© 2019 IJSRSET | Volume 6 | Issue 4 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
International Journal of Scientific Research in Science, Engineering and Technology
doi : 10.32628/IJSRSET

Effect of Hybrid Reinforcements on Hardness and Flexural Properties of 3D-Printed Polymeric Structures

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ABSTRACT : The study explores the impact of hybrid reinforcements, including silicon carbide (SiC) particles (0.5 wt%, 1 wt%, 1.5 wt%) and graphite powder (0.5 wt%), on the mechanical properties of 3D-printed polylactic acid (PLA) structures produced via fused deposition modeling (FDM). Composite filaments were fabricated using a twin-screw extrusion process to ensure uniform dispersion of reinforcements. The study evaluates Shore D hardness and flexural properties of these hybrid composites. Results indicate significant improvements in mechanical properties with increasing SiC content, attributed to the synergistic effects of SiC and graphite reinforcements. The findings underscore the potential of hybrid PLA composites for applications requiring enhanced flexural strength.

Keywords : Hybrid reinforcements, Silicon carbide (SiC), Graphite powder, Mechanical properties, Fused deposition modeling (FDM)

1.0 Introduction

Polylactic acid (PLA), a biodegradable thermoplastic derived from renewable sources, has gained prominence in 3D printing applications due to its ease of processing, eco-friendliness, and good mechanical properties. However, its inherent brittleness and moderate strength limit its use in demanding engineering applications. Enhancing PLA's mechanical properties through reinforcements offers a promising solution to expand its applicability. Hybrid reinforcements, such as silicon carbide (SiC) and graphite powder, provide a unique approach to improve strength, hardness, and wear resistance. SiC particles, known for their exceptional hardness and thermal stability, enhance the composite's structural integrity. Meanwhile, graphite, with its lubricating properties, reduces friction and enhances toughness. The combination of these reinforcements in PLA offers the potential to achieve superior mechanical performance suitable for advanced engineering applications, including automotive, aerospace, and biomedical sectors[1-5]. Salem et al. [6] investigated the additive manufacturing of polymer composites using 3D printing technologies, focusing on materials like ABS and PLA with carbon fiber and carbon nanotube reinforcements. Their study highlighted the impact of reinforcements and 3D printing variables on microstructure and mechanical properties. The results demonstrated that carbon nanotubes significantly improved the strength and elastic modulus of ABS. They also observed consistent trends in elastic modulus across dynamic and mechanical testing, emphasizing the influence of layer height on mechanical performance. The research underscored the need for systematic studies to understand the relationship between reinforcements, processing conditions, and material behavior. Yu et al. [7] explored the incorporation of graphene and carbon nanotubes into PLA-based composites for FDM applications. By repeated melt blending, filaments with graphitic nano-fillers were produced and tested for rheological, thermal, mechanical, and electrical properties. Results revealed that filament diameter significantly affected stiffness and strength of FDM products. Additionally, PLA composites with graphene or CNT exhibited drastically improved electrical conductivity, reaching ~10–1 S/m. The study also found that the mechanical properties depended not just on composition but also on the structural parameters of FDM products, such as raster angles. This research emphasized the dual importance of material composition and processing parameters in achieving functionalized materials. Despite considerable research on reinforced PLA composites, limited studies have focused on hybrid reinforcements using SiC and graphite. Furthermore, while several studies investigate the effects of single reinforcements, the synergistic impact of hybrid fillers remains largely unexplored. This research aims to bridge this gap by systematically evaluating the mechanical properties of PLA reinforced with varying amounts of SiC particles (0.5 wt%, 1 wt%, and 1.5 wt%) and a constant 0.5 wt% graphite powder. The objectives of the study are threefold: first, to investigate the Shore D hardness of PLA composites reinforced with SiC particles (0.5 wt%, 1 wt%, 1.5 wt%) and 0.5 wt% graphite powder; second, to evaluate the flexural properties of hybrid PLA composites under varying SiC reinforcement levels; and third, to analyze the effect of hybrid reinforcements on the dispersion and morphology of PLA composites.

