Effect of 3D Printing on the Mechanical Properties FDM Printed Electrical Components.

Abstract

The Additive manufacturing (AM) technology, also known as 3D printing, reduces production time, enhances the production process and quality, lowers costs, and achieves several other goals when producing solid, three-dimensionally created structures for the application of digital information, medical equipment, automobile, airplane, and many more. By giving the necessary instruction through a human-machine interface, the techniques used to build three-dimensional structures allow for adding material in successively thinner layers, enabling manufacturing objects in almost any shape or geometry.

The polylactic acid filament was used as the feedstock to create a range of 3D-printed electrical parts. The components were created using an FDM 3D printer after being designed in Solidworks. Samples of printed materials were subjected to experimental testing to ascertain their densities, tensile strengths, flexural strengths, thermalgravimetric analyses, and Fourier transform infrared spectroscopy (FTIR) values. Heating PLA polymers change their mechanical properties. The experiment run utilizes the printed samples to compare the findings with the standard values for each parameter.

The production of locally produced 3D printing feedstock and waste management are the two biggest obstacles to 3D printing in Nigeria that this innovation will overcome. This strategy, which would reduce the importation of spare parts, will benefit the industrial sector. Less equipment will need to be discarded because there will be fewer components. Thus, it may be possible to achieve sustainable development goals for infrastructure, innovation, and business.

Keywords: Additive Manufacturing (AM), Fused Deposition Modeling (FDM), Polylactic Acid (PLA), Fourier Transform Infrared Spectroscopy (FTIR), Three-Dimensional (3D).

Nomenclatures

Rx	Rockwell Scale
M	1/4 ball
h	height of ball indentor
f	Applied load (Kg)
D	Indenter diameter (mm)
D_i	Indention diameter (mm)
D^2	Length of the impression diagonal (mm)
v_r	Rebound velocity
v_i	Impact velocity
$C_p{}^r$	heat capacity of reference pan
m	masses
ΔT	DSC signals with empty pans
F_T	Tensile force
A	Normal cross section of the specimen
σ_f	Stress in outer fibres at midpoint
E_f	Flexural modulus of elasticity
f	Load at given point of the load deflection curve
b	Width of the test beam
d	Depth or thickness of tested beam

1. Introduction

The additive manufacturing (AM) method, commonly known as 3D printing, is used to produce solid, three-dimensionally constructed structures for the application of digital information [1]. The procedures used to create three-dimensional structures with the aid of a computer (human-machine interface) allow for the addition of material in consecutive layers, allowing the creation of things with virtually any shape or geometry [2-3]. Three-dimensional printing challenges economies of scale by enabling a more accessible and speedier production process since modern technology makes producing a single object as cost-effective as producing thousands [4].

Numerous 3D printing technologies are presently accessible for the finest component manufacturing. The main differences between newly found methods are the materials used and the layering techniques required to make works of excellent quality [5]. Selective laser melting (SLM), selective laser sintering (SLS), selective heat sintering (SHS), fused deposition modeling (FDM), and fused filament fabrication (FFF) are a few of the processes used in additive manufacturing production. Stereolithography is another method used to dry liquid materials (SLA) [6]. Every method of managing industrial process production has advantages and disadvantages. The most cutting-edge 3D printers use powdered materials to create their output. These particles are then merged selectively using heat, usually from a laser. The advantage of this manufacturing method is that it can print almost any substance with any geometry; in other words, if anything can be in the form of powder, it can typically be printed [7].

The benefits of plastics include their capacity to be molded into completed items, their ability to produce long-chain hydrocarbons and additives, and their synthetic, non-biodegradable polymers, mainly sourced from fossil fuels [8-9]. In the presence of a potent catalyst, these polymers break down into monomers such as ethylene, propylene, vinyl, styrene, and benzene. These monomers can be chemically polymerized to produce a range of polymers, depending on the requirements of the manufacturing process. Two broad groups of plastics are thermoplastics and thermoset plastics. When the finished goods are heated to generate standard products, once thermoplastics are heated, the plastic will again become pliable and melt during the manufacturing process. This group includes hot thermoplastics, including PET, HDPE, LDPE, PP, PVC, and PS. One of the distinctive qualities required in manufacturing components is the ability of thermoset plastics to resist melted and molded. However, unlike thermoplastics, they cannot be remelted after they have solidified and taken on the desired shape. Nylon, polycarbonate, melamine, bakelite, laminated, and layered plastics are among the materials that can never melt if heat is added after hardened [10]. Thermoplastics can therefore be recycled entirely to provide the necessary shape. In addition to their extensive usage in household products and the food processing sector, plastics are one of the materials used for a range of engine parts and other machine components, attaining robust parts with less weight. The IC engine, for instance, has a variety of plastic components depending on its size and use. Due to the thermoplastics' ability to keep their shape even after solidifying, these plastic parts include the armature fan, carburetor floater, engine block cooler, starter catcher, oil gauge, and many more.

