Analysis On Thermal Conductivity of PLA- Based 3d Printed Composites

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***Abstract:** This research paper focuses on the thermal and mechanical behavior of carbon fiber-reinforced PLA and PETG composites fabricated using Fused Filament Fabrication (FFF). Specimens were prepared under varying printing parameters and evaluated for thermal conductivity and tensile properties. PETG-based composites demonstrated higher average thermal conductivity (0.5818 W/mK) and effusivity (932.4 $Ws^{0.5}/m^2K$), while PLA composites showed superior tensile strength and stiffness. The results emphasize the importance of optimizing printing parameters to tailor composite performance for engineering applications involving thermal management and mechanical reliability.*

***Keywords:** 3D printing, Fused Filament Fabrication, Thermal conductivity, Tensile strength*

1. INTRODUCTION

Additive Manufacturing (AM), more popularly known as 3D printing, has revolutionized the way components are designed, developed, manufactured in engineering applications across various industries such as aerospace, automotive, drones, biomedical and consumer electronics.Fused Filament Fabrication (FFF) is the most widely adopted due to its simplicity, affordability, and versatility. The performance of printed components is inherently dependent on the properties of the base materials and the printing parameters used. Polylactic acid (PLA) and polyethylene terephthalate glycol-modified (PETG) are two widely used thermoplastics in FFF due to their biodegradability, ease of printing, and moderate mechanical strength. Carbon fiber reinforcement polymers (CFRPs) is known to improve the thermal and mechanical characteristics.

The mechanical properties of 3D printed parts made of PLA composites filaments have studied extensively in literature. According to some studies, PLA based materials enhanced tensile, youngs modulus and thermal conductivity also. The of 3D printing parameters such as layer height, infill density and printing speed can significantly affects on the inter-layer adhesion, porosity, and fiber orientation.

2. LITERATURE REVIEW

Vasiliki et.al studied the effect of Printing Speed and Layer Height on Geometrical Accuracy of FDM-Printed Resolution Holes of PETG Artifacts. They showed that lower layer heights and moderate print speeds yielded higher geometric fidelity, especially in fine-resolution holes. This highlights the sensitivity of thermoplastic behavior to process variables [1]. Khalifa Almansoori et.al have studied the effect of layer height, print speed and cell geometry on mechanical properties of marble PLA based 3D printed parts. Their mechanical tests showed that hexagonal structures offered superior stiffness, and the performance was strongly dependent on optimized slicing parameters. This aligns with the structural role of infill patterns in load distribution. [2]. Ahmad Adnan Bin Abu Bakar et.al studied the study of mechanical properties of poly(lactic) acid PLA-based 3D printed filament under temperature and environmental conditions. the study concluded that increased ambient temperature leads to deterioration in tensile strength, emphasizing the need for thermal reinforcement in functional applications. [3]. Laszlo Lendvai et.al studied experimental study on the effect of filament-extrusion rate on the structural, mechanical and thermal properties of material extrusion 3D-printed polylactic acid (PLA) products. Higher extrusion rates enhanced thermal transport due to improved fiber alignment and inter-layer adhesion, a principle directly applicable to carbon-reinforced PLA[4]. Rui Guo et.al studied electrical and Thermal Conductivity of Polylactic Acid (PLA)-Based Biocomposites by Incorporation of Nano-Graphite Fabricated with Fused Deposition Modeling. Their experimental results demonstrated a significant increase in conductivity, showing the feasibility of using carbon-based fillers for multi-functional 3D printed materials [5].

Giovanni spinelli et.al studied the experimental and simulation studies of temperature effect on thermophysical properties of graphene-based polylactic acid. Their findings indicated a consistent increase in thermal conductivity with temperature, validating the role of graphene in improving heat transport in printed components [6]. Patrizia lamberti evgeni ivanov et.al nanocarbon/poly(lactic) acid for 3D printing: Effect of fillers content on electromagnetic and thermal properties. By varying filler content, they were able to control both electromagnetic shielding and thermal properties, showcasing the multifunctional potential of these systems in electronic and aerospace applications [7]. Sebastian gradinaru et.al studied analysis of the anisotropy for 3d printed pla parts usable in medicine. Their results underlined the importance of print orientation in determining strength and stiffness, particularly for patient-specific implants [8]. Giovanni Spinelli, Rumiana Kotsilkova Radost Ivanova, et.al studied dielectric spectroscopy and thermal properties of poly(lactic) acid reinforced with carbon-based particles: Experimental study and design theory. Their work combined dielectric spectroscopy with thermal measurements, indicating enhanced performance in both thermal conductivity and electromagnetic shielding [9]. Anna Lapi nskaa et.al studied architecture influence on acoustic performance, emi shielding, electrical and thermal, properties of 3d printed pla/graphite/molybdenum disulfide composites. They examined how different internal architectures in PLA composites affected multiple properties, including acoustic behavior, EMI shielding, and heat conductivity. The addition of molybdenum disulfide and graphite helped achieve a balance between weight and functional efficiency[10].

