consumption. They were also difficult to produce. From existing shredders developed, cutting blades are usually set on the shaft roller. An important factor considered in this work is weight drop, hence, for this research work cutting blades was totally replaced with the use of 6mm thick mild steel rods sharpened at the edges and welded on the roller. In addition, a mesh was placed directly below the shaft's roller to serve as control and to help give the desired size of shredded foam. The need to have a small scale, low-cost shredding machine was developed out of need for foam recycling operation on a small scale needed to be fed into the small-scale processing machine for the foam production. Hence, this machine is more economical in terms of raw materials wastage avoidance that would have been expended using a standard factory size shredding machine. Largely, this work will help improve yield of manufacturing industries and small-scale entrepreneur in Nigeria.

This paper presents the design and development of a low-cost polyurethane (foam) shredding machine that can be used to shred waste foams either in a large foam industry or cottage waste processing companies. This shredding machine was manufactured using locally sourced materials and designed to be safe and easy to use.

2.0 MATERIALS AND METHODS

2.1 Materials

For effective operation of the machine, proper material selection that will maintain a balance between cost, availability, mechanical properties, processing and environment. The materials for the frame, hopper, shaft, roller and the spikes were selected based on criteria selection in Tata [5]. Some of the criteria were cost of the materials, availability, rigidity, fatigue strength, fracture toughness and weldability.

2.2 Methods

Standard methods for machine design and construction were employed as enumerated below.

2.2.1 Figure 1 below is a bar chart showing the outcome of a survey of 13 furniture manufacturing industries and one mattress company in Lagos, Nigeria. The following were the outcomes gathered from the 14 industries contacted: 13 out of 14 industries contacted were concerned with the design of the shredder and its cost, 12 out of 14 were after maximum output and capacity, 10 out of 14 were after the safety and ease of using the shredding machine, 9 of 14 were concerned about the reliability of the machine, while 8 out of 14 were concerned about the maintainability of the machine.

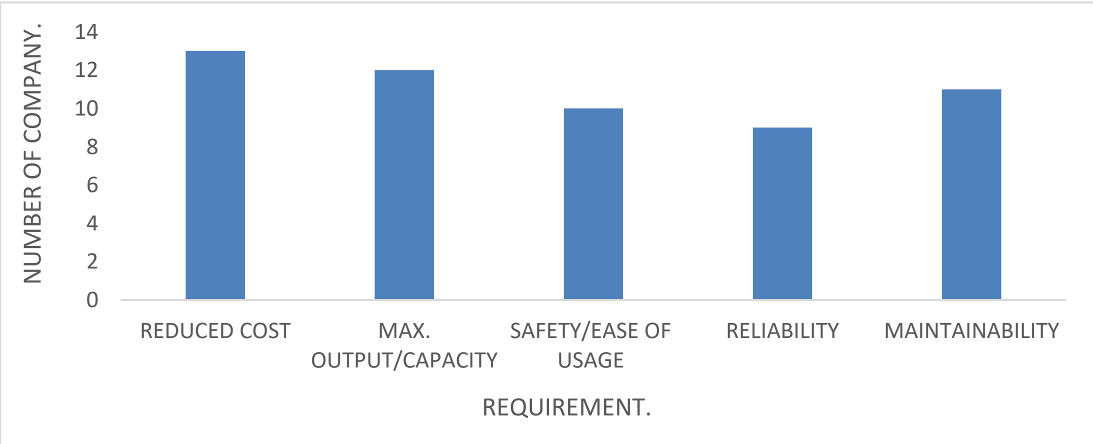


Figure 1: Survey outcome

2.2.2 Frame and pillow bearing: Figure 2 is the frame and pillow bearing. The frame carries the pillow bearing, the shaft, the roller and the Hopper was fabricated by welding pieces of mild steel plate with angle bar of dimension ¼'' x 2'' x 2'' with thickness of 3mm. The frame therefore, serves the purpose of base support. The length, breadth, and height of the frame are 381mm, 319mm and 432mm respectively.

