FUDMA Journal of Engineering and Technology
ISSN: 3092-9385
https://sites.google.com/fudutsinma.edu.ng/fjet
Volume 1, Issue 2, 2025, 639-648

Investigation of the Mechanical and Thermal Properties of Waste Toner Powder Reinforced Polyester Composite for Industrial Applications

Chinemeogo C. OZIOKO[1*], Ikechukwu C.-E. IKE-EZE[2*], Nnanyelugo O. EDWIN[3], Dimelu K. EBUBE[4], Charles MBOHWA[5]

[1,2,3]Department of Metallurgical and Materials Engineering, University of Nigeria, Nsukka, Nigeria
[4]Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria
[5]College of Science, Engineering and Technology, University of South Africa (UNISA), South Africa

[1*]chinemeogo.ozioko@unn.edu.ng, [2*]ikechukwu.ezema@unn.edu.ng, [3]onyeka.nnanyelugo@unn.edu.ng, [4]kenelumchukwu.dimelu@gmail.com, [5]mbohwc@unisa.ac.za

Abstract
This experimental study explores the mechanical, thermal and morphological (SEM), properties of waste toner powder reinforced polyester composite, with an emphasis on its applicability in industrial settings. The research investigates the potential of waste toner powder, an abundant industrial by product, as a reinforcing agent in polyester composites which was made using the hand lay-up method. 5, 10, 15, 20, 25, 30, and 35 weight percent of waste toner loading were used to create the composite. The results of the tensile, flexural, impact, and hardness tests were compared for waste toner/polyester composites and unsaturated polyester with varying weight % loading. The results showed better enhancement in mechanical properties at 15wt. % of waste toner reinforcement. TGA and DTA was also observed to have 15% loading possessing better thermal stability than others. Morphological features of the composites were scrutinized using SEM. The results provide important new information about using waste toner powder as an economical and sustainable filler in polyester composites. presenting promising avenues for a diverse array of industrial applications.

Keywords: *Waste toner powder, polyester composite, mechanical properties, thermal analysis, sustainable materials.*

1.0. Introduction

Because of their special blend of lightweight, processability, and adjustable qualities, polymer matrix composites have drawn more attention in recent decades and can be used in different structural and functional applications [1,2]. Because of their low cost, ease of processing, dimensional stability, and superior mechanical strength, thermosetting resins, like polyester, have been used extensively among the many classes of polymer matrices [3]. A tried-and-true method for improving performance and broadening application domains is the reinforcement of polymer matrices with fibers, fillers, or particles [4]. Specifically, because of their ability to balance mechanical and thermal qualities, polyester-based Composites are now often utilized in the automotive, aerospace, construction, and electrical industries [5]. However, research is now focusing on alternative, environmentally friendly fillers made from waste resources due to the increasing demand for resources that are both high-performing and ecologically sustainable [6,7].

The fast build-up of solid waste, particularly from industrial and electronic sources, is among the most urgent issues facing modern civilization [8]. One of the major contributors to electronic waste streams is waste toner powder, which is a by-product of old printer cartridges [9]. Typically, toner is made up of carbonaceous and fine polymeric particles, pigments, and non-biodegradable, chemically stable additives [10]. Large amounts of waste toner are produced due to the dramatic increase in printer cartridge use worldwide over time, and they are frequently burned or dumped in landfills [11]. These activities pose health risks in addition to contributing to environmental deterioration because of the potential for the discharge of hazardous components [12]. Consequently, researchers are paying more and more attention to waste toner's potential as a secondary raw resource as a means of lessening environmental impact and as a means of advancing materials engineering's circular economy principles [13,14].

As per recent research, the mechanical, thermal, and dielectric properties of polymer matrices may be considerably changed by adding industrial by-products as red mud, fly ash, rice husk ash, silica fume, and carbon black [15–18]. According to these results, because wasted toner contains a lot of carbon particles and thermoplastic resin, it might be a good filler for polymer composites [19]. The use of toner in cementitious systems, asphalt modification, and polymer reinforcement has only been briefly examined in research [20,21]. However, thorough research on polyester–toner composites is still lacking. In particular, even though some studies have shown improvements in electrical resistivity or mechanical strength, the information that is now accessible is dispersed, and thorough evaluations of both mechanical and dielectric performance are absent [22,23]. This knowledge gap is critical, as the combined evaluation of these properties is essential for determining the suitability of new composites for industrial applications.

Such composites potential for multifunctionality accounts for their industrial importance. For example, materials that can simultaneously demonstrate sufficient mechanical integrity and dependable dielectric behaviour are required for applications in electrical insulation, electronic housings, packaging, and lightweight structural components [24]. Despite its mechanical strength, neat polyester has drawbacks, including brittleness and dielectric losses at high frequencies [25]. Some of these drawbacks may be lessened and raw material costs might be decreased by reinforcing polyester with toner particles [26]. Additionally, by keeping hazardous waste out of landfills and turning it into engineering materials with additional value, using waste toner as a filler supports sustainability objectives [27].

2.0. Materials and Methods

2.1 Materials

I. Waste Toner Powder: Used in this study, waste toner powder (WTP) was obtained from used printer cartridges that were gathered at a print waste dump center.
II. Polyester Resin: The matrix material for the composite was unsaturated polyester resin that was purchased from a Nsukka vendor. The resin's favorable mechanical qualities, production simplicity, and compatibility with waste toner powder led to its selection.
III. The catalyst, methyl ethyl ketone peroxide, and the hardener, cobalt naphthenate, were both purchased from the same Nsukka source. Equipment used for the research includes rule, steering rod, bowl, paper tape, beaker, measuring cylinder and moulds etc.