Ignazio Blanco et.al studied specific heat capacity and thermal conductivity measurements of pla-based 3d-printed parts with milled carbon fiber reinforcement. Their data supported the potential of carbon fibers to tailor the heat transfer performance of 3D printed parts for thermal-sensitive designs[11]. Bartolomeo Coppola et.al studied 3dprinting of pla/clay nanocomposites: Influence of printing temperature on printed samples properties. Optimized thermal parameters were crucial for achieving uniform dispersion and higher mechanical integrity[12]. Eda Hazal Tümer and Husnu Yildirim Erbil et.al studied extrusion-based 3d printing applications of pla composites: A review- they reviewed PLA composites in extrusion-based 3D printing. Their comprehensive work categorized composite enhancements into mechanical, thermal, and biodegradability domains, offering a roadmap for further exploration [13]. Rui Guo et.al studied preparation and characterization of 3d printed pla-based conductive composites using carbonaceous fillers by masterbatch melting method. The prepared materials showed promise in EMI shielding and sensor applications, driven by superior filler dispersion [14]. Mohammed Al-Rubaiai et.al studied characterization of a 3D-printed conductive pla material with electrically controlled stiffness. They investigated electrically tunable PLA materials, where conductivity was not only high but controllable via external signals. Such advancements open pathways for smart actuators or adaptive components [15].

Evgeni Ivanov et.al studied pla/graphene/mwcnt composites with improved electrical and thermal properties suitable for FDM 3Dprinting applications. Their samples showed marked improvements in both electrical and thermal properties, making them ideal for high-performance printed parts [16]. P. Maroti, et.al studied differential thermal analysis of the antibacterial effect of pla-based materials planned for 3d printing. This work combines biocompatibility with mechanical resilience, crucial for patient-specific devices [17]. Mvinyas et.al studied experimental evaluation of the mechanical and thermal properties of3dprintedplaanditscomposites. Their experiments confirmed that thermal performance improves significantly with filler addition, though mechanical gains depend on fiber orientation and interfacial bonding [18]. Danijela Pezer et.al studied experimental study of tensile strength for 3d printed specimens of hi-pla polymer material on in-house tensile test machine. They focused on tensile behavior of high-impact PLA specimens tested on a custom-built machine. The study contributed valuable experimental protocols for low-cost mechanical testing. [19]. Ritchie et.al studied the conflicts between strength and toughness. They provided fundamental insight into the trade-off between strength and toughness, relevant when balancing stiffness and fracture resistance in reinforced PLA and PETG [20]. Callister et.al studied materials science and engineering: An Introduction- offered foundational knowledge in materials science, which supports the interpretation of mechanical and thermal behavior in additive manufacturing.[21]. Thesan Appalsamy et.al. Investigated how infill density and print orientation influence tensile strength in 3D printed parts. Their results reinforced the conclusion that anisotropic properties are inherent to layer-based manufacturing.[22]

From the literature review it can be observed that significant influence of material selection, filler reinforcement, and Fused Filament Fabrication (FFF) process parameters on the thermal and mechanical performance of 3D printed components. Studies on PLA and PETG composites reveal that the process of carbon-based fillers such as graphite, graphene and milled carbon fibers substantially improves thermal conductivity and mechanical strength. Moreover, factors such as layer height, print speed, infill density, and print orientation are found to play a critical role in defining the anisotropic behavior and interlayer bonding quality of the printed parts. On the other hand, PETG and modified PLA composites exhibit superior thermal conductivity, ductility, and dimensional stability, which are beneficial for thermal analysis.

This study aims to experimentally analyzing carbon fiber-reinforced PLA and PETG samples under controlled printing conditions, thereby contributing valuable comparative data to guide material and process selection in functional 3D printing applications.

3. MATERIALS& METHODOLOGY

PLA-Carbon and PETG-Carbon filaments were used, each embedded with short carbon fibers to enhance strength and conductivity.

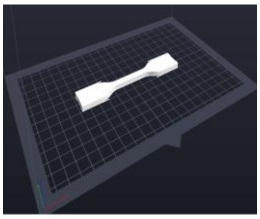
3.1 3D Printing

3D printing is also known as Additive Manufacturing(AM), it is used to create three-dimensional objects by depositing material layer by layer, based on a digital model. Each layer clearly seen as thin slicer in the horizontal direction. Step by step each layer can be created in a required object. 3D Printing is effectively used in manufacturing prototypes, robotics, bio medicals, aerospace.

Fig.1 3D Printer

3.1.1 Working of 3D Printing

In the first step, is to create a object in a Tinker cad software with a required dimensions are width = 6 mm, thickness = 4 mm, length = 40 mm. Tinker cad verifies the errors of the object and gives the out in the STL Files of the design intersections. Next step, the STL files is followed by a software called slicer, which stores the data in the thin sections of the object. Here, PLA carbon and PETG carbon filaments to create designs. The filaments are of dia 1.75mm, by using FDM process (Fused Deposition Method). the printing parameters are layer height, cell geometry, infill density with 6 samples of PLA Carbon and PETG Carbon parts.



