*Nigerian Journal of Technology (NIJOTECH)*
*Vol. 43, No. 3, September, 2024, pp.602 - 609*
*www.nijotech.com*

*Print ISSN: 0331-8443*
*Electronic ISSN: 2467-8821*
*https://doi.org/10.4314/njt.v43i3.24*

# DESIGN AND FABRICATION OF A WASTE PLASTIC FILAMENT EXTRUDER

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**ARTICLE HISTORY:**
**Received:** 06 May, 2023.
**Revised:** 03 July, 2024.
**Accepted:** 05 July, 2024.
**Published:** 20 September, 2024.

**KEYWORDS:**
Plastic recycling, High-density polyeth-lene, Extrusion, Filament.

**ARTICLE INCLUDES:**
Peer review

**DATA AVAILABILITY:**
On request from author(s)

**EDITORS:**
Patrick Akpan

**FUNDING:**
None

## Abstract

*Plastic pollution causes serious environmental issues and endangers the health of humans and animals in both land and aquatic environments. Despite the fact that Nigeria produces hundreds of tons of plastic waste every day, a greater proportion still finds its way back into the ecosystem because only a small portion of it is recycled. Nigeria's growing production of single-use plastics and careless disposal of plastic waste into the land and ocean are the main causes of the country's growing plastic pollution problems.. For this reason, recycling and reusing plastics is necessary to lessen the harmful effects that plastic utilization has on both human and the environment.. Plastics can be recycled into filaments used in 3D printing also known as additive manufacturing. In this study, a plastic filament extrusion machine for waste plastic was designed and developed with the aim of recycling high-density polyethene, thereby lessening the negative environmental effects that come with disposing of it.. The basic components of the extruder comprised of a hopper, screw, barrel, die, and motor system. Temperature, oxygen, and shear stress all cause the plastics to deteriorate during the extrusion of plastics for filament.. Thus, this study examined the impact of different extrusion temperatures on the filament quality made from high-density polyethylene polyethene (HDPE). The plastic pellets melt and flow into the die as a result of friction between them and the barrel surface and the heat generated by the heating bands. Plastic filament was extruded with a combination of optimal pellet compression, temperatures between 150 and 230 degrees Celsius, and a gradual increase in the pressure of the molten pellets inside the barrel.. Melted plastic adhered itself to the barrel at low temperatures but turned to char at high temperature. Consequently, in order to produce quality 3D filament using HDPE, it is imperative to maintain acceptable temperature conditions. Based on the results, the extruder produced excellent filament suitable for 3D printing at 200 °C. The results of this study emphasize the significance of temperature regulation during the extrusion process in order to guarantee the intended filament quality.*

## 1.0 INTRODUCTION

Plastics' low weight, flexibility, affordability, and unique properties have made them suitable for use in a variety of applications in the food, packaging, and health industries. Nigeria imported over 20 million tonnes of raw plastics and plastic products between 1996 and 2017, making her Africa's second-largest plastic importer, contributing 17% of the continent's overall plastic consumption [1]. Plastic production and use in Nigeria are growing rapidly with a projected import and consumption of 41.57 million metric tons by 2030. In Nigeria, more than 32 million tons of waste are produced, with plastic waste making up over 2.5 million tons [2]. Plasticizers, pigments,

***HOW TO CITE:***
Ogbonnaya, M., and Ojolo, S. J. "Design and Fabrication of a Waste Plastic Filament Extruder", *Nigerian Journal of Technology*, 2024; 43(3), pp. 602 – 609; *https://doi.org/10.4314/njt.v43i3.24*

antioxidants, lubricants, and other chemicals and additives that are hazardous (toxic) to people and the environment can be found in plastic, depending on its type, and used application. Toxic emission from plastics contaminates water and food, thereby causing various health challenges in aquatic animals and humans. The increasing manufacturing of single-use plastics and improper dumping of plastic waste into terrestrial and marine environments are contributing to the pervasive pollution of plastics and blocking of water channels in rivers and drainages, also their disposed in marine environment blocks the digestive systems of aquatic animals when consume or cause suffocation, thereby resulting in their death [3]. Most plastics are non-biodegradable, and its debris may remain in the environment for decades while breaking into what is known as microplastics or nanopalastics which can easily penetrate into the environment through water or air, thereby causing harm to humans and animals [4].