2.2 Composite Production

A manual lay-up method was used to create the polyester composite reinforced with waste toner powder. The following steps were taken throughout the manufacturing process: To start the curing process, the polyester resin was combined with the catalyst and hardener in the suggested amounts. To get rid of any remaining moisture that had been absorbed from the surroundings, the waste toner was dried for an hour at 60 degrees Celsius in an oven. To guarantee even dispersion of the toner particles, the polyester resin and waste toner powder were thoroughly combined. The needed volume of polyester resin was measured in a beaker and poured into a bowl with addition of the right quantity of catalyst and accelerator at room temperature. To achieve consistency, waste tonner (5, 10, 15, 20, 25, 30, and 35 weight percent) was added to the corresponding resin and properly mixed. A smooth surface that had been treated with a releasing agent to inhibit adhesion was used for the lay-up procedure. To finish the polymerization process, the composite was left to cure for 24 hours at room temperature.

2.3 Characterization of The Composite

2.3.1 Mechanical Testing

These tests include impact, tensile, flexural and hardness test were carried out on the produced materials at the NLNG laboratory of Metallurgical and Materials Engineering, University of Nigeria Nsukka.

2.3.1.1 Impact test

The composite samples' impact test was conducted in compliance with ASTM D256-93 (1990). The specimens were exposed to a rapid impact force under controlled conditions in order to assess the toughness of the manufactured composites. The Charpy impact test method was employed for this purpose. Rectangular notched specimens with dimensions of 55 × 10 × 10 mm were prepared according to the standard. The test was performed at room temperature (27 ± 2 °C) using a pendulum impact tester with an impact velocity of 3.5 m/s and a hammer energy capacity of 2.7 J. Each sample was positioned horizontally with the notch facing opposite to the striking edge of the pendulum. The impact energy absorbed by the material was determined from the dial reading of the machine and calculated using the experimental results with the following equation:

$$E= \frac{mgh}{A} \qquad \text{……….. (1)}$$

where:

- E is the impact energy absorbed (in joules).
- m is the mass of hammer (in kilograms).
- g is gravitation energy (approximately 9.81 m).
- h is the height of hammer falls before striking the sample (in meters).
- A is the cross-sectional area of the fractured specimen (in square meters).

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

This equation gives an indication of the energy absorbed by the material during the impact, which helps assess its toughness and resistance to fracture. The utilized impact machine model number is IS17562-1963

2.3.1.2 Hardness test

The material's resistance to scratching and indentation was evaluated using a hardness test. The Rockwell 150A-5757 hardness testing machine was utilized. The samples' hardness was assessed using a depth measurement after applying an initial minor load followed by a major load. The result is read from a dial gauge using rockwell B scale calibration.

2.3.1.3 Tensile strength

A tensile test was performed on the samples using (ASTM, 1990) to determine their mechanical properties under tension. The utilized tensile machine model number is M500-25CT. In this machine, the specimen is pulled apart using a controlled force until it fractures. The test measures several important parameters which includes:

I. *Ultimate Tensile Strength (UTS):* This is the maximum stress a material can withstand before breaking. It is the ability material to resist breaking under tension.
II. *Yield Strength:* This is the point a material undergoes significant plastic deformation, but still returns to its original shape when the load is removed. It's an important parameter for determining the material's strength.
III. *Elongation*: This is the amount of deformation a material can under before breaking.
IV. *Young's Modulus (Modulus of Elasticity):* This is the slope of the initial linear area of the stress-strain curve, indicating the material's resistance to deformation under tension.
V. $\delta c = \frac{Force}{Area}(N/m^2)$ ………..(2)

2.3.1.4 Flexural Strength

The capacity of the composite samples to withstand deformation under applied bending loads was assessed using flexural strength, also known as bending strength. The test was carried out utilizing a universal testing machine (Model: M500-25CT) in compliance with the ASTM D790 (1990) standard. A three-point bending configuration was employed, in which the specimen was supported at two ends while a load was applied at the midpoint. The crosshead speed throughout the test was 2 mm/min, and the span length-to-depth ratio of the specimens was maintained at 16:1 as recommended by the standard.
The flexural strength (σf) was calculated using the relation:

$$Flexural\ (\sigma f) = \frac{3PL}{2bd2}(N/m^2) \quad \text{…………. (3)}$$

2.3.2 Thermal Analysis

Thermogravimetric analysis (TGA) and Differential thermal analysis (DTA) was conducted at DICON Kaduna State using equipment such as Perkin Elmer QSQ1 and TEMP QSQ1.

2.3.2.1 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was performed on the materials using the PerkinElmer instrument at DICON Kaduna to assess their thermal stability. To determine the onset and maximum decomposition rate temperature, a platinum pan was filled with 14.859 mg of the control sample and 15.103, 15.107, 14.104, and 15.03 mg of the 5%, 10%, 15%, and 20% loading. The pan was heated from 30 ^{O}C to 950 ^{O}C at a rate of 10 ^{O}C per minute.

Under controlled atmospheric circumstances, this was used to investigate how a sample's mass changed with temperature (or time). A tiny quantity of pulverized material was put in a crucible and heated steadily while its mass was continuously recorded using a very sensitive balance. As the temperature changes, different physical and chemical processes occurred within the sample, leading to alterations in its mass. These processes can term decomposition. The data obtained from the TGA experiment was represented graphically as a thermogram, which shows the change in sample mass as a function of temperature.

2.3.2.2 Differential Thermal Analysis (DTA)

This was used to investigate phase transitions, reactions, and thermal behaviour of materials. It was used to measure temperature differences between a sample and a reference material as they are subjected to controlled heating cycles. The DTA instrument consists of a sample holder for the test material and a reference holder containing an inert material (often Alumel or Chromel). The sample and reference material were subjected to the same heating conditions. The device measured the temperature differential (ΔT) between the reference material and the sample. The sample and reference material's temperature differential (ΔT) was plotted against the temperature. This graphical representation helped in identifying various thermal events such as endothermic or exothermic reactions, phase transitions and decomposition, etc.