2.0 Experimental

The PLA used in this study was a high-purity commercial-grade material, widely recognized for its consistent printability and biodegradability, making it an ideal choice for 3D printing applications. As reinforcements, nano-sized silicon carbide (SiC) particles with an average size of 50 nm were selected for their exceptional hardness and thermal resistance. Graphite powder, characterized by a particle size of 10 μm, was incorporated as a secondary reinforcement due to its ability to enhance toughness and reduce wear through its inherent lubricating properties. To ensure the uniform dispersion of these reinforcements within the PLA matrix, a twin-screw extrusion process was employed, which effectively minimized agglomeration and promoted homogeneity. The SiC particles exhibited a spherical morphology with smooth surfaces, which contributed to their even distribution within the PLA matrix, while the graphite powder demonstrated a layered structure with high aspect ratios, enhancing its compatibility and reinforcing the matrix with its lubricating and stress-dissipating properties.

The fabrication process began with compounding PLA, SiC, and graphite powders using a twin-screw extruder, operating within a controlled temperature range of 180–200 °C. This ensured proper mixing and dispersion of reinforcements into the PLA matrix. The compounded material was pelletized and subsequently extruded into 1.75 mm diameter filaments, suitable for use in fused deposition modeling (FDM). Using a commercial FDM printer, specimens were printed with optimized parameters, including a nozzle temperature of 210 °C, a bed temperature of 60 °C, and a print speed of 60 mm/s, resulting in uniform and defect-free samples.

The Shore D hardness of the 3D-printed specimens was evaluated in accordance with ASTM D2240 standards. A calibrated indenter was applied to the specimen's surface under a standardized load, and hardness values were recorded using a durometer. Each specimen was conditioned at room temperature for 24 hours before testing, and three readings were taken for each sample to ensure consistency and reliability of the results. For flexural properties, a three-point bending test was conducted following ASTM D790 standards. Rectangular specimens with dimensions of 80 mm × 10 mm × 4 mm were printed and tested on a universal testing machine at a crosshead speed of 1.28 mm/min. Flexural strength were calculated using the load-deflection data obtained from the tests, with each test repeated five times to ensure accuracy and reproducibility. This comprehensive fabrication and testing approach provided valuable insights into the mechanical behavior of PLA composites reinforced with SiC and graphite, figure-1 shows (a) Dimension of the Flexure test & (b) Flexural test specimens of PLA.

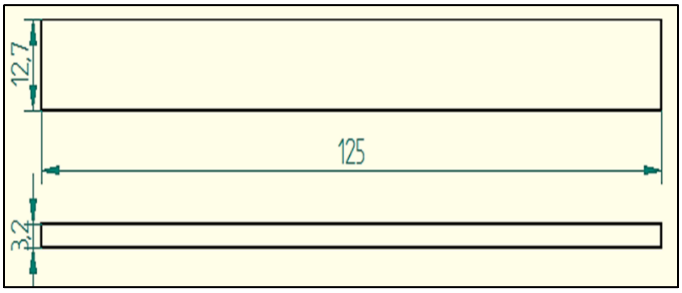

Figure-1(a). Dimension of the Flexure test

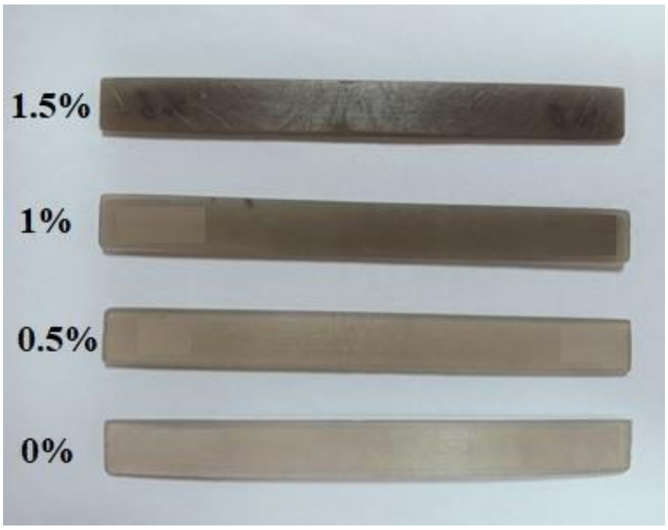

Figure-1(b): Flexural test specimens of PLA.