Land is a factor of production that is necessary for the development of a country's economy, manufacturing, and agriculture sectors. However, it has been noted recently that the majority of plastic waste obtained in Nigeria is not properly managed and is instead disposed of improperly in landfills.. There is a limited amount of landfill area, and the total amount of plastics held each year is growing quickly, taking up valuable space that could be utilized for industrial and commercial growth. Consequently, it becomes imperative to look for alternate methods of disposing of or recycling plastics. Manufacturers mostly utilize plastics derived from fossil fuels, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinyl chloride (PVC). Using more and more plastic will contribute to the depletion of fossil fuel resources in the long run , and plastic waste released into landfills releases greenhouse gasses such as ethylene and methane that eventually deplete the ozone layer [5].

This is yet another major issue related to the use of plastic. Amidst these challenges, recycling is necessary to reduce plastic single-use and its detrimental impact on both the environment and human health.. Plastic recycling is the process of gathering waste or scrap plastic and turning it into something new and functional. Recycling plastic is meant to reduce plastic pollution while easing the demand on virgin materials that go into making new plastic products. One method that has been suggested to lessen the threat of plastic pollution is the recycling of plastics to produce filaments for additive manufacturing. Additive manufacturing (AM) or 3D printing has become a major industrial process that plays an important role in the advancement of production processes. Various industries are paying close attention to additive manufacturing that involves extruding materials and layering the materials on top of one another until the whole design is fully built [6]. Typically, filament used in 3D printing is made of polymers such as polylactic acid (PLA), polyethylene terephthalate (PET), polyethylene (PE), and polyamide (PA) and acrylonitrile butadiene styrene (ABS) [7].

This process is formed by inserting a granulate or polymer powder into an extruder, which produces the material as a large wire wound around a spool. The extrusion process is temperature dependent. Amongst the plastics produced, thermoplastics are commonly used to produce filament used in additive manufacturing. Materials selection for 3D printing filament and utilization of recycled PET in a redesigned breadboard was studied by [6]. The ELECTRE multi-criteria decision-making process was utilized in the material selection of plastics for 3D printer filaments. Among the alternatives being considered, the virgin LDPE outranked the virgin HDPE, PET, and PP. Moreover, recycled PET is better compared to virgin. PET. It was concluded in the study that the 3D filament produced from the recycling of PET using the extrusion method, can be used as alternative filament for 3D printing. According to Alzahrani [8], the recycled PET is sensitive to the temperature, causing it to be susceptible to flow at low viscosity. The low viscosity is an outcome of the inconsistent flow rate that produce the 3D printer filament with non-uniform diameter.

Oussai et al. [9] analysed the material properties of recycled PET and virgin PET used as filament for 3D printing and reported that the tensile strength of recycled PET was higher than that of virgin PET. The average mechanical properties of the recycled samples decreased within the range of 3-9% when compared with virgin samples. Flaws and degradation in the mechanical properties in the recycled filaments could be caused by potential presence of microscopic impurities and nozzle clogging. Bremer et al. [10] conducted a feasibility study for a material recycling approach of the plastic polyethylene terephthalate (PETG) for additive manufacturing. In this study, glycol was added to PET to form PETG with the aim of obtaining better filament properties for 3D printing. The influence of the recycling process on the quality of the filament and the diameter of the extruded filament were analysed while the dimensional accuracy of the printed tensile specimens and the mechanical parameters of the tensile tests were controlled. The filament made from recycled material had a slightly lower tensile strength than filament made of conventional purchased material.

The use of extruders in the recycling of plastics for filament is recommended for all users of 3D printers, as they generate high savings of up to 80% [11]. The adaptability of 3D printers and extruders permits users to modify the filament obtained from recycled plastic to their printer model and can transform waste into feedstock [12]. The shear stress, temperature, and oxygen occurring during extrusion degrades PLA and PE polymers [13]. Raza [14] studied the effects of extruder speed and heater temperature on filament quality. It was discovered that the cutter speed and heater temperature had an impact on the filament's thickness. The thickness of the filament remains in the threshold value set when the temperature and speed of the extruder remained constant throughout the process. Using recycled polypropylene to produce 3D filament, it was observed that the average filament diameter of 1.6 mm was produced at a spooler speed of 4 rpm, extrusion speed of 40 rpm and extrusion temperature of 200 $^{O}$C [15]. The filament obtained had a rough and easily curved surface. The application of heat to PLA during extrusion caused a lowering of the cold crystallization temperature and diminishes the melting point [11] thereby affecting the grade of the filament produced.