2.3.3 Morphological Characterization

The SEM was carried out at ACE-SPED with Thermo fisher scientific, 2023 model. This exposed the details of the Nano structures of the samples. The EDS also showed the specimen's elemental compositions. In this process, the atoms in the sample were excited by the primary electron beam's interaction with the specimen, resulting in the emission of distinctive X-rays that are specific to each element. In order to ascertain the specimen's elemental composition, EDS was used to finds and examines these distinctive X-rays.

3.0 Results and Discussion

Sample coding: Control=0%wt, A=5%,B=10%,C=15%,D=20%,E=25%,F=30%,G=35%

3.1 Mechanical Tests

The Tensile strength, flexural strength, impact strength and hardness value of the control and waste toner composites is shown in Figures 1 to Figure 4.

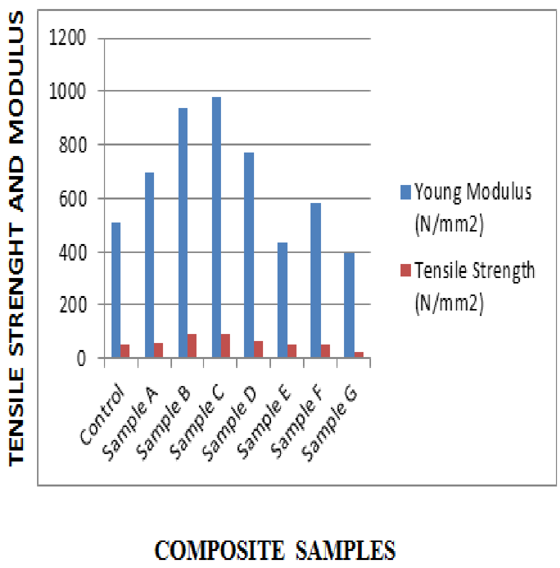

Figure 1: Effect of waste toner percentage variation on the Tensile on the Tensile

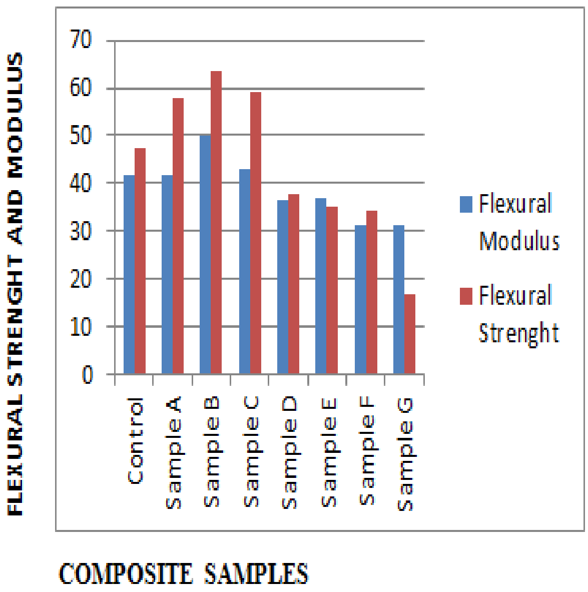

Figure 2: Effects of waste toner percentage variation on the Flexural strength

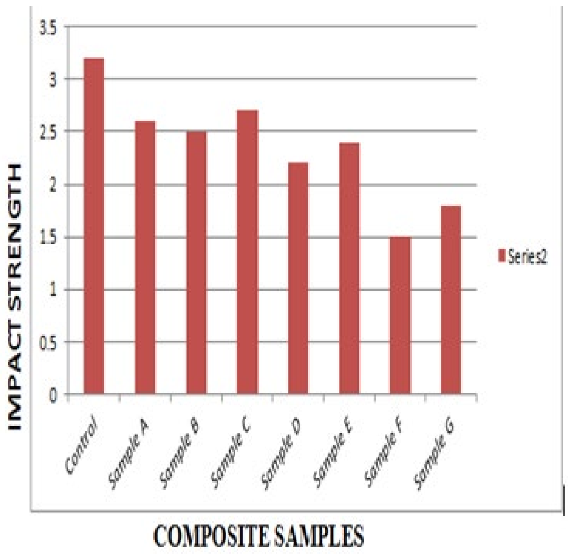

Figure 3: Impact Strength of waste toner-polyester composites with varying waste toner weight percentages

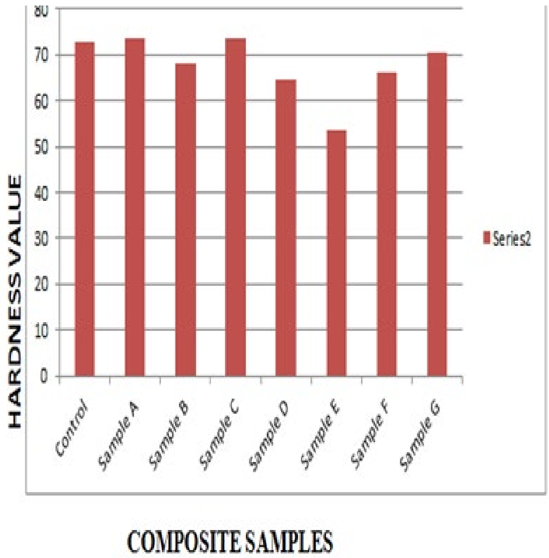

Figure 4: Hardness Test of waste toner-polyester composites with varying waste toner weight percentages

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

In Figure 1, the bar chart showed that adding waste toner to the reinforced composites improved their tensile strength and young modulus. The tensile strength of the unreinforced polyester increased from 50.33N/mm² to 59.11N/mm² with 5% of waste tonner loading. But once 5% more waste tonner was added, the composites' strength rose at 10% and 15% loading, But, as seen in Figure 1, the modulus of the unreinforced polyester and polyester/waste toner composite also decreased from 20% to 35% loading. This could be because, as waste toner particles disperse in the polyester matrix, the viscosity of the resin system rises, making it difficult for the particles to move freely and causing an uneven distribution of waste toner particles in the matrix. Alternatively, this can be the result of a mild chemical interaction between the waste toner and polyester that lessens the transmission of tensile stress from the matrix to the filler.