Figure 2: The frame and pillow bearing

2.2.3 Hopper: The scrap foam to be shredded is fed into the hopper, shown in Figure 3 below before been shared and expelled for collection. The hopper houses the scrap foam to be cut and was carefully fabricated to have a shape which facilitates charging of the foam and relatively high-volume utilization. It was made of mild steel metal sheet having a thickness of 2mm. The hopper has lower square area of 152mm by 152mm and upper square area of 305mm by 305mm respectively and height of 279mm.

Figure 3: The hopper.

2.2.4 Hopper cover: There is need to make a cover for the hopper, shown Figure 4 below, for safety reasons, in other to avoid the splashing of the content on the operator's face or body and spilling of the materials. A metal plate of the same thickness (2mm) with the body of the hopper was cut and joined to the hopper. A hinge was used for the joining to allow the cover move freely.

Figure 4: Hopper cover.

2.2.5 Electric motor: A1hp single phase electric motor shown in Figure 5 was used after appropriate design and has the primary purpose of feeding the machine with the needed turning torque. It is the major device that sets the crusher roller in motion. Speed was also traded off for high torque Hunag [6].

Figure 5: Electric motor.

Calculation of Angle of Wrap.

$$\theta = (180 - 2a)(\pi/180) \quad \ldots\ldots (1)$$

$$a = Sin^{-1}\{(D_1 - D_2)/2x\} \quad \ldots\ldots (2)$$

where:

D_1 = Diameter of big pully (Driven pully) = 6 in.

D_2 = Diameter of big pully (Driving pully) = 3.5 in.

x = Distance between the 2 pullies = 18in

Hence:

$$a = Sin^{-1}\{2.5/36\} = 3.982 \quad \ldots\ldots (3)$$

Inserting the value of (a) from equation (3) into equation (1).

$$\theta = (180 - 2a)(\Pi/180) = (180 - 2x3.982) \times (\Pi/180)$$

$$\theta = (172.036)(0.01745) = 3.0020 = 3$$

From Euler- Eytelwein's Formula.

$$T_1 = T_2 (X\ e^{\mu\theta}) \quad \ldots\ldots (4)$$

Where:

T_1 = Tight side tension and it's the maximum the belt can endure before breaking.

T_2 = The loose side tension.

e = Euler's number, a constant equal to 2.718
μ = Co-efficient of friction. The co-efficient of friction of foam against steel = 0.2 [7]
θ = Angle of wrap.
Inserting the value of μ and θ in equation 4, it becomes.

$T_1 = T_2 \quad X \; 2.718^{0.2x3}$

$T_1 = T_2 \; X \; 1.8222$ …………………………………………………………………… (5)

To get the value of T_1 and T_2 we will have to first determine the velocity of the V-Belt.

$V = \frac{\Pi d1N1}{60}$ ……………………………………………………………………….. (6)

Where:
d_1 = Diameter of the driver pully attached to the electric motor= 3.5in
N_1 = Angular speed of the driver pully in rpm= 1725rmp
Hence:

V = Π x 3.5 x 1725/ 60 …………………………………………………………… (7)

V= 316.25in/sec = 8.04m/s

After the value of V has been gotten, we consider power transmitted per V-Belt , this will help in getting the value of the tension.

$P = (T_1 - T_2)\, V$ ……………………………………………… …………………… (8)

According to Khurmi and Gupta [7], tension in the tight side is expressed as

$T_1 = T - T_C$ …………………………………………… ……………………… (9)

Where
T_1 = tension in the tight side
T = maximum tension in the belt
T_c= centrifugal tension

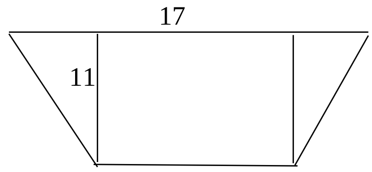
Centrifugal tension $T_c = mv^2$ ………………………………………………………… (10)

Where
m = mass of the belt per meter length = Area * length * density
v = velocity of the belt

Table 1: Belt Types [7]

Types of belt	Power ranges (Kw)	Top width (b, mm)	Thickness (t, mm)
A	0.7-3.7	13	8
B	2-15	17	11
C	7.5-75	22	14
D	20-150	32	19
E	30-350	38	23

From the above table, the type B belt is selected
Belt type: B
Top width (b): 17mm
Thickness (t): 11mm
By calculation, bottom width was obtained as 8.39 mm
and cross-sectional area was also obtained as 137.5 mm^2



