Mechanical characterization of 3D-Printed carbon fiber-reinforced polymer composites and pure polymers: Tensile and compressive behavior analysis

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ABSTRACT

Fused deposition modeling (FDM) 3D printing is widely utilized for producing thermoplastic components with functional purposes. However, the inherent mechanical limitations of pure thermoplastic materials necessitate enhancements in their mechanical characteristics when employed in certain applications. One strategy for addressing this challenge involves the incorporation of reinforcement materials, such as carbon fiber (CF), within the thermoplastic matrix. This approach leads to the creation of carbon fiber-reinforced polymer composites (CFRPs) suitable for engineering applications. The utilization of CFRPs in 3D printing amalgamates the benefits of additive manufacturing, including customization, cost-effectiveness, reduced waste, swift prototyping, and accelerated production, with the remarkable specific strength of carbon fiber. This study encompasses tensile and compressive testing of distinct material compositions: recycled polylactic acid (rPLA), PLA enriched with 10 wt.% carbon fiber, pristine polyethylene terephthalate glycol (PETG), and PETG bolstered with 10 wt.% carbon fiber. Tensile tests adhere to the ASTM D3039 standard for specimens of rectangular shape, while the ASTM D695 standard governs the compressive testing procedures. Additionally, an inquiry into the influence of the primary 3D printing build orientation parameter on the tensile and compressive strengths of diverse materials was conducted. The outcomes reveal that rPLA exhibits superior mechanical properties in both tensile and compressive tests, irrespective of flat or on-edge build orientations. In the context of tensile strength analysis, it is noteworthy that rPLA demonstrated a superior performance, surpassing CFPLA by 30% in flat orientation and exhibiting a remarkable 39.2% advantage in on-edge orientation. Moreover, PLA reinforced with carbon fiber exhibits superior tensile and compressive properties compared to its PETG counterpart. A comparative analysis between CFPLA and CF-PETG indicates that CF-PLA demonstrates higher tensile strengths, with increases of 26.6 and 27.6% for flat and on-edge orientations, respectively. In the context of compressive strength analysis, rPLA surpassed CFPLA, PETG, and CF-PETG by 23.7, 53, and 67%, respectively. Intriguingly, the findings indicate that the incorporation of 10 wt.% carbon fiber diminishes the tensile and compressive properties in comparison to pure PETG.

KEYWORDS

FDM, recycled polylactic acid (rPLA), carbon fiber reinforced PLA (CFRP), polyethylene terephthalate glycol (PETG), carbon fiber reinforced PETG, tensile properties, compression strength

1. INTRODUCTION

Composite materials, formed by merging distinct elements, are instrumental in enhancing the structural and mechanical attributes of engineering products. In domains like automotive,
aerospace, sports, and defense, reinforced polymer composite (FRP) materials reign supreme. Renowned for their lightweight, robust, and high-tensile properties, these materials offer an economically efficient and streamlined fabrication process. To address the surging industry demand, substantial quantities of fiber-reinforced polymers are produced [1]. Anisotropic by nature, FRP composites’ characteristics are influenced by the choice, volume, and alignment of fibers, as well as the matrix’s structural strength and form [2].

3D printing, an additive manufacturing (AM) technology, facilitates the creation of complex structures and products by layering materials based on 3D model data [3, 4]. A contrast to subtractive methods such as CNC milling, 3D printing constructs objects through successive material layering [5]. Initially relegated to prototyping, 3D printing evolved since the 1980s, now boasting heightened repeatability, accuracy, material versatility, and industrial viability [6]. This technology’s prowess lies in crafting intricate shapes, including sectioned or hollow components, through the layering of material, thereby minimizing weight [5]. In this additive process, materials fuse, cool, and solidify, sculpting 3D geometries sans the need for intricate molds [3]. Leveraging computer-aided design (CAD) files, products transform into stereolithography (STL) files, divided into printable layers [7].

Reinforcing pure polymers with fibers yields substantial improvements in the mechanical attributes of printed polymer products. Glass fibers (GF), carbon fibers (CF), and Kevlar fibers are extensively harnessed for their reinforcing prowess in additive manufacturing [8]. These fibers, either discontinuous or continuous, find utilization in Fiber-Reinforced Composites (FRCs), manufactured through varied AM techniques, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), and Direct Ink Writing (DIW) [8]. While FDM, among these methods, has garnered significant attention, its remarkable mechanical performance, cost-efficiency, and rapid production render it a promising choice for composite manufacturing [9, 10]. The realm of AM also encompasses processes like SLA, serving medical applications, SLS exhibiting promise in orthotic designs, and LOM demonstrating potential in continuous CFRP production [11–13].

Central to CFRPs are the matrix materials, spanning both thermoplastic and thermosetting polymers [14]. Widely employed thermoplastic matrix materials include polyphenylsulfone (PPSU), polyether ether ketone (PEEK), and polaryletherketone (PAEK), while polyethylene terephthalate glycol (PETG) and polyactic acid (PLA) emerge as common choices [15]. Characterized by thermal resilience and flexibility, PETG finds application, whereas PLA, esteemed for its biodegradability, cost-effectiveness, and high stiffness, boasts a green footprint [16, 17].