Injection molding as a plastic production technique was the most popular manufacturing method for generating plastic parts before the development of 3D printing. However, problems like the expensive expense of creating new molds, the existence of faults (such as bubbles, empty portions, sink marks, and many more.), the difficulty of making complicated pieces in one piece and the uneven color of molded parts prompted the invention of injection molding.

A thermoplastic polymer, PLA (Polylactic Acid), is created from renewable resources, such as maize starch or sugar cane, and sets the material apart from other types of popular plastics, which are created by distilling and polymerizing non-renewable petroleum reserves. Since PLA decomposes in three to six months compared to up to 1,000 years for other thermoplastic polymers, it is substantially more environmentally friendly than those coupled to the type of substance which serves as a raw material in its formation. The popularity and utilization of FDM 3D printing have brought the awareness of PLA material into the public eye. Numerous colors and combinations of PLA filament are available and affordable. New PLA-based items are introduced consistently for the best uses and most valuable commodities. In addition to being used for 3D printing, making disposable dinnerware, food packaging, plastic components for home appliances, other electrical appliances, and medical implants, resulting from its properties dissipated, are printed using PLA filament.

With an FDM 3D printer that uses PLA filament, household electrical parts, including switches, wall sockets, multiple sockets, junction boxes, fan canopies, fan regulators, resistors, and capacitors, may be 3D printed in a variety of colors, forms, or designs.

2. Materials and Methods

Materials

Materials and equipment used in this study include Flexural strength testing machine, Laboratory weights, Solidworks software, Personal computer, Teren digital hardness tester, TA Instruments Differential Scanning Calorimeter DSC 2920, Ametek EZ 250, Tensile/Compression testing machine, Veiner caliper, Sartorius BP410 Measuring scale, Measuring cylinder, Eureka can, Digital mass balance. 3D Printed samples utilized for laboratory test as seen in Figure 1 to Figure 4.

Fig. 1: Fan canopy sample

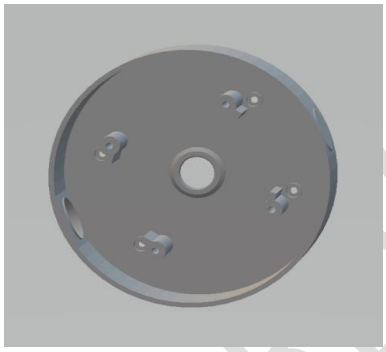

Fig. 2: Junction box sample

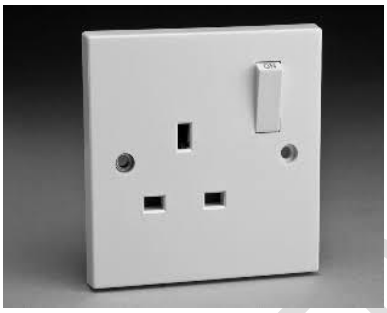

Fig. 3: Socket sample

Fig. 4: Lamp holder sample

Methods

Procedures for the Characterization of the 3D Printed Components

The following characteristics of the 3D-printed components, including their mechanical, physical, thermal, and chemical characteristics, were established after examination of the produced parts to guarantee suitable use. Some of the properties investigated include Density, flexural strength, tensile strength, hardness, Differential scanning calorimetry test, thermal gravimetric analysis, and Determination of Fourier Transform Infrared Spectroscopy (FTIR).

Determination of Hardness

The resistance of the printed materials to local plastic deformation brought on by the indentation or penetration of a specific geometry indenter onto a flat metal surface while under strain is what gives them their hardness. The hardness of ductile materials measures how pliable the printed materials react. In the case of yield and tensile strength, hardness, and mechanical strength typically exhibit a more or less linear connection. The test used three printed electrical component samples.