According to published research, the quality of filaments produced from plastics for recycling purpose is influenced by the extrusion temperature and speed, plastic feedstock, and shear stress. Therefore, this study examined the impact of different extrusion temperatures on the filament quality made from high-density polyethylene polyethene (HDPE). With the intention of implementing additive manufacturing (3D-Printing) in Nigeria and other sub-Saharan countries, an extruder capable of effectively converting HDPE plastic waste into filaments was designed in this study. This technology offers the potential to transform plastic waste into new and more valuable products for use at home and industries.

## 2.0 METHODOLOGY

### 2.1 Design Analysis and Development of the Filament Extruder

The filament extruder and its components were designed using various mechanical design principles. Autodesk Inventor 2021 was used to develop the design and assemble the filament extruder machine's various parts. To reduce the cost of production, the extruder was made to portable (tabletop) and flexible enough to work with waste HDPE plastics. Table 1 summarizes the HDPE's properties.

**Table 1:** Properties of HDPE [16]

| Properties | Value |
|---|---|
| Density (ρ) | 954 kg/m$^3$ |
| Coefficient of viscosity (μ) | 5 x 10$^4$ pas. sec |
| Heat capacity at constant pressure ($C_p$) | 1.55 kJ/kg°C |
| Latent heat of fusion ($H_f$) | 178,600 J/kg |
| Melting temperature ($T_m$) | 130.8°C |
| Crystallization temperature | 111.9°C |
| Power law index | 0.5 |

#### 2.1.1 Determination of hopper's volume

The hopper was designed to take the shape of an inverted trapezium with a volume of 42,000 m$^3$, to enable it to accommodate more shredded plastic and allow free flow to the extruder. Volume of hopper is which is gotten from volume of a trapezoidal shape. Figure 1 shows the CAD 2D design of the hopper.

$$V_h = LH\frac{(a+b)}{2} \quad (1)$$

Where, the length (L) = 300mm, height (H) = 400mm, shorter breadth (a) = 300mm, longer breadth (b) = 400mm.

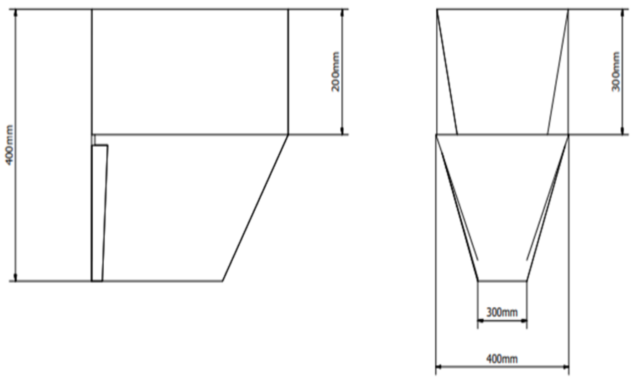



**Figure 1:** CAD design for hopper

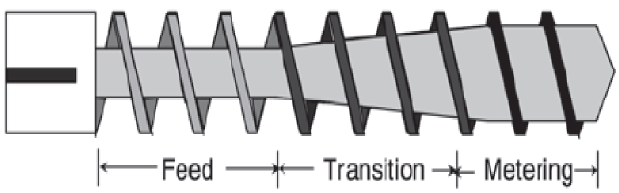



**Figure 2:** Extruder screw sections (Harold et al., 2005)

#### 2.1.2 Extruder screw design

The feed, transition, and metering sections are the three sections that make up the single screw extruder shown in Figure 2. The feed section possesses a deep flight which aids in transporting powder or pellets away from the feed throat. The transition section changes progressively from deep flights with unmelted pellets to shallow flights containing the melt. Resin is compressed in the transition section during the melting process. With the shallowest flight depths, metering is the final screw portion.

Since the internal diameter of the barrel and the external diameter of this rotating screw are same, the screw was constructed considering the barrel's dimensions. To enable efficient compression of the plastics, the screw was also made to be 200 mm longer than the barrel. Figure 3 displays the CAD design of the extruder's screw.