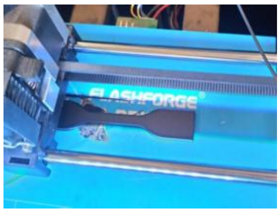


Fig.2 Tensile Test Specimen ASTMD638.stl Fig.3 Working of 3D Printing

3.1.2 3D Printing Setup

- Printer: FlashForge FDM 3D Printer
- Nozzle Temp: 210 °C
- Bed Temp: 40 °C
- Layer Heights: 0.2–0.4 mm
- Infill Densities: 60% and 100%
- Print Speed: 100 mm/s
- Geometry: Honeycomb pattern

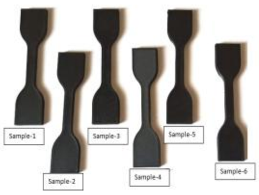


Fig.4 Samples of PLA Carbon Fig.5 Samples of PETG Carbon

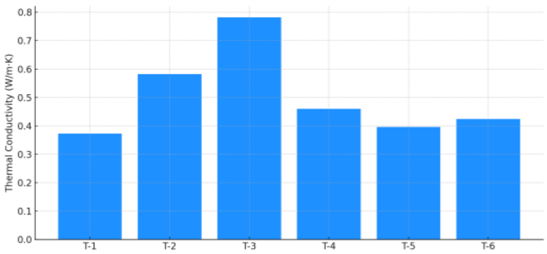
3.2 *Thermal Testing*

Thermal conductivity and effusivity were measured by using a C-Therm Trident system with an MTPS sensor at room temperature (~27 °C), without any contact agents. The MTPS sensor was pre-calibrated using a standard reference material provided by the manufacturer. No additional contact agent was used. The specimen was placed directly on the MTPS sensor, ensuring full surface contact without external pressure or adhesives. The test was initiated through the C-Therm software interface. The time taken to the specimen is 5-10 mins to record the thermal conductivity and thermal effusivity. For one specimen, C-Thermr data records the 5 readings automatically and calculated the average thermal conductivity and thermal effusivity. We calculated 6 samples of PLA Carbon and 6 samples of PETG Carbon with average thermal analysis.

Fig.6 C- THERM (Thermal Analyzer) Fig.7 Working of C-Therm (Thermal Analyzer)

Table.1 Average Thermal readings of PLA Carbon Samples

Sample ID	Avg. Conductivity (W/mK)	Avg. Effusivity ($Ws^{0.5}/m^2K$)	Conductivity RSD (%)	Effusivity RSD (%)	Temp (°C)
T-1	0.3730	727.9	0.4844	0.2493	~28.7
T-2	0.5819	932.9	0.4534	0.2711	~28.1
T-3	0.7819	1120.6	0.6037	0.3865	~27.8
T-4	0.4599	814.4	0.8212	0.4569	~27.4
T-5	0.3961	751.1	0.9248	0.4873	~27.3
T-6	0.4245	779.4	1.1456	0.6195	~27.1



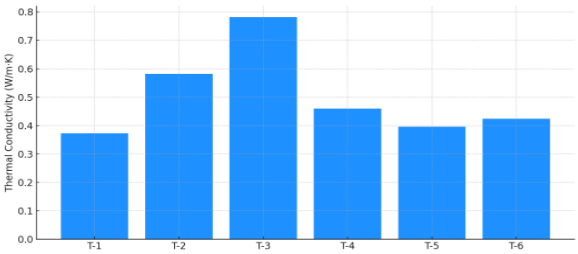
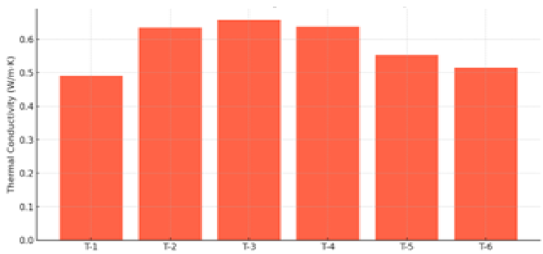


Fig.8 Thermal Conductivity PLA Carbon Samples Graph Fig.9 Thermal Effusivity PLA Carbon Samples Graph

Table.2 Average Thermal readings of PETG Carbon Samples

Sample	Avg. Thermal Conductivity (W/mK)	Avg. Effusivity ($Ws^{0.5}/m^2K$)	Conductivity RSD (%)	Effusivity RSD (%)	Temp (°C)
T-1	0.4918	845.7	1.74	0.99	~26.4
T-2	0.6352	983.7	1.13	0.69	~26.7
T-3	0.6579	1005.1	4.09	2.53	~26.6
T-4	0.6376	986.0	2.97	1.82	~26.8
T-5	0.5528	904.9	1.26	0.74	~26.4
T-6	0.5154	868.7	0.69	0.40	~26.8