Values produced from the experiment done on the printed parts include the Rockwell hardness number (HRC), Vickers pyramid number (HV), Brinell hardness, and Leeb hardness value (HL). Equations 1 through equation 4 show the relationship between the sample parameters and the related hardness values.

$$HRC = \qquad Rx = M - \frac{(h_2 - h_1)}{0.002} \tag{1}$$

$$HB = \frac{2f}{\left[3.14D\left(D - (D^2 - {D_i}^2)^{\frac{1}{2}}\right)\right]} \tag{2}$$

$$HV = 1.854 \times \frac{f}{D^2} \tag{3}$$

$$HL = \frac{v_r}{v_i} \times 1000 \tag{4}$$

Determination of Differential Scanning Calorimetry

The differential scanning calorimetry thermo-analytical technique measures the amount of heat needed to elevate the temperatures of a sample and a reference as a function of temperature. The temperatures of the printed model and the reference pan are maintained essentially constant throughout the experiment. "DSC" refers to the apparatus that directly sensed energy and permitted accurate heat capacity measurements. The investigation made use of the modulated DSC gadget. The printed parts utilize the extracted 15mg sample from the material. The sample was placed into an aluminum sample pan and weighed using a digital scale. The furnace of the modulated DSC apparatus is placed within the sample pan and properly sealed to avoid heat loss.

The experiment started after thoroughly entering the experimental parameters into a computer system attached to the DSC machine. The machine interface was programmed to raise the temperature by 10°C/min to 300°C. At 190ºC, the sample material began to melt, and at 259°C, it began to burn off. DSC makes it possible to quantify heat capacity and fusion enthalpy. Equation 5 yields the sample's CPS, or specific heat capacity.

$${C_p}^s(T) = {C_p}^r(T)\frac{m^r \Delta T_3 - \Delta T_1}{m^s \Delta T_2 - \Delta T_1} \tag{5}$$

Determination of Tensile Strength

A sample of the printed part is put through a controlled tension until it fails in a test procedure called tensile testing, sometimes referred to as tension testing. A tensile test may determine maximum elongation, area reduction, ultimate tensile strength, and breaking strength. These findings can also compute the young modulus, Poisson ratio, yield strength, and strain hardening properties. The uniaxial analysis is the most used technique for figuring out an isotope material's mechanical characteristics.

Samples were obtained for use by cutting PLA-printed bits into rectangular shapes. Digital AmatekEz250 hardware made up the setup. An object, a grip between two fixtures, clamps the sample. Before applying force, the components were weighed using a computerized Vernier caliper, held at one end, and secured at the other. The force was measured up until the material cracked. Three experimental methods were performed to guarantee correctness throughout the entire process. The ultimate tensile strength, commonly known as the tensile strength, is obtained by dividing the load at failure by the initial cross-sectional area (6).

$$\sigma = \frac{F_T}{A} \tag{6}$$

Determination of Flexural Strength

The stress seen in the 3D printed material right before it yields in a flexure test is known as flexural strength, modulus of rupture, bend strength, or transverse rupture strength. The most common test is the transverse bending test, which employs a three-point flexural test technique to bend the printed specimen with a circular or rectangular cross-section until it fractures or yields. The three-point bending flexural test provides values for the modulus of elasticity in bending (E), flexural stress (σ), flexural strain (ɐ), and the flexural stress-to-strain response of the material. The main advantage of a three-point flexural test is the ease of specimen preparation and testing. The flexural strength (σ) of the 3D printed material represents the highest stress experienced within the printed sample at its yield moment. Flexural strength is shown mathematically in equation 7. A rectangular PLA object created in 3D was sliced into a specimen whose dimensions were then precisely measured using veneer calipers and tested for tensile strength on a universal tensile tester (Ametek EZ250). Two pins spaced precisely apart from each other support the sample. The specimen's center was loaded until it shattered before taking the readings. The experiment made use of three distinct printed models.

$$\sigma_f = \frac{3fl}{2bd^2} \tag{7}$$

Flexural modulus

$$E_f = \frac{L^3 m}{4bd^3} \tag{8}$$

Determination of Density

The density of a material is its mass per unit volume, as shown in equation 9 Mathematically. For a pure substance, the density has the same numerical value as its mass concentration. The PLA printed material's density was obtained by immersing the sample in water and allowing it to displace the excess water. After taking readings, values were added. The experiment made use of three unique specimens.