From standard, density of leather belt = 1000kg/m^3
Hence, m = 0.1154044kg

Centrifugal tension $T_c = mv^2 = 0.1154044 * (6.54)^2 = 4.936N$

According to Khurmi and Gupta [7], maximum tension in the belt is expressed as

$T = \sigma * a$ ……………………………………………… (11)

Where σ = tensile stress
a = crossectional area of the belt

Allowable tensile stress σ for leather belting is between 2 - 3.45Mpa
Selecting $\sigma = 2Mpa$,

$T = 2 * 105.2 = 210.4N$

Inserting equation (10) and (11) into equation (9)
Therefore, tension in the tight side is

$T_1 = (210.4 - 4.936)\, N = 205.5N$

Since the value of T_1 is known T_2 can be found by inserting value of T_1 in equation (5)

$T_2 = 206/1.822$

$T_2 = 112.788N$………………………………….………. (12)

Inserting T_1 and T_2 into equation (8)

P = $(T_1 - T_2)\ V$ …………………………………………….. (13)

P = (205.5 – 112.788) 8.04

P= 745.404W

Where 1hp = 746W

Therefore, 745.404W≈ 1h.p

Therefore, a 1h.p single phase electric motor is selected

2.2.6 The mesh: The Mesh, shown in Figures 6a and 6b, are designed to have holes each of diameter 6mm. was bent and welded carefully to the lower square area (152mm by 152mm) of the hopper beneath the cutting roller. The main purpose of the mesh is to help control the size of the shredded scrap foam been discharged. Ultimately the size coming out will be equal or less than size of the hole in the mesh.

Figure 6(a): The mesh

Figure 6(b): Mesh welded to frame.

2.2.7 Shaft and pillow bearings: The shaft and pillow bearing are shown in Figure 7 below. The pillow bearings each of diameter 30mm were used for this work and the two pillow bearings hold the shaft. The actual size of the shaft was found to be 30mm, and there was need to decrease the diameter of the shaft (rod) by feeding the cutting tool on the late machine over the shaft as it rotates. With every pass, the cutting tool was adjusted towards the shaft until the desired diameter of 29.5mm was achieved.

2.2.8 The roller: A mild steel pipe of outside diameter of 102mm, inner diameter of 97mm and width of 152mm was rolled into a cylinder and closed at both ends and drilled at the centre to a hole size equal to that which can just accommodate the shaft diameter to form the roller. The roller is shown in Figure 8 below.

Figure 7: Shaft and Pillow Bearings Assembly

Figure 8: The roller.

2.2.9 Cutter prior modification: After the roller was made, there was need to make blades that will be responsible for sharing the foam, in doing this, the conventional type of blade was not used because previous research works showed that their usage contribute to weight increase of the machine and also the possibility of foam jam as a result of back flow of foam alongside the blades is high [8]. Three blades made from stainless steel plate of 2.5mm thickness and having same length with the roller were then used as shown in Figure 9 below. The choice of stainless-steel material for the blade was based on the fact that stainless steel material is very easy to sharpen, tough and have high resistance to corrosion attack. Although the 3-blades were able to shred the foam waste but the cutting rate was too slow hence, not effective enough and then the cutting blades were modified.

Figure 9: Cutter blade prior to modification

2.2.10 Modified cutter used: The 3 stainless steel cutting blades were then replaced with mild steel rods with thickness of 6mm shown in Figures 10 (a) & (b) below. These rods were sharpened, carefully cut to varying lengths and welded systematically to the roller. The mild steel rods were able to shred the scrap foam at the desired cutting rate. The following were the qualities for choosing mild steel rod. Presence of carbon in mild steel causes hardness, the rod therefore has better ability to retain its sharpness over a long period of time. This means less time is needed for maintaining the edges of the rods. Although, the stainless steel has better resistance to corrosion but this was traded off for affordable price of buying mild steel, considering the fact that the shredder was designed for shredding dry foam [5].

Figure 10 (a): Image of modified cutter.