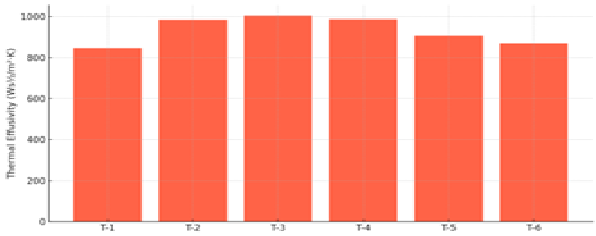


Fig.10 Thermal Conductivity PETG Carbon Samples Graph Fig.11 Thermal Effusivity PETG Carbon Samples Graph

3.3 Mechanical Testing

Tensile tests were carried out per ASTM D638 using specimens of 40 mm × 6 mm × 4 mm dimensions. The strain rate was set at 1 mm/min. Tensile testing is a destructive process which calculates ultimate tensile strength, youngs modulus, yeild strength, ductility of the PLA Carbon and PETG Carbon specimens. Here, a servo-hydraulic machine to testing process. It involves a stress, strain and time of the specimen. The specimen is fitted between the upper jaw and lower jaw of the machine, once the machine is operated the specimen started converted to elongation of the length.

It describes the stress, strain along with time until the specimen breaks (reaches to its ultimate strength). the data records automatically in the system stress versus strain readings of the 6 samples of PLA Carbon and 6 samples of PETG Carbon.

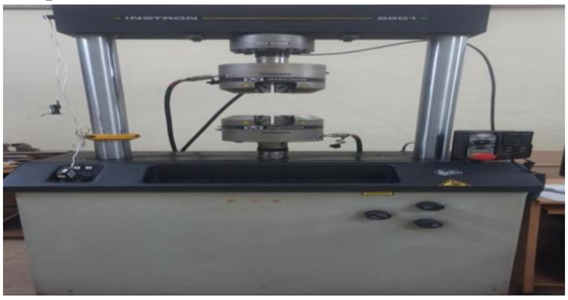


Fig. 12 Universal Testing Machine (Instron)

Fig.13 Testing on PLA Carbon Samples

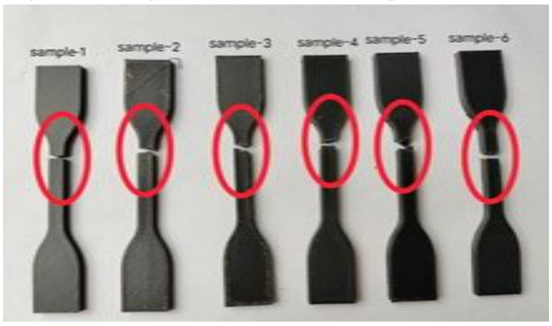


Fig.14 Tensile Test samples of PLA Carbon

Sample	Max Load (N)	UTS (MPa)	Modulus (MPa)	Yield Stress (MPa)	Break Stress (MPa)	Strain at Break (mm/mm)
T-1	635.58	26.48	1753.43	25.00	16.99	0.07399
T-2	678.96	28.29	1869.46	24.73	18.50	0.06445
T-3	601.11	25.05	1839.35	23.55	16.41	0.05821
T-4	666.10	27.75	2081.74	26.38	17.39	0.04829
T-5	558.88	23.29	1606.97	21.97	14.83	0.07869
T-6	666.10	27.75	2081.74	26.38	17.39	0.04829

Table.3 Tensile properties from PLA Carbon samples

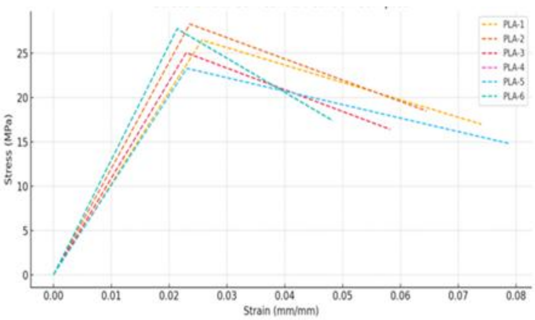


Fig.15 Stress - Strain Curve of PLA Carbon Samples Graph

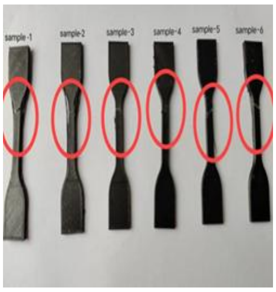


Fig.16 Testing on PETG Carbon Samples

Fig.17 Tensile Test samples of PETG Carbon

Table.4 Tensile properties from PETG Carbon samples

Sample	Max Load (N)	UTS (MPa)	Modulus (MPa)	Yield Stress (MPa)	Break Stress (MPa)	Strain at Break (mm)	Strain @ UTS
T-1	476.87	19.87	1127.49	17.73	4.31	0.08147	0.03205
T-2	409.78	17.07	952.66	15.67	6.21	0.07462	0.03683
T-3	673.05	28.04	1477.77	24.40	17.54	0.05617	0.02896
T-4	560.99	23.37	1206.90	20.35	14.91	0.07044	0.03094
T-5	619.79	25.82	1308.48	21.68	16.29	0.08659	0.04239
T-6	502.21	20.93	1077.16	18.19	13.27	0.05243	0.03102