The values of the flexural strength behave similarly to those of the tensile strength in Figure 2. The strength gradually dropped after increasing steadily up to 10 weight percent of waste toner loading. The incompatibility of the waste toner particles and polyester resin is the cause of this. The flexural modulus with different weight contents is also displayed in Figure 2. The flexural modulus was found to steadily grow up to 10 weight percent, then gradually fall between 15 to 20 weight percent, and then slightly increase at 25 weight percent.

Figure 3 shows that the impact strength of polyester/waste toner composites increased and decreased with waste toner content ranging from 5 wt% to 15 wt%. The control had the highest impact strength of 3.2 kJ/m2, followed by a composite at 15% with an impact strength of 2.7 kJ/m2. However, strength falls after 15 wt.% of the reinforced composite. It was seen in Figure 4. that the hardness result of the polyester/WT composites showed a little increase in hardness of 5% and 15% loading, which were highest and the other loading having a lower hardness than the control which might be as a result of microscale voids formed due to poor wettability of particulates and unavoidable voids formation associated with hand lay-up technique.

Comparing with what Bensalah et al. (2017) [28]. did, in their work, they looked at the rheological, mechanical, and thermal characteristics of clay and graphite-reinforced polypropylene hybrid composites. These composite materials were created utilizing twin-screw extrusion followed by injection moulding. The study focused on the impact of reinforcement content and the ratio of clay to graphite particles on the composites' morphological, mechanical, rheological, and thermal properties. The findings indicated that adding clay and graphite particles significantly enhanced the thermal stability, with an increase of 40–50°C observed at a 20 wt.% reinforcement content. Additionally, the combination of clay and graphite yielded Superior mechanical qualities of hybrid composites. Also, Ndiaye et al. (2010) [29] studied the mechanical and thermal characteristics of polypropylene/wood-flour composites (WPCs). These composites were blended with varying contents of wood flour, maleated polypropylene (MAPP), and clay. The addition of MAPP or clay significantly improved the dispersion of wood fibers within the composite, suggesting that they acted as adhesion promoters. Clay was also found to function as a flame retardant. Thermal testing revealed increases in crystallization temperature (Tc), crystallinity, and melting temperature (Tm) with higher wood content. The increase in Tc and crystallinity was attributed to wood flour acting as a nucleating agent, while the Tm increase was linked to wood's insulating properties, which reduced heat conduction. Flexural strength and modulus improved with increasing wood-flour content, whereas impact strength, tensile strength, and strain decreased, primarily due to the level of dispersion of wood flour in the polymeric matrix.

3.2. Thermo Gravimetric Analysis (TGA) And Differential Thermal Analysis (DTA).

TGA and DTA of polyester/waste toner composites are shown in Figures 5 and 6.

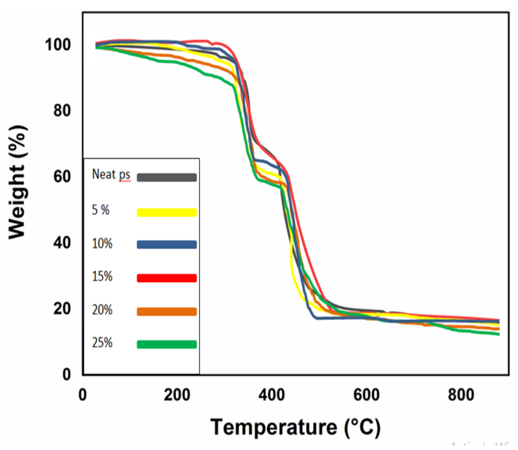

Figure 5 TGA Test of reinforced and unreinforced waste toner/polyester

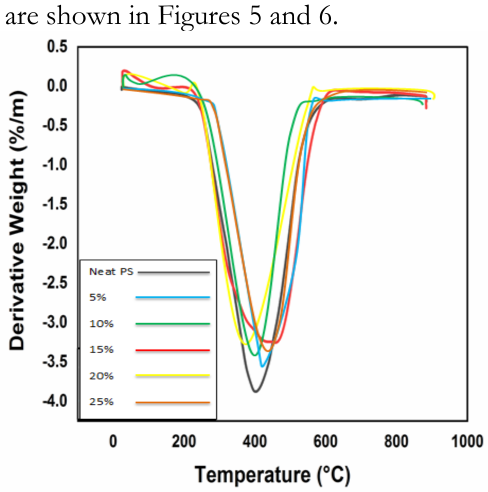

Figure 6 DTA Test of reinforced and unreinforced waste toner/polyester

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

Thermogravimetric analysis (TGA) was employed to investigate the heat stability of the composite and control. In Figure 5, the TGA curves of 15% loading shows that at 300 °C the composite had a good thermal stability better than other waste toner loading before it decomposed at 330°C while the control started decomposing slightly from 150°C and has lost 4% weight at 300°C. On the second steps between 360°C and 520°C, the unreinforced sample and other reinforced sample decomposed more than that of the 15% loading as seen on the graph in Figure 5. Because of its high thermal stability, these fillers (waste toner), which operate as a barrier to stop heat from the environment from spreading throughout the polymer matrix and prevent volatile disintegration of the composite, the 15% loading has a higher thermal stability. Thus, the waste toner served as a thermal stabilizer for the composite, which has a variety of possible uses.