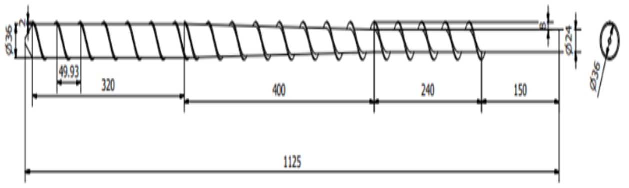



**Figure 3:** CAD design for extruder screw

### 2.1.3 Barrel design

To withstand the pressure exerted on it by the screw and molten plastic materials, the barrel was constructed with a thick-walled cylinder. The screw measures 52 mm in outer diameter (OD), 42 mm in internal diameter (ID), and 940 mm in length (L). Figure 4 shows the CAD design for the barrel.

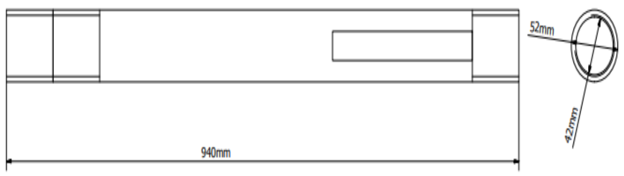



**Figure 3:** CAD design for barrel

### 2.1.4 Diameter of the die

The die was made to have a 2 mm diameter because most plastic filaments used in 3D printers have a 1.75 mm diameter and given that crystallization causes the filament to shrink to roughly 1.75 mm as it cools [17].

### 2.1.5 Pressure drop inside the barrel

The quantity of material handled at a time in the system, or "throughput," is one of the elements that affects the pressure drop in the barrel. To determine the pressure drop inside the barrel, Equation (2) was used [16].

$$\Delta P = \frac{8\times\rho Q\times\mu\times L}{\pi\times\rho\times r^4} \quad (2)$$

Where, ρQ is the throughput production rate, μ is the coefficient of viscosity, L is the length, ρ is the density and radius (r) are given as 20 x $10^{-3}$ m. The values of the properties are obtained from Table 1.

### 2.1.6 Estimation of motor size

Equation (3) is used to calculate the theoretical power of 100% mechanical energy efficiency, and this can be utilized to determine the extruder's motor size under adiabatic conditions [18], [17]. It is assumed in this analysis that the extruder's minimum motor size has a mechanical energy efficiency of 70%, 1.5 kg of extrusion output per hour as the desired rate of output. The pellets are fed at room temperature, with an estimated melting point of 200 °C.

$$P_0 = \rho Q C_p(-T_{in} + T_{out}) + \rho Q H_f + Q\Delta P \quad (3)$$

Where, throughput production rate (ρQ) is 1.5kg/hr, specific heat capacity at constant pressure ($C_p$) is 2000 J/kg°C, room temperature ($T_{in}$) is 20°C, exit temperature/melting temperature ($T_{out}$) is 200°C, latent heat of fusion ($H_f$) is 178600 J/kg, and change in pressure (ΔP) is 2.77GPa.

### 2.1.7 Shear rate at the feed

The rate at which the flakes, or fragments of plastic, are deformed inside the barrel is known as the shear rate. When two forces acts in opposing directions on a material, deformation takes place. As the layers of the plastic start to shrink and tug on one another, tension is created within the material. Hence, plastic shearing is induced by the screw's rotational crushing force, friction between the plastic and the screw, friction between the plastics and the barrel wall, and friction between the plastics themselves. The shear rate (θ) was calculated using Equation (4) [19].

$$\theta = \frac{\pi\times D\times N}{60\times H} \quad (4)$$

Where, the diameter of screw (D) is 40 x $10^{-3}$m, shaft speed (N) is 100rpm and channel depth of feed (H) is 8 x $10^{-3}$ m.