$$\rho = \frac{m}{v} \tag{9}$$

Determination of Thermal Gravimetric Analysis

Thermal gravimetric analysis (TGA) is a thermal analysis technique that measures a specimen's weight changes as its temperature increases. This measurement gives information on chemical phenomena like chemisorption, thermal breakdown, solid-gas interactions, and physical qualities and behavior like phase transitions, absorption, and desorption of the printed samples. This technique involves monitoring variations in a specimen's weight as its temperature rises. TGA can be used to measure a sample's volatile and moisture contents. The instrument mainly comprises a programmable furnace to control the heat-up rate of the specimen and an empathetic scale for measuring weight changes in the sample.

A TGA-55 device performs a thermal gravimetric study of the printed sample. Cutting a 20 mg sample from the printed section provided a substance sample. The material was weighed and then put into the sample pan. The sample pan is placed within the furnace of the Thermal Gravimetric Analyzer, which is then carefully sealed to retain heat. Following the complete entry of the experimental conditions into a computer system connected to the Thermal Gravimetric Analyzer, the temperature had a setpoint to increase by 10 degrees per minute until it reached 1000 degrees (TGA-55 Equipment). The sample was heated in air to 1000 degrees from ambient temperature, after which the weight loss that resulted from semi-volatile chemicals, polymer breakdown, ash content, carbon black, and moisture was estimated. Thermal stability and the effect of fillers may be quantified using TGA.

Determination of Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a technique for analyzing materials that help to discriminate between organic, polymeric, and occasionally inorganic ones. The FTIR analysis technique uses infrared light to scan test samples and look at chemical properties. FTIR analysis, usually employed as the first step in the material analysis process, is a recognized technique for quality control when evaluating industrially produced materials. A change in the recognizable pattern of absorption bands demonstrates a shift in the material's composition or the presence of contamination. Smaller particles, usually 10 to 50 microns in size, and more significant surface areas can be chemically analyzed using this method.

A Perkin-Elmer Spectrum 1000 FT-IR spectrometer performs the FT-IR measurement. The sample was ground with KBr and made into a pellet for measurements in diffused reflectance mode at 4 scans and at 2.0 cm^{-1} resolutions. The substance was examined using an FTIR spectrometer, which

exposes the sample to IR beams and measures how much of the beam and at what frequencies the sample absorbs. The reference database contains thousands of spectra used to identify samples, and it is possible to identify the compounds through this process.

3. Results and Discussion

This part presents and discusses the experimental study's findings per the experimental techniques stated in the preceding sections.

Hardness Test

Table 1 shows the results of the hardness tests performed on three samples of the printed components.

Table 1: Result of hardness test

Samples	HRC values	HV values	HB values	HL values
1	50.3	518	501	722
2	52.4	551	535	741
3	49.9	512	495	718
Average	50.86	527	510.33	727

Table 1 shows the results of the hardness test conducted on the samples. HRC, HV, HB, and HL refer to Rockwell Hardness number, Vickers pyramid number, Brinell Hardness, and Leeb Hardness Value, respectively. The table shows that HL values were the highest for the three test samples, while HRC values were the lowest. The average HRC, HV, HB, and HL values were obtained as 50.3, 527, 510, and 727, respectively. The HRC standard number for PLA ranges from 84 to 118. Hence the 3D printing process reduces the hardness of the material.

Differential Scanning Calorimetry Test Result

Figures 5 and 6 show the DSC test outcomes performed on three printed component samples.