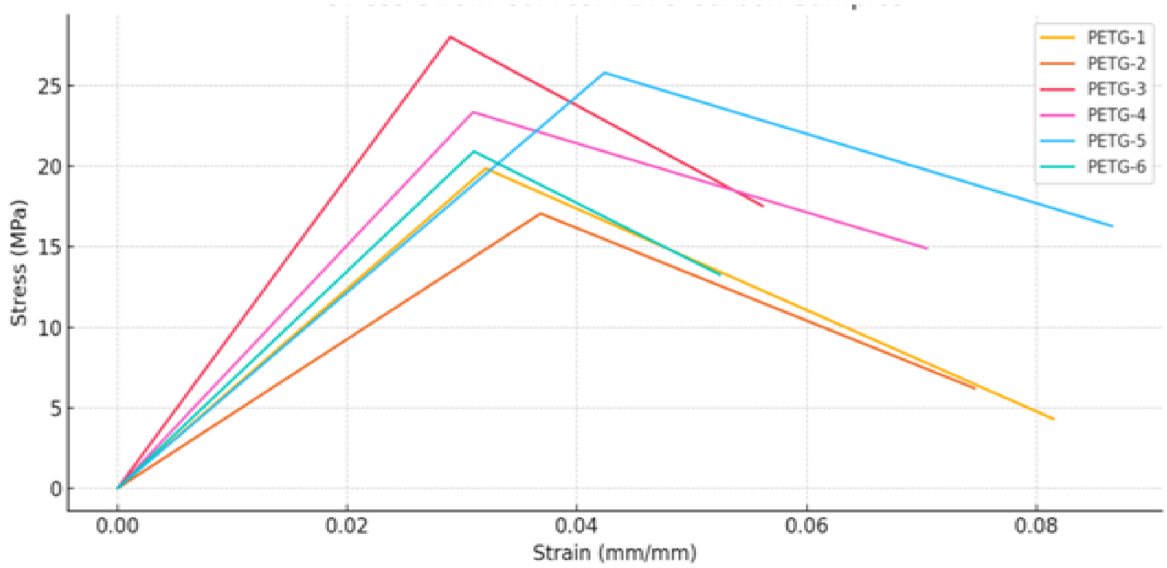


Fig.18 Stress - Strain Curve of PETG Carbon Samples Graph

4. RESULTS

The experimental data for average thermal conductivity, thermal effusivity, and tensile strength of PLA and PETG composites are presented below.

4.1. Thermal analysis comparison:

Table 5. Differenced in Thermal analysis in between PLA Carbon and PETG Carbon Polymers

Material	Average Conductivity	Average Effusivity	General Traits
PLA Carbon	0.5022 W/mK	854.9 $Ws^{0.5}/m^2K$	Lower conductivity, more variability
PETG Carbon	0.5818 W/mK	932.4 $Ws^{0.5}/m^2K$	Better thermal transport performance

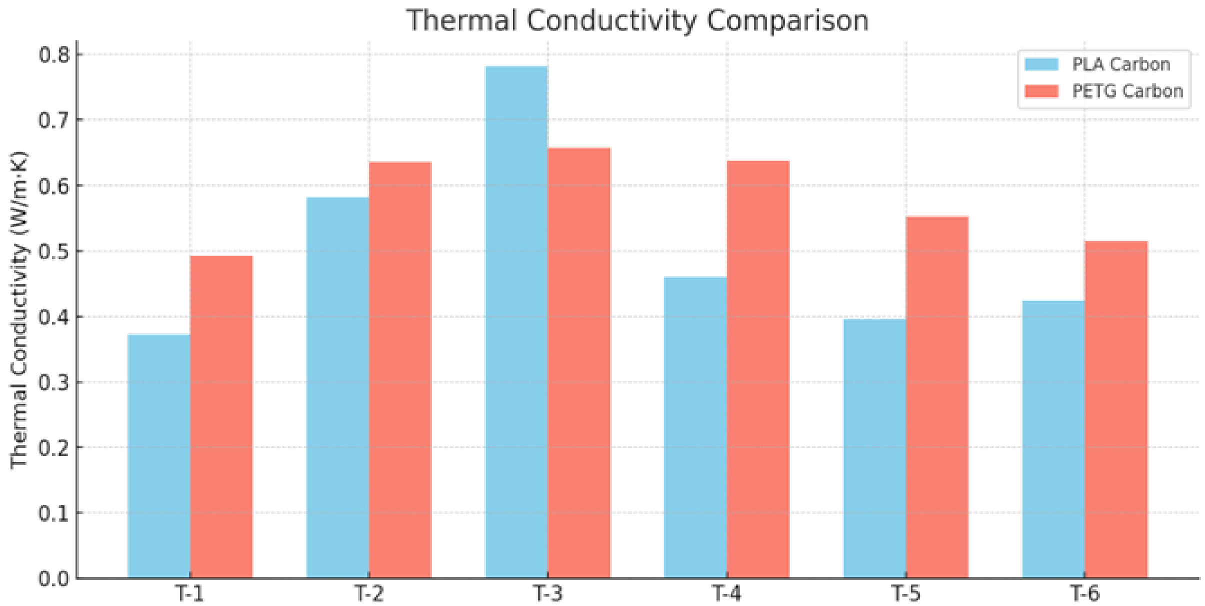


Fig.19 Comparison of thermal conductivity in PLA Carbon and PETG Carbon fibers Graph