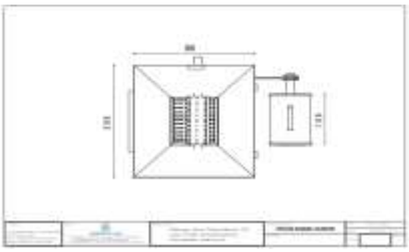


Figure 10 (b): Drawing of modified cutter.

2.3 Design Calculations.

2.3.1 Design calculation for the hopper.

The hopper is an inverted truncated pyramid as shown in Figure 11 below and it is designed according to Kurmi and Gupta [7]

Volume of the Hopper (Truncated Pyramid) = $\frac{1}{3}h\,(\,Base\ area + Top\ area + \sqrt{(Base\ area\ x\ Top\ area)}\,)$………..(14)

3

Where: a = top side =0.31m ; b= base side = 0.152m ; h= height = 0.279m ; base area= 0.023104m^2 ; top area= 0.0961m^2

Volume of the Hopper = 0.0155m^3 =0.016m^3…………………………(15)

Lateral Area of the hopper = 0.2679m^2………………………………...(16)

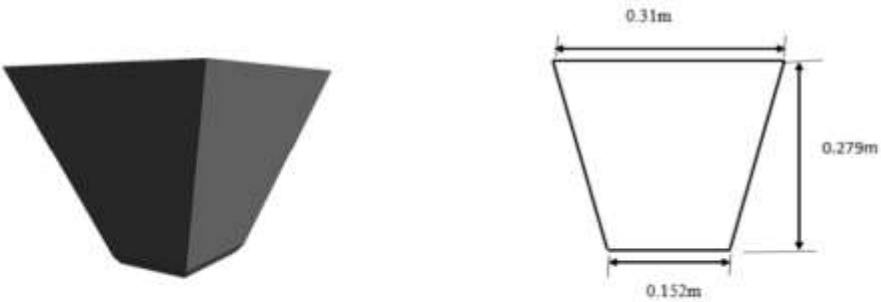


Figure 11: Hopper

2.3.2 Design calculation for the shaft.

The assembly of shaft, roller and spike is shown in Figure 12 below. The shaft loadings and sizing were calculated according to Kurmi and Gupta [7].

Weight of the roller = 4kg = 39.2N
Total weight of the spikes welded to the roller serving as the cutter = 0.3kg = 2.94N
Weight of the pulley acting on the shaft = 5.5kg = 54N ….. (17)

For a single batch of foam fed into the hopper having density of 13kg/m^3 the weight = 0.2kg = 1.95N

A = Weight of pulley + Summation of forces of the belt (Since the tension of the belt is acting downward) ……………………… (18)

 ISSN: 2645-2685

Hence:

A = Weight of pulley + T_1 + T_2 *= (54+206+113) N = 373N*
B = Weight of the auger + Total weight of the cutting spikes + weight of scrap foam [9].
Hence: B = (39.2 + 2.94+ 1.96) N = 44N……………………….(19)

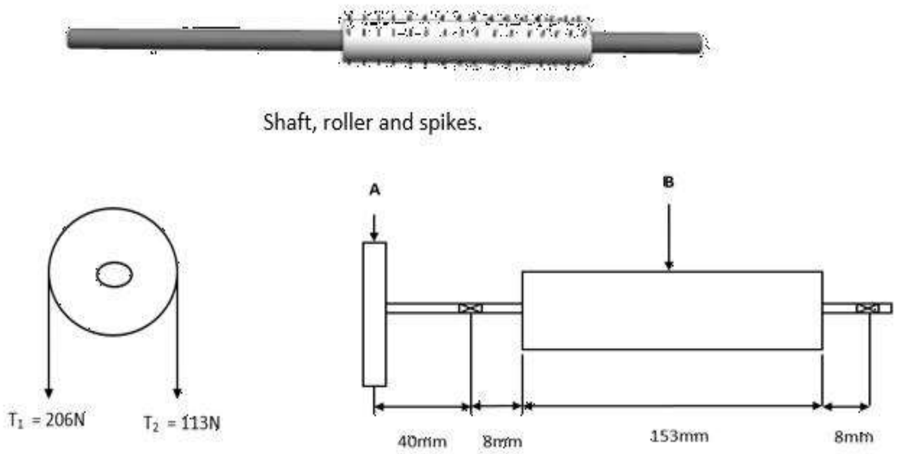


Figure 12: The assembly of shaft, roller and spikes and the FBD

The force loading (free body diagram), the shear force and the bending of the shaft is represented in Figure 13 below.