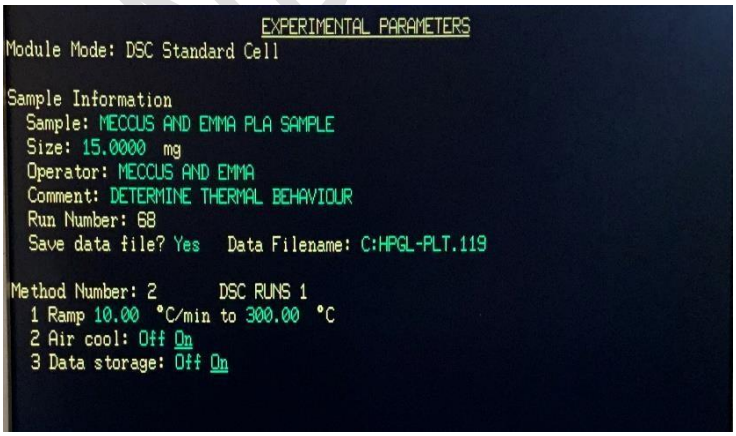

Figure 5: Experimental parameters used to carry out the test

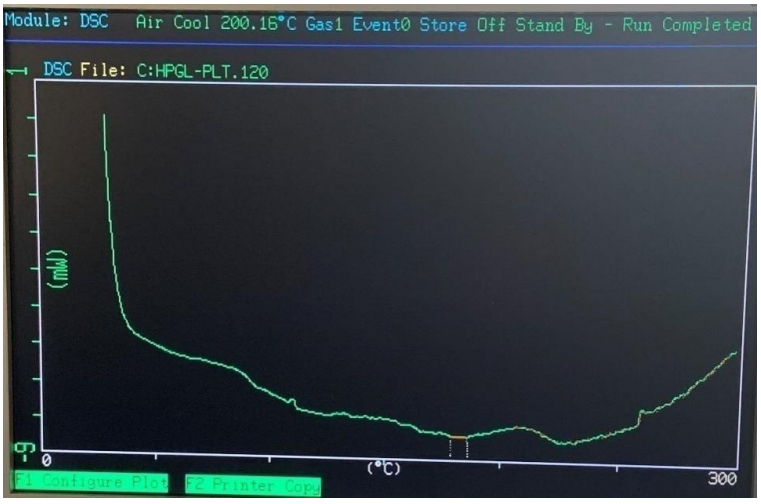

Figure 6: Graph of Heat Flux versus Temperature

Figure 6 shows a sample of printed PLA and a graph showing heat flux (MW) vs temperature (°C). Around 40°C after formation, the material's behavior remained stable, but around 45°C, it began to change as the temperature increased. The sample started to melt at 180°C, and as seen in the graph, it did so for a limited period. The sample started to burn off at 259 °C, reaching a temperature of 300 °C towards the end. The glass transition temperature of 170°C –180°C is close and in line with, who established the glass range transition temperature of printed PLA as 155°C-165°C.

Result for Tensile Test

Table 2 shows the outcomes of a tensile test performed on three samples of printed components.

Table 2: Result of tensile test

Test no.	Cross section area (mm)	Length (mm)	Width (mm)	Gauge length (mm)	Peak force (N)	Tensile strength (Nmm^2)
1	1.30	63.50	7.75	34.20	354	272.30
2	1.35	61.05	7.62	35.65	373	276.30
3	1.09	60.00	6.71	37.06	259	237.62
Average	1.25	61.52	7.36	35.64	328.66	262.07

Table 2 shows the result for the tensile strength of PLA printed materials. For every test sample, the following four variables were measured: gauge length, cross-sectional area, length, and breadth. The three samples' peak forces were calculated as 354N, 373N, and 259N, respectively, and their tensile strengths as 272.30Nmm^2, 276.30Nmm^2, and 237.62Nmm^2, respectively.

Flexural Test Result

Table 3 shows the findings of a flexural test performed on three samples of printed components.

Table 3: Result of flexural test

Sample no	Cross section area	Length (mm)	Width (mm)	Peak force (N)	Flexural strength (N/mm^2)
1	3.73	52.40	9.78	111	29.75
2	3.67	60.46	13.22	124	33.78
3	3.99	51.97	9.15	115	28.82
Average	3.79	54.94	10.72	116.67	30.78

Table 3 shows the result for the tensile strength of PLA printed materials. Each test sample had its cross-sectional area, length, breadth, and gauge length measured. The three samples had peak forces of 111N, 124N, and 115N, respectively, and flexural strengths of $29Nmm^2$, $75Nmm^2$, $33Nmm^2$, and $28.82Nmm^2$, respectively. Farah et al. [11] estimate that PLA has a flexural strength of 106; hence the material's flexural strength was decreased.