Differential Thermal Analysis (DTA) of reinforced and unreinforced waste toner/polyester composite is presented in Figure 6

From the graph, at 0°C to 100°C the derivative weight of the10%, 15% and 20% loading is shown to be above 0% while that of the unreinforced polyester is lower than 0%. From 230°C to 350°C the derivative weight were almost uniform except that of 15% loading. The other reinforced and unreinforced composite except 15% and 20% loading dropped below -3.75% derivative weight between 380°C to 480°C. The derivative weight of that of the 15% and 20% loading had highest derivatve weight between temperature of 580°C to 800°C the 15% loading had higher derivative weight at temperature of 610°C before it aligned uniformly with the 20% loading. So, from the observation deduced from the graph Observations revealed that the presence of waste tonner affected temperature difference with identical heat flow in which the composite sample had better thermal properties.

3.3 Morphology of the composite.

The morphology of the control, 10% and 15% of polyester/waste toner composites is presented in plate 1 to 3.

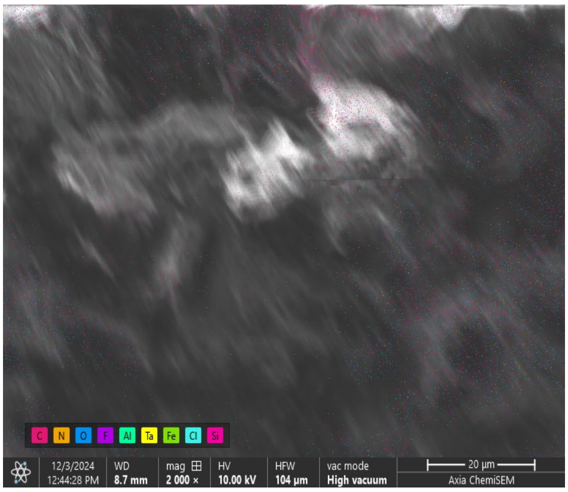

Plate 1: 2000x magnification of the control sample

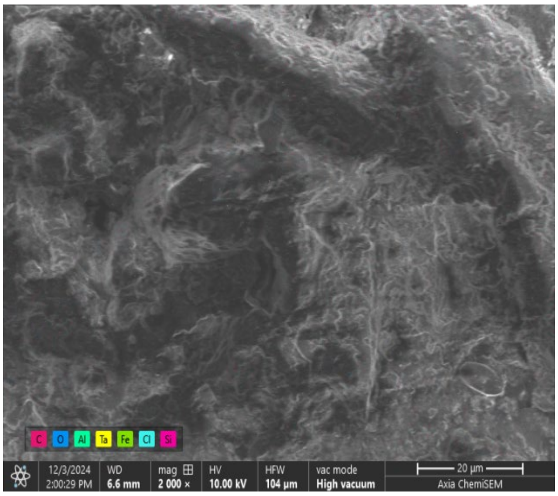

Plate 2: 2000x magnification of the 10% loading of waste toner

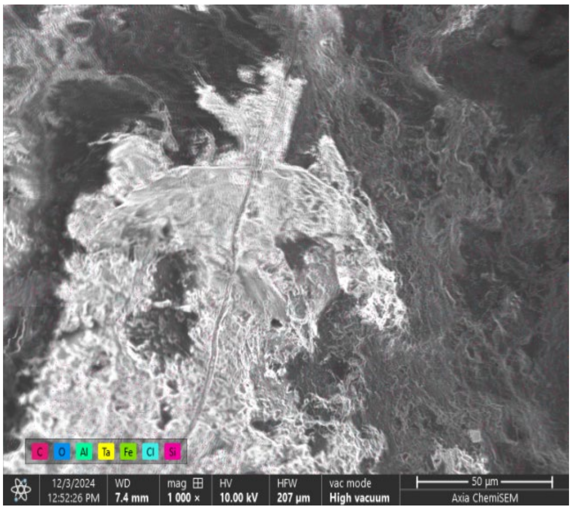

Plate 3: 2000x magnification of the 15% loading of waste toner

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

It was discovered that the main particle size varies from 7μm and above. However, particle aggregation can result in a big particle of around 50–120 μm. They tend to be spherical particles; however the waste toner form is generally uneven. Most likely, electrostatic forces are the source of particle aggregation. At 2000 magnification, Plate 3 displays the 15wt% fillers. Because of the toner in the resin, the picture appears rougher at higher magnification. Long, cylindrical forms that the toner utilized were closely packed together. As demonstrated by the study's tensile result data, the increased waste toner content beyond 15% led to a considerable drop in tensile strength due to the comparatively wide particle size dispersion of the toner fills and apparent weaker adhesion inside the polymer resin.

3.4 Energy-dispersive X-ray Spectroscopy (EDS)

Table 1 shows the EDS of the unreinforced polyester.