Taking moment about point d, RA = 483.81N ……. (20)
Therefore, RB = - 66.81N …………………………... (21)

The bending moments and shear forces of the shaft is calculated based on Kurmi and Gupta [7] and are illustrated in Figure 13 below.
BM about points a, b, c and d are 0, -14.9Nm, -5.6Nm, and 0 respectively. While the Shear Forces (SF) between A and B; B and C; C and D; are -373N, 110.81N, and 66.81N respectively.

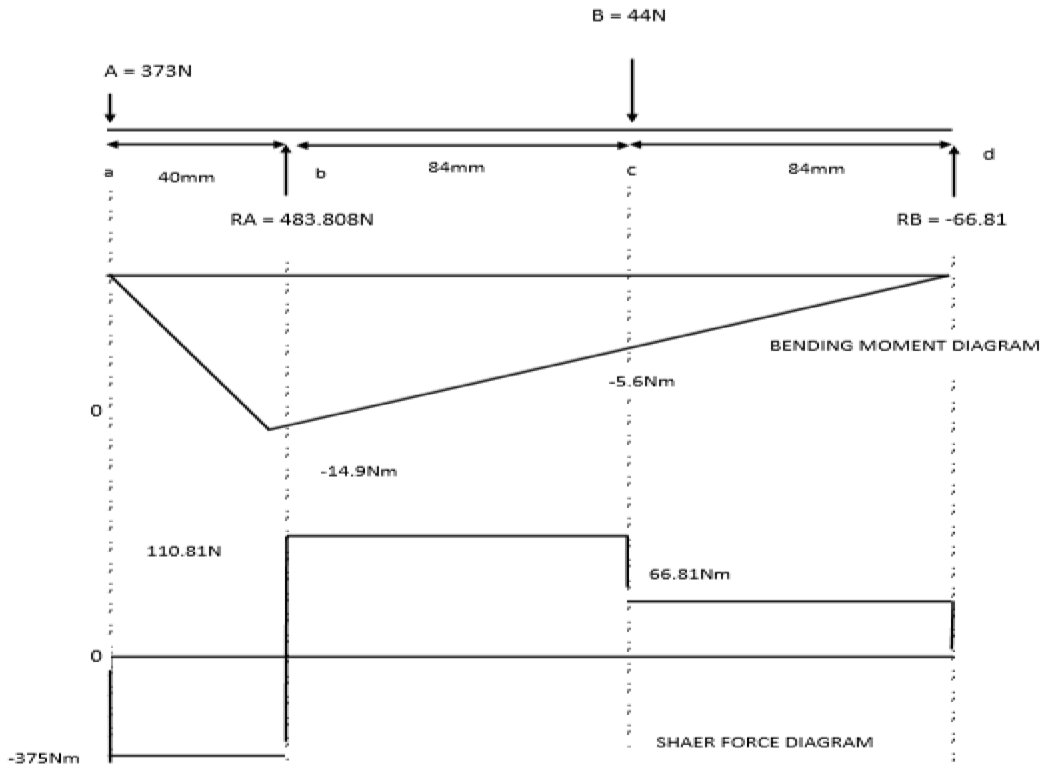


Figure 13: Free body diagram of the shaft

 ISSN: 2645-2685

3.1 RESULT AND DISCUSSION

The testing, evaluation, and observation were carried out to determine the shredding rate, capacity and efficiency of the machine.

3.1.1 Working Principle, Testing and evaluation of the machine: Before the machine working was started, the belt and the wall socket connections were properly checked, the wall switch turned on and the machine set into motion. The hopper cover was set opened and the scrap foam poured in gradually until the hopper was almost full, at this point the hopper was closed for the full shredding operation to take place for a period of time dependent on the density of foam scrap as stated in Table 2. The process was repeated until the scrap foams were completely shredded and the wall switch turned off. The waste foams used for this project have the following densities: 13kg/m^3, 16kg/m^3, 18kg/m^3, 20kg/m^3, 22kg/m^3, 25kg/m^3, and 13kg/m^3 respectively. These densities were chosen because these are the standard practice in the industry. Figure 14 (a) shows the wastes foams packed and Figure 14 (d) shows the waste foam being shredded. The average shredding rate, average shredding capacity and shredding efficiency of the shredding machine was determined with respect to each of the densities used. Figure 14 (b) below is the 3-D rendering of the machine while Figure 14 (c) is the picture of the real machine.