Density Test Result

Table 4: Result of density test

Test no.	Volume of water (cm^3)	Mass of sample (g)	Density (g/cm^3)
1	74.1	91.29	1.232
2	74.1	93.14	1.257
3	74.1	91.81	1.239
Average	74.1	92.08	1.243

Table 4 shows the result for the density of PLA printed material. The volume of the water is $74.1cm^3$, respectively, and the mass of the sample (1.232g, 1.257g, and 1.239g), respectively. According to Orellana et al. [12], the density of PLA printed material was $1.24g/cm^3$, which is consistent with the average density of the experiment. As a result, printing did not change the material's density.

Thermal Gravimetric Analysis (TGA) Result

Figure 7 and Table 5 show the outcomes of the TGA test performed on the printed components.

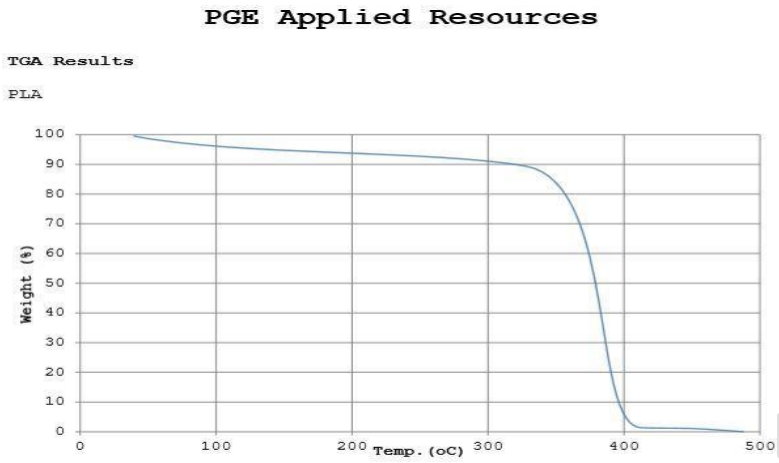

Figure 7: Graph of weight loss % versus Temperature.

Table 5: TGA Curve Table

°C	%
51.2	99.4
99.7	97.1
149.3	96.6
200.2	95.1
249.3	93.7
299.6	91.3
355.9	80.6
400.5	6.3
451.9	2.2
490.9	0.0

Figure 7 shows a weight loss (%) graph versus temperature (°C) for printed PLA samples. From the origin, the material's behavior was constant for about 50°C; from 51.2°C, the material's demeanor changed as the temperature increased. At 299.6°C, the sample started losing weight rapidly, as seen in the graph. At 355.9°C, the sample started burning off till the final temperature of 500°C. At 500°C, all the polymeric materials have burnt off, and no residue remains.