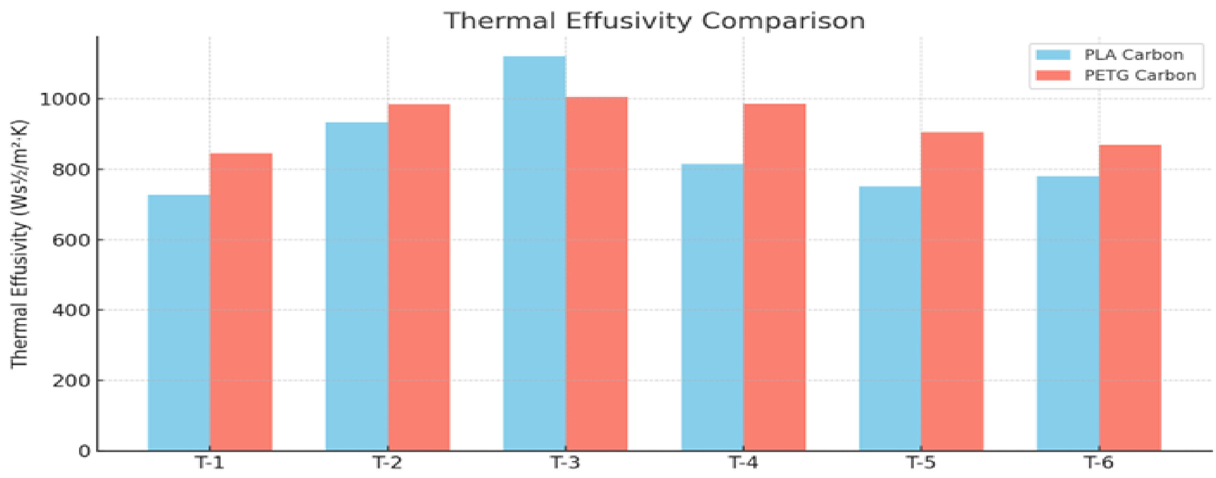


Fig. 20 Comparison of thermal effusivity in PLA Carbon and PETG Carbon fibers Graph

Table 6. outlining the main observations gleaned from the graphs.

Property	PLA Carbon	PETG Carbon	Observation
Thermal Conductivity	Lower in most cases, peak at T-3	Higher overall except T-3	PETG (Overall)
Thermal Effusivity	Lower across all test points except T-3	Higher consistently	PETG

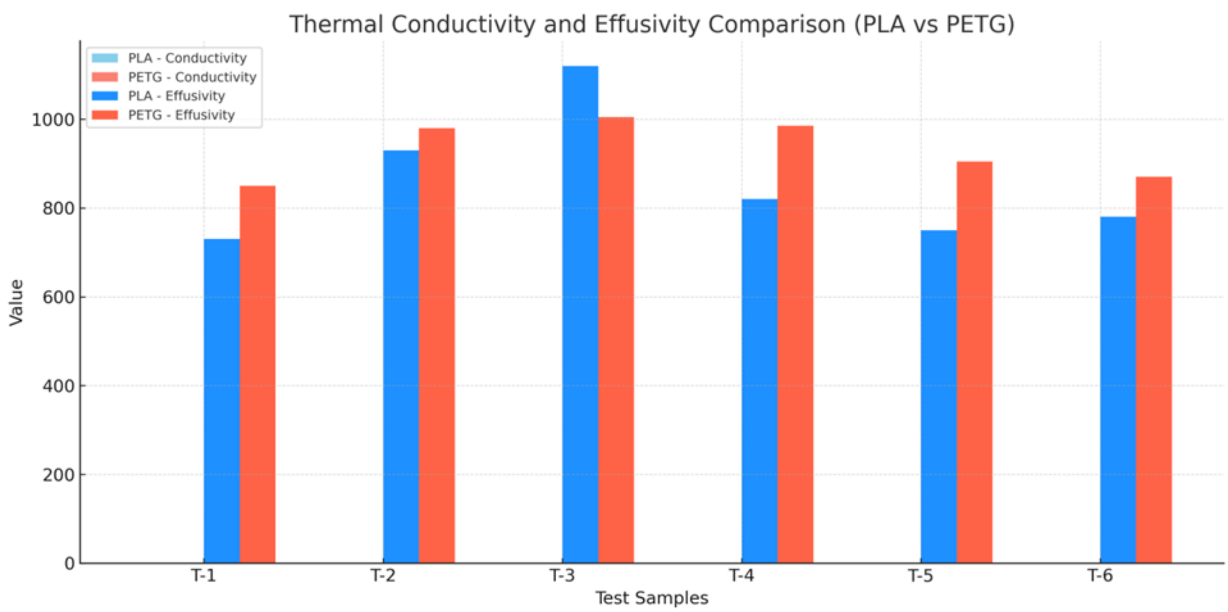


Fig.21 Comparing a PLA Carbon & PETG Carbon, considering all thermal analysis Graph