Figure 14 (a): Waste foams of various densities.

Figure 14 (b): The 3-D rendering of the Shredding machine

Figure 14 (c): The constructed Shredding machine

Figure. 14 (d): The shredding process with the machine.

3.1.2 Results from testing and evaluation of the machine

Table 2, shows the table of densities and total shredding time, average shredding rate, average shredding capacity, recovered weight of shredded foam after shredding, and shredding efficiency.

Table 2: Densities and other parameters.

Density (Kg/m^3)	Total shredding time(Min)	Average shredding rate(Kg/Min)	Average shredding capacity(Kg/hr)	Recovered weight of foam after shredding(Kg)	Shredding efficiency (%)
13	115	0.087	5.217	8.5	85.00
16	107	0.093	5.607	9.3	93.00
18	99	0.101	6.061	9.4	94.00
20	87	0.115	6.897	9.4	94.00
22	72	0.139	8.333	9.3	93.00
25	64	0.156	9.375	9.4	94.00
36	60	0.167	10.000	9.7	97.00

Where:

Recovered weight of foam after shredding was determined with the aid of a weighing scale.

Average shredding capacity of foam

$$= \frac{Averageof\ total\ weight\ of\ the\ foam\ to\ be\ shredded\ in\ their\ different\ densities\ (kg)}{Average\ total\ time\ taken\ (\text{min})} \text{ x } 60^{min}/_{hr} \ldots (22)$$

$$\text{Average shredding rate} = \frac{Average\ Weight\ of\ shredded\ foam\ (kg)}{Average\ Time\ (\text{min})}$$

$$\text{Efficiency} = \frac{Mean\ Weight\ of\ Shredded\ Foam\ Wastes}{Mean\ Weight\ of\ Plastic\ Waste} \text{ x } 100\%$$

3.2. DISCUSSIONS

Figures 15, 16, and 17 below are the plots of densities against average shredding rate, average shredding capacity, and shredding efficiency respectively. It can be observed that the shredding rate, shredding capacity and shredding efficiency were increasing with increasing densities. This is because the weight of the load was increasing and the weight of the loads (waste foams) were easily attracted to the cutter/roller for effective shredding.

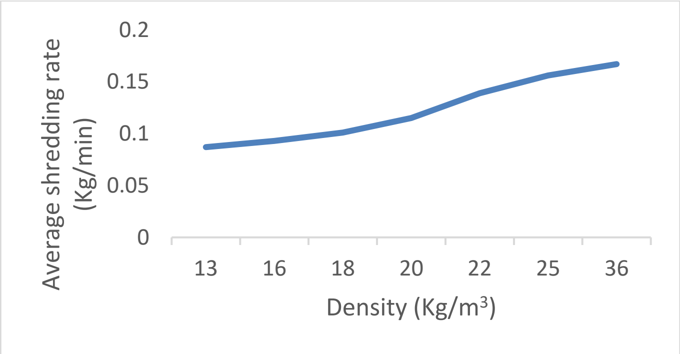


Figure 15: Average shredding rate.