Table 1: EDS of the unreinforced polyester

Element	Line	At. %	Wt. %	Net Counts	At. % Error	Wt. % Error
C	K	43.7	35.5	1 487	1.3	1.1
O	K	51.5	55.5	1 531	1.6	1.7
Al	K	1.7	3.0	138	0.2	0.3
Si	K	3.1	6.0	263	0.2	0.3
Cl	K	0.0	0.0	0	---	---
Fe	K	0.0	0.0	0	---	---
Ta	M	0.0	0.0	0	---	---

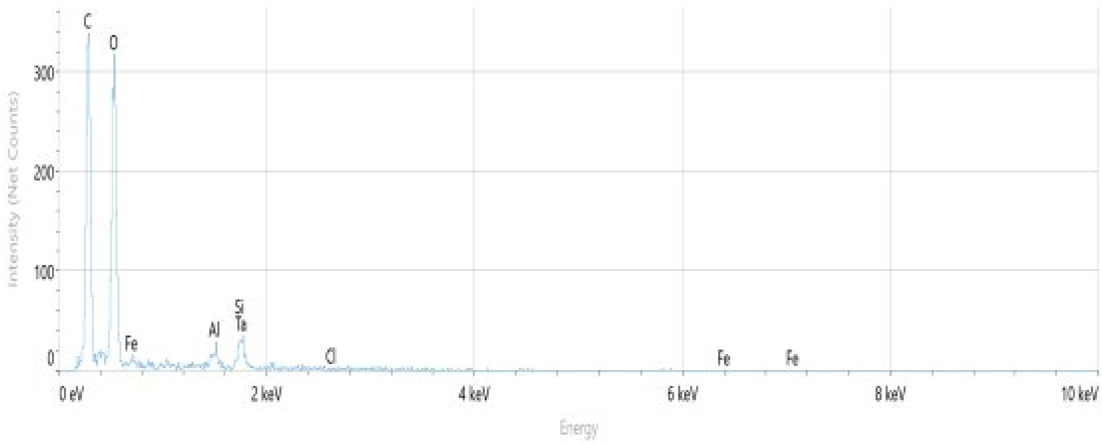

Figure 7: EDS of the unreinforced polyester

Figure 7 shows the EDS of the unreinforced polyester.

Table 2: EDS of the 10% reinforced polyester composite

Element	Line	At. %	Wt. %	Net Counts	At. % Error	Wt. % Error
C	K	49.1	40.5	8 197	0.7	0.6
N	K	4.8	4.7	367	1.3	1.3
O	K	40.8	44.9	4 777	1.1	1.2
F	K	0.7	0.9	70	0.6	0.8
Al	K	1.9	3.5	696	0.1	0.1
Si	K	2.4	4.7	895	0.1	0.2
Cl	K	0.2	0.4	49	0.1	0.1
Fe	K	0.1	0.4	4	0.1	0.3
Ta	M	0.0	0.0	0	---	---

Figure 8 shows the EDS of the 10% reinforced polyester composite

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

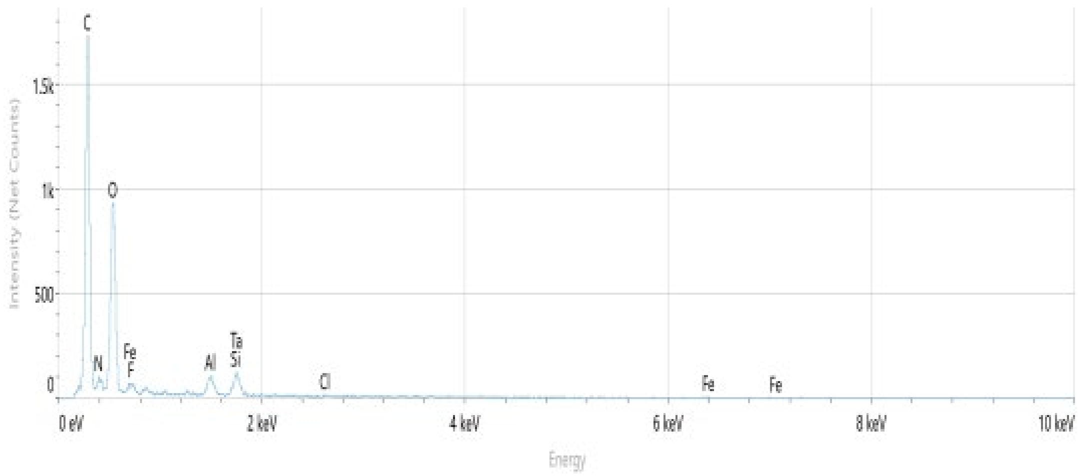

Figure 8: EDS of the 10% reinforced polyester composite

Table 3 shows the EDS of the 15% reinforced polyester composite.

Table 3: EDS of the 15% reinforced polyester composite

Element	Line	At. %	Wt. %	Net Counts	At. % Error	Wt. % Error
C	K	55.5	47.0	6 699	0.8	0.7
O	K	41.4	46.8	3 212	1.0	1.1
Al	K	1.1	2.1	273	0.1	0.1
Si	K	1.8	3.6	457	0.1	0.2
Cl	K	0.2	0.5	37	0.1	0.2
Fe	K	0.2	0.6	5	0.1	0.3
Ta	M	0.0	0.0	0	---	---

Figure 9 shows the EDS of the 15% reinforced polyester composite.