### 2.1.8 Shear rate at the end of die

Plastic shearing at the end of the die is caused by the crsuhing force on plastics by rotating screw, friction between the plastic and the rotating screw, friction between the plastics against themselves, and friction between the plastics and the die. Finally, the shear rate at the end of the die was calculated using Equation (5). [18].

$$\theta = \frac{4\rho Q}{\pi\rho r^3} \quad (5)$$

### 2.1.9 Flow rate

This is an important process that aids in determining the speed at which the molten plastic is flowing within the barrel. Equation (6) was used to calculate the plastic's molten flow rate. [18].

$$Q_{smooth\ barrel} = Q_{drag} - Q_{pressure} - Q_{leakage} \quad (6)$$

$Q_{leakage}$ is negligible (No leakage in barrel)

$$\therefore Q_{sb} = Q_d - Q_p \quad (7)$$

$$Q_{drag} = \frac{1}{2} \times \pi^2 \times D^2 \times H \times N \times sin\theta \times cos\theta \quad (8)$$

$$Q_{pressure} = \frac{\pi \times D \times H^3 \times sin^2\theta}{12 \times} \times \frac{dP}{dL} \quad (9)$$

Where, the diameter (D) is 40 x $10^{-3}$ m. height (H) is 8 x $10^{-3}$ m, coefficient viscosity $\mu = 5 \times 10^4$ pas. sec, N is 100rpm, helix angle of screw, where the universal accepted angle (θ) is 17.6568, ΔP= 2.77GPa, and change in length (ΔL) = 700 x $10^{-3}$ m.

### 2.1.10 Melting power required

To obtain the temperature at which the band heater is required to melt the plastic shreds, the melting power should be determined. The required melting power was calculated using Equation (10) [18].

$$E = mC_p\Delta T + m\Delta H_f \quad (10)$$

Where, the mass flow rate (m) is 3 kg/hr, specific heat capacity ($C_p$) is 1.55 KJ/kg, change in temperature (ΔT) is 110°C and change in heat is ($\Delta H_f$) is 178.6 KJ/Kg.

### 2.1.11 Cooling fan rating

To determine the total energy needed to cool the extruded molten plastic filament back to crystallization, the cooling fan's rating is required. The HDPE crystallization temperature is 111.9 °C. Equation (11) was used to determine the cooling fan rate [20].

$$E = mC_p\Delta T + m\Delta H_f \quad (11)$$

Where the mass flow rate (m) is 3 kg/hr, specific heat capacity ($C_p$) is 1.55 KJ/kg, change in temperature (ΔT) is 18.1°C, and change in latent heat of fusion ($\Delta H_f$) is 178.6 KJ/kg.

Table 2 gives the values of the design parameters used in the design and development of the waste plastic filament extruder.

**Table 2:** Design parameters

| Design Parameter | Value |
|---|---|
| Pressure-drop inside the barrel | 1.176 GPa |
| Motor size | 2 hp |
| Min. speed of motor | 100 rpm |
| Max. speed of motor | 2300 rpm |
| Shear rate at the feed | 26.18/sec |
| Shear rate at the end of die | 0.0695/sec |
| Flow rate | 0.00181 kg/min |
| Melting power | 0.291 kW |
| Cooling fan rate | 120.4 W |

The materials used in the production of the various component of the filament extruder (Figure 2) are presented in Table 3. The development of the filament extruder was carried out in University of Lagos Mechanical Engineering workshop as shown in Figure 5.

**Table 3:** Extruder components and its materials

| Components | Material |
|---|---|
| Hopper | Aluminium sheet, welded, black |
| Screw | Steel |
| Barrel | Steel |
| Die | Iron |
| Table | Aluminium sheet |
| Heating band | Steel, carbon |
| Motor | Steel, cast |

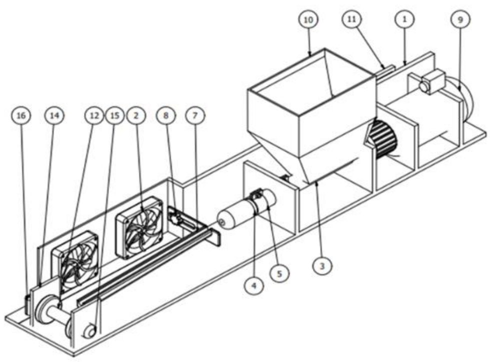
**Figure 5:** Filament extruder

**Figure 6:** Shredded HDPE

### 2.2 Extrusion of 3D Printing Filament

The high tensile and specific strength, stiffness, UV resistance, and superior resistance to solvents (alcohols, acids, and alkalis), makes the recycling of high-density polyethylene (HDPE) attractive in the production of high-quality 3D filament. . The HDPE plastic waste was collected from the University of Lagos and its surroundings. It included bottle caps from carbonated drinks and bottled water, shampoo bottles, motor oil containers, bleach containers, and crates. The waste HDPE plastic in different colours was gathered, sorted, cleaned, and allowed to dry completely before it was put in the shredder to be shredded. During the filament extrusion procedure, gravity was used to feed the shredded plastics (Figure 6) into the barrel through the hopper at the top.