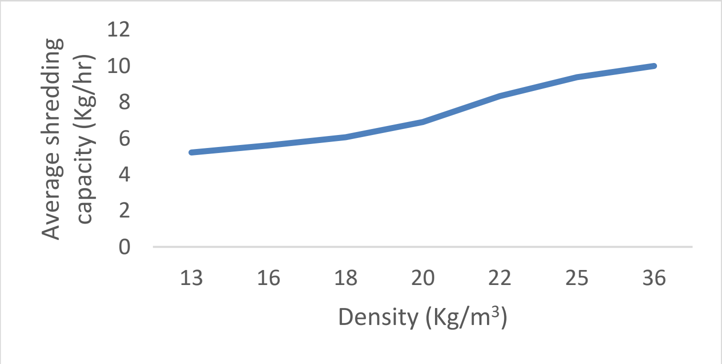


Figure 16: Average shredding capacity

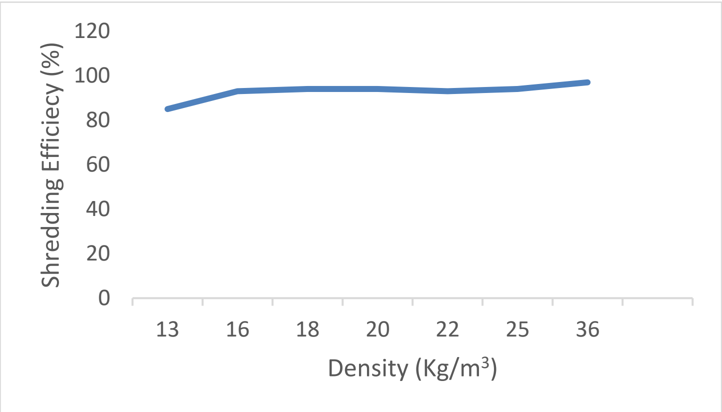


Figure 17: Shredding efficiency

4.0 CONCLUSIONS

The design and development of a low-cost polyurethane (foam) shredding machine that can be used to shred waste foams either in large foam industries or cottage waste processing companies was designed, developed and tested. This shredding machine was developed using locally sourced materials and designed to be safe and easy to use. The overall achievement of this project is that foam wastes shredding can be done on a small scale thereby converting waste to wealth. Although, there are so many research works in this area but this present work reduces the huge costs that are associated with the acquisition of the industrial machine. Technical problems usually associated with the large shredding machine namely, sound level during operation going beyond standard level; shredded foam waste stacking in the chute; size of the foam cannot be fixed to one size only: feeding of foam inconvenient, weight of the machine too much; the colour not attractive enough were all addressed.

REFERENCES

[1] Fauzia, S., Harshad, P., Swapnil, R., Omkar, W., Swapnil, T. (2017). Design and Fabrication of Paper Shredder Machine. *International Journal of Scientific & Engineering Research*, *8*(3), 18-25. Retrieved at https://www.ijser.org

[2] Chang, F. (2000). *Blade Assembly for Paper Shredder*, US Patent 6089482, BO2C 18/06, BO2C 18/18. Retrieved at https://www.academia.edu/36638636/Design_and_Fabrication_of_Paper_Shredder_Machine

[3] Joseph, Y. K. (2002). *Paper Shredding Device*, US Patent 6390397 B1. Retrieved at https://patents.google.com/patent/US6390397B1/en

[4] Gu-Ming, Z. (2006). *Blade of Paper Shredder*, US Patent 2008/0040934A1. Retrieved at https://patents.google.com/patent/US20080040934A1/en

[5] Tata, R. P. (2011). *Elements of Machine Design, Course No M04-032*. Stony Point NY 10980. CED Inc. Retrieved at https://dergipark.org.tr/en/pub/ijesa/issue/46528/532272

[6] Hunag, S. (2011). *Rotation Speed Controlling System for Shredder Motor*, US Patent 8008882B2. Retrieved at https://patents.google.com/patent/US8008882B2/en

[7] Khurmi, R.S., Gupta, J.K. (2005*). A textbook of machine design* (14th ed.) Ram Nagar, New Delhi, Eurasia Publishing House (PVT.) LTD. Retrieved at https://www.academia.edu/38675030/A_Textbook_of_Machine_Design_by_R.S.KHURMI_AND_J.K.GUPTA

[8] Okunola, O.I., Oyebode, D.A., Olanrewaju, O.O (2019). *Design of shredding And Washing Machine for Polyethylene Terephthalate (PET) Bottles Pelletizer*, *International Journal of Engineering Science and Application*, *3*(2), [[[[[[[[[[[[103-109. Retrieved at https//www.ijser.org

[9] Engineering ToolBox, (2020). *Friction and Friction Coefficients*. [Available online at: https://www.engineeringtoolbox.com/friction-coefficients-d_778.html [Accessed on 12/03/2020]