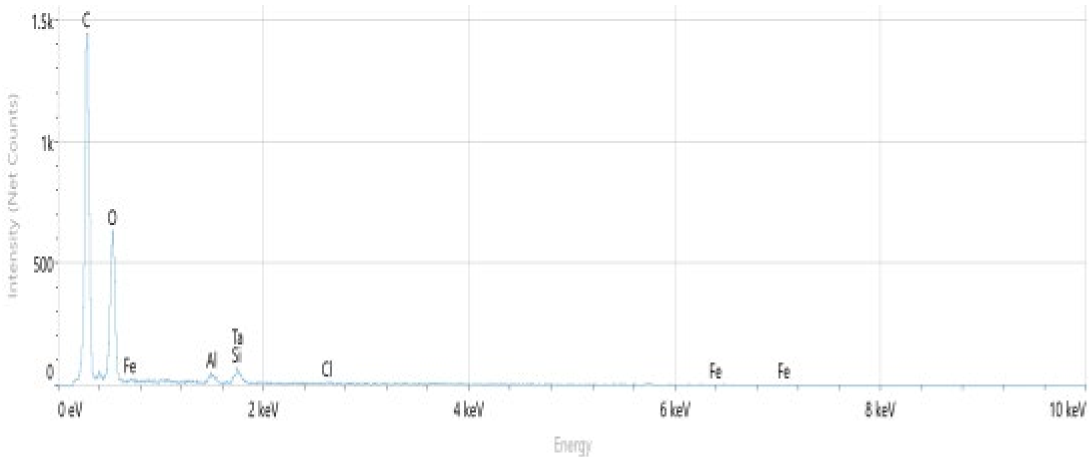

Figure 9: EDS of the 15% reinforced polyester composite

From the EDS, the element presents can be seen looking at the spectra peaks corresponding to the elements making the true compositions of the samples analysed, this is possible because of the fundamental principle that each elements has a unique atomic structure which produces a unique emission spectrum. table 1 which is the EDS for neat polyester showed the weight concentration of carbon to be 35.5 % where that of 10 % and 15% loading in table 2 and 3 is 40.5% and 47% which may be because of the waste tonner presence. Other weight concentration of other Element can also be seen both in the control and the reinforced sample.

4.0 Conclusion

This study demonstrated that reinforcing polyester composites with waste toner powder significantly enhances their mechanical and thermal properties. The incorporation of 15% filler loading yielded the highest tensile strength and optimal thermal stability, outperforming both lower (10%) and higher (20%) loadings. The improved tensile, flexural, and impact strengths indicate that the composites are suitable for load-bearing applications in

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025

industries such as automotive, aerospace, construction, and consumer electronics. Additionally, the enhanced thermal resistance demonstrates their potential for application in electrical insulation, electronic packaging, and components exposed to elevated temperatures. Beyond the technical benefits, this research emphasizes the environmental relevance of utilizing waste toner powder as a reinforcement material. Repurposing this waste stream not only promotes sustainable waste management but also the ideas of a circular economy, offering eco-friendly pathways for material development.

Future research should aim to optimize filler loading to balance mechanical strength, toughness, and processbility, as well as to explore compatibility with alternative polymer matrices. Long-term durability assessments under various service conditions, together with advanced modifications such as nanoscale enhancements for flame retardancy or electrical conductivity, are recommended to further expand the scope of industrial applications.

Conflict of Interest: There is no conflict of interest.

Acknowledgment

The authors wish to acknowledge the support and sponsorship of TETFUND, partly for this research, through their IBR grant 2024

References

[1] S. Hammani, A. Barhoum, and S. Nagarajan, "Toner waste powder (TWP) as a filler for polymer blends (LDPE/HIPS) for enhanced electrical conductivity," *Materials*, vol. 12, no. 19, p. 3062, 2019, doi: 10.3390/ma12193062.

[2] M. Gargol, S. Rónka, and B. Podkościelna, "The application of waste toner material as a filler for the synthesis of composites based on Epidian® 5," *Physicochem. Probl. Miner. Process.*, vol. 58, no. 2, art. no. 146358, 2022, doi: 10.37190/ppmp/146358.

[3] M. Parthasarathy, "Challenges and emerging trends in toner waste recycling," *Recycling*, vol. 6, no. 3, p. 57, 2021, doi: 10.3390/recycling6030057.

[4] M. I. Shahib, G. C. Dsouza, and R. P. Vijayakumar, "A review on end-of-life waste toner powder: recovery, utilization and upcycling," Waste Management, vol. 204, p. 114911, 2025, doi: 10.1016/j.wasman.2025.114911.

[5] V. Phunpeng, K. Saensuriwong, and T. Kerdphol, "Comparative Manufacturing of Hybrid Composites with Waste Graphite Fillers for UAVs," Materials, vol. 15, no. 19, art. no. 6840, 2022, doi: 10.3390/ma15196840.

[6] M. Gargol, T. Klepka, Ł. Klapiszewski, and B. Podkościelna, "Synthesis and thermo-mechanical study of epoxy resin–based composites with waste fibers of hemp as an eco-friendly filler," *Polymers*, vol. 13, no. 4, p. 503, 2021, doi: 10.3390/polym13040503.

[7] S. Lazăr, D. Dobrotă, R.-E. Breaz, and S.-G. Racz, "Eco-Design of polymer matrix composite parts: A review," *Polymers*, vol. 15, no. 17, p. 3634, 2023, doi: 10.3390/polym15173634.

[8] C. Bogiatzidis, "Thermoset polymer matrix composites of epoxy (construction and demolition waste-based)," Polymers, vol. 13, no. 5, 2021, doi: 10.3390/polym13050644.

[9] V. K. Nimmagadda, P. S. Reddy, and A. K. Reddy, "Investigation of industrial waste utilization: Effect of fly ash fraction on mechanical properties of unsaturated polyester composites," J. Polymer Eng., vol. 34, no. 3, pp. 319–341, 2014, doi: 10.1515/polyeng-2013-0341.

[10] A. Pattanaik, A. Chand, and H. Jain, "Influence of curing condition on thermo-mechanical behaviour of fly ash filled unsaturated polyester composites," *Compos. Part B: Eng.*, vol. 165, pp. 462–474, 2019, doi: 10.1016/j.compositesb.2019.03.039.

[11] M. S. Sreekanth, V. A. Bambole, S. T. Mhaske, and P. A. Mahanwar, "Effect of particle size and concentration of flyash on properties of polyester thermoplastic elastomer composites," *J. Miner. Materials Characterization Eng.*, vol. 8, no. 3, pp. 237–248, 2009, doi: 10.4236/jmmce.2009.83021.