As seen in Figure 7, the screw, barrel, band heater, and die make up the core extrusion unit. The plastic material meets the revolving screw after passing through the feed throat. In addition to producing heat and building up enough pressure to force the molten plastic pellets into the barrel, the rotating screw in the barrel also serves to create friction between the plastics and the screw itself. Melted plastic pellets flow through the die, forming the required filament geometry based on the die's cross section.. The screw rotates around its axis with the assistance of the motor. In order to achieve complete melting of the solid plastic pellets, a band heater was affixed to the barrel to elevate its temperature and facilitate efficient melting of the plastic pellets inside. It's crucial to adjust the heating element so that the barrel's temperature rises gradually from rear to front and varies with a controller. To prevent excessive heat loss to the surroundings, the barrel was insulated.. The revolving screw applies constant pressure, forcing the molten polymer through the die forming the filament with the required shape. Lastly, to lower the filament's temperature and hasten its solidification, an external fan was employed.




| ITEM | QTY | PART NUMBER |
|---|---|---|
| 19 | 1 | extruding screw |
| 16 | 1 | roller DC motor |
| 15 | 1 | roller screw cap |
| 14 | 1 | roller stand |
| 13 | 1 | roller pin |
| 12 | 1 | roller |
| 11 | 1 | pin controller |
| 10 | 1 | hopper |
| 9 | 1 | motor |
| 8 | 1 | bolt1 |
| 7 | 1 | fillament support |
| 5 | 2 | Band heater |
| 4 | 1 | Die |
| 3 | 1 | Barrel |
| 2 | 1 | fan |
| 1 | 1 | Frame Support |
| | | PARTS LIST |

**Figure 7:** Components of the extruder

## 3.0 RESULTS AND DISCUSSION

Before every test, the band heater was turned on for around twenty minutes. Shredded HDPE was put into the hopper and the motor was turned on once the PID's constant temperature was achieved.

### 3.1 Production of 3D Filament at varying Heating Band Temperature

#### 3.1.1 Temperature of 230 ºC

300g of shredded plastic were put into the machine; after a short while, the system began to emit fumes, and the extruded section seemed nearly burnt and black, indicating that heating had occurred. After that, the temperature was dropped from 250 ºC to 230 ºC, this generated a filament with dotted lines, long bubbles, and pits (Figure 8). The overheating of the barrel was the reason behind the defects found in the filament. Once the shredded plastics in the barrel had been extruded, the system was shut off to allow the temperature in the barrel to drop.

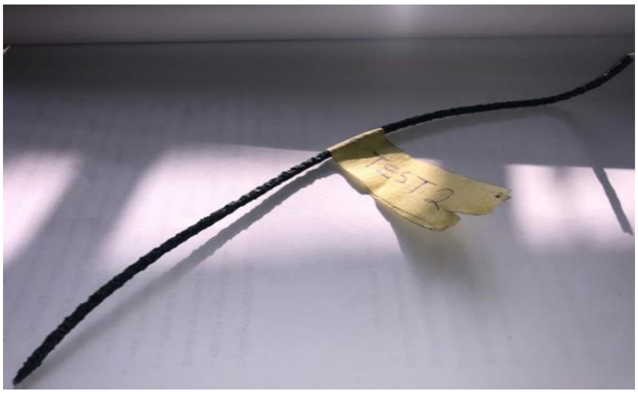


**Figure 8:** Filament at extruding temperature of 230ºC

#### 3.1.2 Temperature of 200 ºC

Setting the temperature to 200°C produced a higher quality filament with a diameter of 3 ± 0.1 mm and minimal surface imperfections (Figure 9). At this temperature, two more tests were conducted, and the outcomes showed smooth surface finished filament as well. Thus, the temperature of 200°C was found to be ideal for the recycled HDPE extrusion process.. Important factors that affect the diameter of the filament include the barrel's temperature, the die opening's diameter, and the speed at which the filament is pulled from the die. The results showed that waste HDPE plastics could be recycled at 200 ºC to produce 3D filaments of comparable quality to those manufactured from virgin plastics.