Fourier Transform Infrared Spectroscopy (FTIR) Result

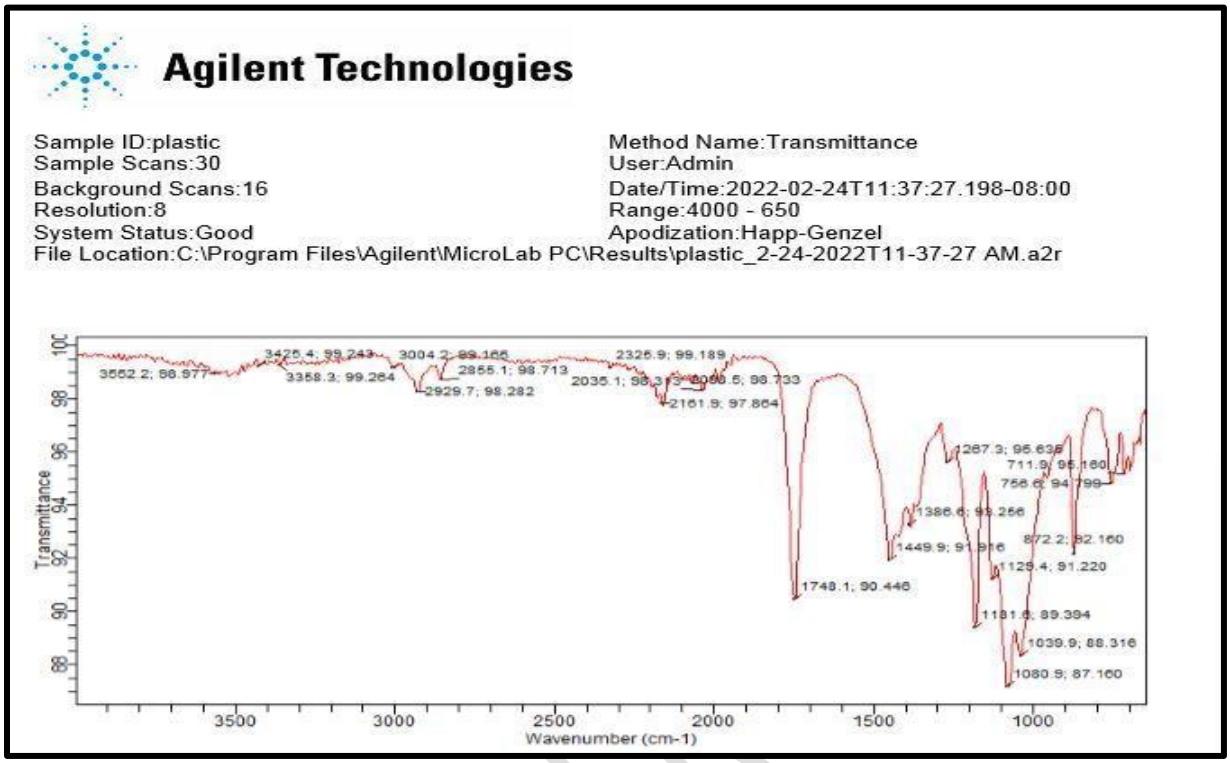

Fig. 8: FTIR spectra of PLA

The FTIR spectrum provided proof of PLA's chemical composition. The FTIR spectra of polylactic acid (PLA) shown in Figure 8 show strong bands at various wavelengths, with the band at 1080.87 cm^{-1} representing the stretching of the C-O bond and the bands at 2929.7 cm^{-1} and 2855.1 cm^{-1} representing the extension of the C-H stretching in -CH3 being the most recent. At 1181.6 cm^{-1}, the ester C-O testing absorption is the most significant. The FTIR spectrum of PLA agrees with the published FTIR spectra [13].

Comparative Evaluation Result

Table 6: Experimental values of PLA and their parameters compared with standard values

Samples	Hardness (HRC)	DSC	Tensile (N/mm^2)	Flexural (N/mm^2)	Density (g/cm^3)
PLA	50.8	Melting point of 180°C	262.07	30.78	1.243
ASTM	D785	D7426	D638	D5023	D792
ISO	2039-2	11357-1	527	178	-
ANSI	-	-	-	-	F602

Table 6 shows the average experimental values obtained for PLA and their parameters. The data were contrasted with averages for comparable thermoset polymers used as standards in the industry.

4. Conclusions

The polylactic Acid filament was used as the feedstock to develop and print a variety of 3D-printed electrical components. The components were created using Solidworks and printed using an FDM 3D printer. Experimental tests were performed on printed material samples to determine their hardness, differential scanning calorimetry, tensile strength, flexural strength, density, thermalgravimetric analysis, and Fourier transform infrared spectroscopy (FTIR). Heating changes the mechanical properties of PLA polymers. Printed samples were used as the basis for the experiment to compare the experiment's findings with each parameter's standard values.

This development will address the most considerable difficulty of 3D printing in Nigeria: managing plastic waste and producing locally generated 3D printing feedstock. This invention will decrease the importation of spare parts and is especially beneficial to manufacturing companies. Due to a lack of components, there will also be a significant decrease in the equipment that needs discarding. As a result, the aims of sustainable development for business, innovation, and infrastructure are made possible.

Recommendations

This study recommends:

1. It is necessary to conduct further research to identify improved PLA materials so that everyone who requires it may get them.
2. With the ability to create vitally essential feedstock locally, regional manufacturers and industrial companies should embrace and fully utilize the technology's many benefits.
3. Production of PLA plastic materials should be encouraged because of their biodegradable ability, which makes them environmentally friendly.
4. It is necessary to perform research to increase the durability of PLA-printed objects.

List of abbreviations

Additive manufacturing (AM)

Additive Manufacturing (AM)

Fused Deposition Modeling (FDM)

Polylactic Acid (PLA

Fourier Transform Infrared Spectroscopy (FTIR)

Three-Dimensional (3D).

Rockwell Hardness number (HRC)

Vickers pyramid number (HV)

Brinell Hardness (HB)

Leeb Hardness Value (HL)

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