[12] G. Gañán, F. López, D. Gómez, and A. Rodríguez, "The evolution and future trends of unsaturated polyester resin (UPR)," Polymers, vol. 15, no. 8, p. 1705, 2023, doi: 10.3390/polym15081705.

[13] I. Haider, M. A. Baloch, M. Rafiq, and S. U. Rehman, "Investigation of dielectric, mechanical, and thermal properties of fly ash–reinforced polypropylene composites," Polymers, vol. 15, no. 8, p. 1706, 2023, doi: 10.3390/polym15081706.

[14] K. T. Varughese, P. Sudarshan, S. K. Bose, and S. Ramakrishnan, "Fly ash as fine aggregate in polyester-based polymer concrete," Cement and Concrete Research, vol. 26, no. 8, pp. 1165–1175, 1996, doi: 10.1016/0008-8846(96)00053-4.

[15] A. A. M. Fadiel, N. S. Mohammed, A. B. Abdul Rahman, E. A. B. Ali, T. Abu-Lebdeh, and F. I. T. Petrescu, "Effect of fly ash on mechanical properties of polymer resin grout," *Biomimetics*, vol. 8, no. 5, p. 392, 2023, doi: 10.3390/biomimetics8050392.

[16] S. Hammani, A. Barhoum, and S. Nagarajan, "Toner waste powder (TWP) as a filler for polymer blends (LDPE/HIPS) for enhanced electrical conductivity," Materials, vol. 12, no. 19, p. 3062, 2019, doi: 10.3390/ma12193062.

[17] E. Peşman, A. Dönmez Çavdar, and S. Boran Torun, "The investigation of the mechanical, thermal and physical properties of using waste toner/MCC/old newspaper fiber in polypropylene hybrid composites," Polymer Composites, vol. 45, no. 16, pp. 14757–14769, 2024, doi: 10.1002/pc.28797.

[18] S. Zahi, D. Daud, *"Enhanced Properties of Fly Ash-Reinforced Unsaturated Polyester Composites," International Journal of Materials Engineering Innovation*, vol. 4, nos. 3-4, pp. 241-257, October 2013. doi: 10.1504/IJMATEI.2013.057151

[19] K. Moraczewski, "Versatile polypropylene composite containing post-printing process waste as filler," *Polymers*, vol. 14, no. 2, 2022, doi: 10.3390/polym14020234.

[20] E. Moland, "Mechanical, electrical and thermal properties of Nylon-66 / fly ash composites: Effect of fly ash," Organic Polym. Mater. Res., vol. 4, no. 2, 2022, doi: 10.30564/opmr.v4i2.5233. journals.bilpubgroup.com+1

[21] M. S. Sreekanth, S. Joseph, S. T. Mhaske, et al., "Effects of mica and fly ash concentration on the properties of polymer composites," *J. Composite Mater.*, vol. 45, no. 17, pp. 1811–1820, 2011, doi: 10.1177/0021998310389291.

[22] T. Chaowasakoo and N. Sombatsompop, "Mechanical and morphological properties of fly ash / epoxy composites using conventional thermal and microwave curing methods," *Compos. Sci. Technol.*, vol. 67, no. 11–12, pp. 2282–2291, 2007, doi: 10.1016/j.compscitech.2007.06.016.

[23] A. D. Çavdar, B. Yılmaz, M. Ülker, and Z. Öztürk, "Effect of waste toner powder on the performance of microcrystalline-cellulose/talc reinforced polypropylene hybrid composites," Polymer Composites, vol. 45, no. 2, pp. 802–815, 2024, doi: 10.1002/pc.27832.

[24] Z. Guo, H. Zhou, and X. Zhang, "New recyclable and self-healing elastomer composites using waste from toner cartridges," Composites Science and Technology, vol. 244, art. no. 110981, 2023, doi: 10.1016/j.compositesa.2023.110981.

[25] K.-Y. Chen, M. Yan, K.-H. Luo, Y. Wei, and J.-M. Yeh, "Comparative studies of the dielectric properties of polyester imide composite membranes containing hydrophilic and hydrophobic mesoporous silica particles," *Materials*, vol. 16, no. 1, p. 140, 2023, doi: 10.3390/ma16010140.

[26] V. Phunpeng, K. Saensuriwong, and T. Kerdphol, "Comparative manufacturing of hybrid composites with waste graphite fillers for UAVs," Materials, vol. 15, no. 19, art. no. 6840, 2022, doi: 10.3390/ma15196840.

[27] F. I. T. Petrescu, "Mechanical, electrical and dielectric performance of polymer composites with industrial by-products (fly ash, red mud, silica fume, carbon black, etc.)," Polymers, vol. 15, 2023, art. no. 1706, doi: 10.3390/polym15081706.

[28] H. Bensalah, K. Gueraoui, H. Essabir, D. Rodrigue, R. Bouhfid, and A. el Kacem Qaiss, "Mechanical, thermal, and rheological properties of polypropylene hybrid composites based on clay and graphite," J. Composite Materials, vol. 51, no. 25, pp. 3563–3576, 2017, doi: 10.1177/0021998317690597.

[29] D. Ndiaye, L. M. Matuana, S. Morlat-Therias, L. Vidal, A. T. Adams Tidjani, and J.-L. Gardette, "Thermal and mechanical properties of polypropylene/wood-flour composites," J. Appl. Polymer Sci., vol. 119, no. 6, pp. 3321–3328, 2011, doi: 10.1002/app.32985.

Received: 17/09/2025; Revised: 08/10/2025; Accepted: 12/10/2025; Published: 23/10/2025