Table 7. Average Tensile test values

Property	PLA Carbon (Avg)	PETG Carbon (Avg)	Observation
Ultimate Tensile Strength (MPa)	26.45	22.85	PLA is stronger in tension
Young's Modulus (MPa)	1872.45	1191.41	PLA is stiffer
Yield Stress (MPa)	24.67	19.34	PLA has higher yield resistance
Tensile Stress at Break (MPa)	16.92	12.76	PLA handles higher stress before fracture
Strain at Break (mm/mm)	0.06282	0.07029	PETG is more ductile
Strain at UTS (mm/mm)	0.02376	0.03370	PETG elongates more before peak stress

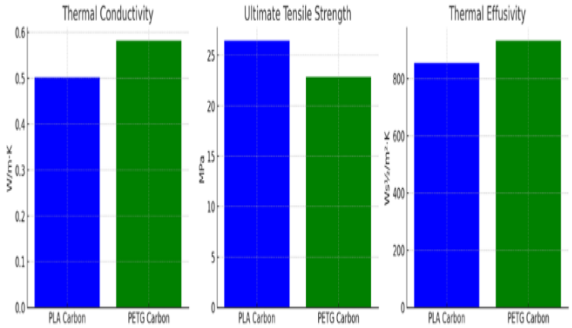


Fig.22 Comparison of thermal conductivity, effusivity, and tensile strength for PLA and PETG Carbon Composites Graph

4. DISCUSSION ON RESULTS

PETG Carbon composites exhibit greater thermal conductivity and effusivity, which is advantageous for heat-spreading applications. However, PLA Carbon composites demonstrate higher tensile strength and stiffness, making them ideal for structural components. The performance variation is also attributed to differences in fiber distribution, bonding quality, and inter-layer adhesion achieved through different printing parameters.

5. CONCLUSION

Both materials exhibit strengths in different domains. PLA Carbon is ideal for rigid and high-strength components, while PETG Carbon is better for applications requiring toughness and moderate thermal performance. The choice of material should be guided by the specific demands of the end-use application.

A comprehensive comparison of PLA Carbon and PETG Carbon polymers in terms of both tensile and thermal properties is made. Tensile testing revealed that PLA Carbon offers higher tensile strength and modulus, making it suitable for rigid structural applications. On the other hand, PETG Carbon exhibits superior ductility and moderate strength, indicating its suitability for applications requiring flexibility and impact resistance. Thermal analysis demonstrated that PETG Carbon has better thermal conductivity and effusivity, enhancing its applicability in heat-dissipating environments. Overall, the findings guide material selection for engineering applications based on mechanical and thermal performance requirements.

REFERENCE

[1] Vasiliki E. Alexopoulou, Ioannis T. Christodoulou and Angelos P. Markopoulos, " Effect of Printing Speed and Layer Height on Geometrical Accuracy of FDM-Printed Resolution Holes of PETG Artifacts", *1st International Electronic Conference on Machines and Applications*, 2022.

[2] Khalifa Almansoori , Salman Pervaiz, "Effect of layer height, print speed and cell geometry on mechanical properties of marble PLA based 3D printed parts", *Smart Materials in Manufacturing,* 2023.

[3] Ahmad Adnan Bin Abu Bakar, Muhammad Zulhilmi Bin Zainuddin, Ahmad Nurhelmy Bin Adam, Ikhwan Syafiq Bin Mohd Noor, Nizam Bin Tamchek, Muhammad Syafiq Bin Alauddin,d, Mohd Ifwat Bin Mohd Ghazali, "The study of mechanical properties of poly(lactic) acid PLA-based 3D printed filament under temperature and environmental conditions", *Materials Today: Proceedings*, 2022.