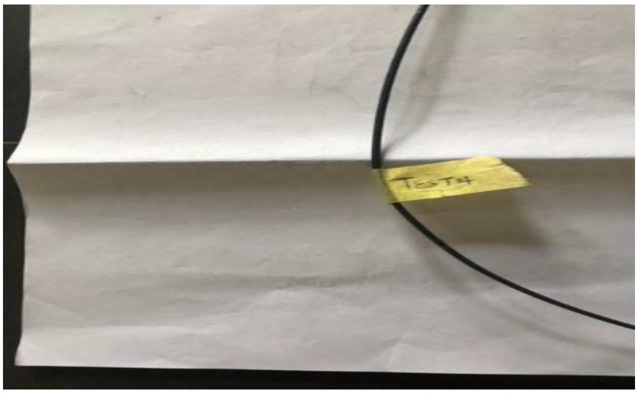


**Figure 9:** Filament at extruding temperature of 200ºC

#### 3.1.3 Temperature of 150 ºC

In order to examine the filament's quality at a considerably lower temperature, the heating band's temperature was further lowered to 150 (C). 300 g of shredded plastic were also put into the extruder. The extruded filament this time had an irregular diameter of 3mm ±0.2 and a rough surface (Figure 10). This occurred because the temperature was too low to completely melt the plastics, and and the roughness was brought about by the filament being drawn off the extruder by hand.

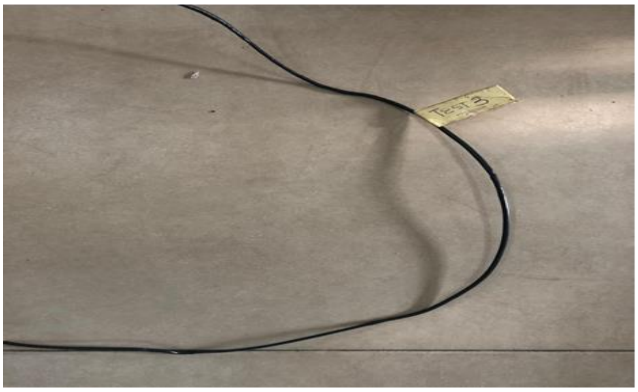


**Figure 10:** Filament at extruding temperature of 150 $^oC$

Table 4 gives a summary of the physical property of the filaments produced from waste HDPE plastic at various temperature using the extruder designed and developed in this research.

**Table 4:** Summary of the physical property of filament

| Temperature ($^O$C) | Physical properties of filament |
|---|---|
| 230 | The filament had dotted lines, long bubbles, and pits |
| 200 | Smooth surface finished filament |
| 150 | The filament had lumpy surface and uneven diameter |

## 4.0 CONCLUSION

The recycling of waste plastic to 3D printer filament can reduces the costs of production using additive manufacturing and help in tackling the environmental menace of plastic pollution in Nigeria and sub-Saharan Africa. In this study, a 3D filament extruder using HDPE waste plastics as feedstock was designed and developed locally in the University of Lagos, Nigeria. The study examined the influence of different extrusion temperatures at varying heating band temperature of 230 $^oC$, 200 $^oC$, 150 $^oC$ on the filament quality made from high-density polyethylene polyethene (HDPE). The result revealed that the extruding temperature affects the quality of filament produced from recycled high-density polyethylene and the filament produced at 230 $^oC$ was highly dotted lines, long bubbles, and pits due to overheating of the heating band while at 150 $^oC$, the filament had lumpy surface and uneven diameter because the temperature was too low to melt the waste plastics.

The best quality filament with smooth surface finish was obtained at 200 $^oC$. The recycling of HDPE waste plastics in the production of 3D filament can mitigate the negative effect of plastics disposal on humanity and the environment. The results of this study assist in the development of sustainable filament and environmentally friendly production techniques and it is recommended that further research be carried out to analyze the mechanical properties of the filament and its finished products after 3D printing.

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