3.0 Results and Discussions:

Fig.2 illustrates the Shore D hardness values of neat PLA and PLA composites reinforced with 0.5 wt%, 1.0 wt%, and 1.5 wt% SiC along with 0.5 wt% graphite. Neat PLA exhibited the lowest hardness value of approximately 76 Shore D units. Upon reinforcement with 0.5 wt% SiC and 0.5 wt% graphite, the hardness increased to 80 Shore D units, representing a 5.3% improvement. This increase can be attributed to the addition of SiC particles, which are known for their exceptional hardness, and the uniform dispersion of reinforcements in the PLA matrix. The composite containing 1.0 wt% SiC and 0.5 wt% graphite showed further improvement, achieving a hardness of 83 Shore D units, representing a 9.2% increase compared to neat PLA. This is due to better interfacial bonding between the PLA matrix and the reinforcements, which enhances load transfer during the hardness test. The maximum hardness was observed in the composite with 1.5 wt% SiC and 0.5 wt% graphite, reaching 86 Shore D units, a 13.2% improvement over neat PLA [8-10]. Fig.3 represents the flexural strength of neat PLA and its composites. Neat PLA displayed the lowest flexural strength of approximately 55 MPa. The composite with 0.5 wt% SiC and 0.5 wt% graphite exhibited a flexural strength of 60 MPa, showing an improvement of 9.1%. The increase can be attributed to the reinforcement effect of SiC particles, which enhance stiffness, and graphite, which improves stress distribution. The composite containing 1.0 wt% SiC and 0.5 wt% graphite demonstrated a further enhancement, achieving a flexural strength of 64 MPa, a 16.4% improvement. This is due to the homogenous dispersion of SiC and graphite within the matrix, which improves load-bearing capabilities and reduces crack propagation. The composite reinforced with 1.5 wt% SiC and 0.5 wt% graphite showed the highest flexural strength of 68 MPa, representing a 23.6% increase compared to neat PLA [11-12].

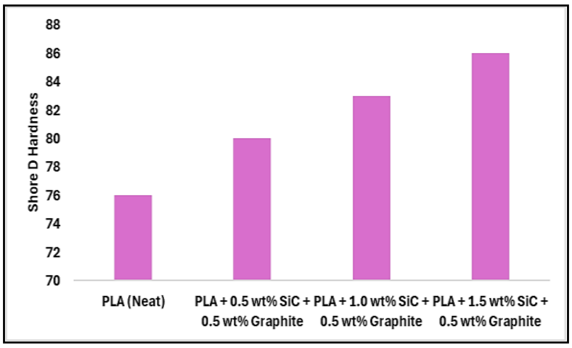

Fig.2 Variation of Shore D Hardness with reinforcement

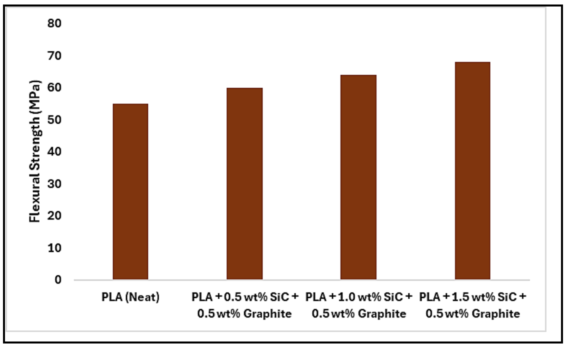

Fig.3 Variation of flexural strength with reinforcements

4.0 Conclusions

1. The Shore D hardness of PLA composites improved significantly with the addition of SiC and graphite reinforcements. The composite with 1.5 wt% SiC and 0.5 wt% graphite showed a 13.2% improvement in hardness compared to neat PLA, reaching a value of 86 Shore D units.
2. Flexural strength increased consistently with reinforcement content. The composite containing 1.5 wt% SiC and 0.5 wt% graphite exhibited a maximum flexural strength of 68 MPa, a 23.6% improvement over neat PLA.
3. The synergistic effect of SiC and graphite resulted in improved mechanical properties, as SiC provided hardness and stiffness while graphite enhanced toughness and stress distribution.
4. Uniform dispersion of reinforcements in the PLA matrix through the FDM process ensured effective load transfer, which contributed to the observed enhancements in mechanical properties.

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