[4] Laszlo Lendvai, Imre Fekete, Daniele Rigotti, Alessandro Pegoretti. "Experimental study on the effect of filament-extrusion rate on the structural, mechanical and thermal properties of material extrusion 3D-printed polylactic acid (PLA) products", *Springer*, 2024

[5] Rui Guo, Zechun Ren, Hongjie Bi, Min Xu, and Liping Cai., "Electrical and Thermal Conductivity of Polylactic Acid (PLA)-Based Biocomposites by Incorporation of Nano-Graphite Fabricated with Fused Deposition Modeling", *Polymers*, 2019

[6] Giovanni Spinelli, Rosella Guarini, Rumiana Kotsilkov, Vittorio Romano, Todor Batakliev 2, Evgeni Ivanov., "Experimental and Simulation Studies of Temperature Effect on Thermophysical Properties of Graphene-Based Polylactic Acid", *Materials*, 2022

[7] Giovanni Spinelli, Patrizia Lamberti Evgeni Ivanov, Vincenzo Tucci, Dzhihan Menseidov, Carlo Naddeo, Rumiana Kotsilkova, Vittorio Romano, Liberata Guadagno, Renata Adami Polina Kuzhir., "Nanocarbon/Poly(Lactic) Acid for 3D Printing: Effect of Fillers Content on Electromagnetic and Thermal Properties", *Materials,* 2019.

[8] Sebastian gradinaru, Diana tabaras, Dan gheorghe, Daniela gheorghita, Raluca zamfir, Marius VASILESCU, Mircea DOBRESCU,

Gabriel GRIGORESCU, Ioan CRISTESCU., "Analysis Of The Anisotropy For 3d Printed Pla Parts Usable In Medicine", *University of Medicine and Pharmacy Bucharest Romania and University politehnica of Bucharest Romania*, 2019

[9] Giovanni Spinelli, Rumiana Kotsilkova Radost Ivanova, Carlo Naddeo, Evgeni Ivanov and Vittorio Romano., "Dielectric Spectroscopy and Thermal Properties of Poly(lactic) Acid Reinforced with Carbon-Based Particles: Experimental Study and Design Theory", *Polymers*, 2020

[10] Anna Lapi nskaa, Natalia Grochowska, Kamil Cieplak, Paweł Płatek, Paul Wood, Piotr Deuszkiewicz, Anna Duzy nska, Bogna Sztorch, Julia Głowcka, Robert Przekop, Paweł Jozwikf, Tomasz Gołofit, Andrzej Plichta., "Architecture influence on acoustic performance, EMI shielding, electrical and thermal, properties of 3D printed PLA/graphite/molybdenum disulfide composites", *Materials & Design*, 2024

[11] Ignazio Blanco, Gianluca Cicala, Giuseppe Recca and ClaudioTosto., "Specific Heat Capacity and Thermal Conductivity Measurements of PLA-Based 3D-Printed Parts with Milled Carbon Fiber Reinforcement", *Entropy*, 2022

[12] Bartolomeo Coppola, Nicola Cappetti, Luciano Di Maio, Paola Scarfato and Loredana Incarnato., "3DPrinting of PLA/clay Nanocomposites: Influence of Printing Temperature on Printed Samples Properties", *Materials,* 2018

[13] Eda Hazal Tümer and Husnu Yildirim Erbil., "Extrusion-Based 3D Printing Applications of PLA Composites: A Review", *Coatings,* 2021

[14] Rui Guo, Zechun Ren, Xin Jia, Hongjie Bi, Haiying Yang, Tong Ji, Min Xu, and Liping Cai., "Preparation and Characterization of 3D Printed PLA-Based Conductive Composites Using Carbonaceous Fillers by Masterbatch Melting Method", *Polymers*, 2019

[15] Mohammed Al-Rubaiai, Thassyo Pinto, David Torres, Nelson Sepulveda, Xiaobo Tan., "characterization of a 3d-printed conductive pla material with electrically controlled stiffness", *Proceedings of the ASME 2017 Conference on Smart Materials, Adaptive Structures and Intelligent Systems SMASIS2017*, 2017

[16] Evgeni Ivanov, Rumiana Kotsilkova Ricardo K. Donato, Hesheng Xia, Yinghong Chen, Katarzyna Donato, Anna Paula Godoy Clara Silvestre, Sossio Cimmino and Verislav Angelov., "PLA/Graphene/MWCNTComposites with Improved Electrical and Thermal Properties Suitable for FDM 3DPrinting Applications", *Applied Science*, 2019

[17] P. Maroti, B. Kocsis, A. Ferencz, M. Nyitrai, D. Lorinczy., "Differential thermal analysis of the antibacterial effect of PLA-based materials planned for 3D printing", *Journal of Thermal Analysis and Calorimetry*, 2020

[18] MVinyas, SJAthul, DHarursampath and TNguyenThoi., "Experimental evaluation of the mechanical and thermal properties of 3DprintedPLAanditscomposites", *Materials Research Express*, 2019

[19] Danijela Pezer*, Filip Vukas, Marin Buti "Experimental study of tensile strength for 3d printed specimens of hi-pla polymer material on in-house tensile test machine".*Technium Vol. 4, No.10 pp.197-206 (2022)*

[20] Ritchie, R.O. (2011). The conflicts between strength and toughness. Nature Materials, 10(11),817822.

[21] Callister, W.D., & Rethwisch, D.G. (2020). Materials Science and Engineering: An Introduction. *Wiley.*

[22] Thesan Appalsamy, J. Compos. Sci. 2024, Tensile Test Analysis of 3D Printed Specimens with Varying Print Orientation and Infill Density.