FDM leverages a continuous polymer filament as feedstock, channeled through an extruder, heated to a near-liquid state, and extruded onto a print platform to form successive layers [18]. Although thermoplastics, owing to their low melting temperatures and cost-efficiency, dominate FDM raw materials, resulting FDM products often fall short in elastic attributes compared to injection-molded counterparts [19, 20]. The dearth of strength and functionality in pure FDM-produced polymers impedes their use as fully functional, load-bearing parts, relegating them mainly to conceptual prototypes [21, 22]. Despite efforts to refine mechanical properties through parameter optimization, conventional FDM-produced polymers lag due to the limitations of the thermoplastic matrix [23, 24]. However, emerging interest in utilizing these technologies for primary structural components drives the push for polymer composites with enhanced mechanical attributes, achieved through the integration of reinforcements like fibers and particles, enabling high-performance polymer matrix composites [25, 26].

Prominent reinforcements in Fiber-Reinforced Polymer Composites (FRPC) encompass continuous or discontinuous carbon, glass, and aramid fibers, with continuous fiber yielding superior mechanical properties [27]. Continuous Fiber-Reinforced Polymer Composites (CFRPC) have the potential to elevate mechanical performance substantially [27]. Carbon fibers within CFRP composites function to bear load, while the thermoplastic matrix affords binding, protection, and load transfer to the fibers [28, 29]. Thermoplastic matrix CFRPCs find diverse applications, including Airbus A350 fuselage, automotive components, wind turbine blades, and endoscopic surgery tools [30, 31].

Researchers have honed their attention on fortifying 3D printed parts using fiber-reinforced composites to enhance mechanical attributes. For instance, Ning et al. [32] probed the impact of fiber length on ABS/CF composite mechanical properties. Their findings showcased heightened tensile strength and modulus in composites with 150 μm fiber lengths. Ferreira et al. [33] noted a 2.2-fold increase in tensile modulus through short carbon fiber addition to PLA. Hodzic et al. [34] examined the influence of carbon fibers on PLA and PETG, revealing pronounced impact on yield strength and ultimate tensile properties. Hanon [35] unveiled PETG’s superior elongation performance over PLA. Similarly, Jasym et al. [36] showcased a 1.28% increase in tensile strength for carbon fiber reinforced PETG. Singh et al. [37] attested to the overall enhanced performance of CF/PETG components over PETG. The benefits of carbon fiber reinforcement extended to compressive strength, as demonstrated by Mansour et al. [38], whereas Hsueh et al. [39] underscored PLA’s superior compression properties. Furthermore, Gauss and Pickering [40] developed a method to enhance PLA composites for 3D printing with grafted nanofibrillated cellulose, resulting in improved tensile and thermo-mechanical performance. Awad et al. [41] assessed the characterization efficiency of PLA biocomposites reinforced with natural fibers for 3D printing, noting enhanced mechanical and thermal properties. Muthe et al. [42] provided an overview of the advancements in 3D/4D printing PLA composites with bio-derived reinforcements, highlighting the enhancement of physical, mechanical, and thermal properties.
Recycling PLA has gained traction, offering eco-friendliness and improved compatibility for composite PLA products. This is especially pertinent considering the array of applications that benefit from PLA-based composites, underscored by their low toxicity, ease of processing, and mechanical strength [43]. Anderson [44] highlighted the impact of recycled PLA on mechanical properties, noting reductions in tensile strength and hardness. However, the elastic tensile modulus remained statistically unchanged. Existing literature has generally limited short fiber loadings to below 5 wt.% due to issues like discontinuous flow and nozzle clogging [45]. A notable gap exists in the study of tensile and compression properties, particularly in fiber-reinforced thermoplastic composites using FDM [45].

In this work, we present an innovative empirical investigation aimed at enhancing the mechanical properties of FDM-fabricated parts through strategic incorporation of carbon fibers into PETG and PLA materials. This research distinguishes itself by rigorously applying compression and tensile tests in alignment with ASTM standards D695 and D3039, respectively, to a novel assembly of materials including recycled PLA (rPLA), carbon fiber reinforced PLA (CFR-PLA), carbon fiber reinforced PETG (CFR-PETG), and pure PETG. Notably, our study pioneers the application of the ASTM D3039 standard for tensile testing to 3D printed specimens, a methodology not widely adopted in existing literature, thus offering a unique contribution to the field. Additionally, we investigate the mechanical behaviors of these materials under various build orientations—specifically, flat and on-edge configurations—to understand the impact on tensile properties. This multi-faceted approach not only advances the technical knowledge on optimizing the mechanical performance of 3D printed parts but also introduces a novel application of a standardized testing method to the realm of fiber-reinforced thermoplastic composites produced via the FDM process, marking a significant novelty and practical application in the advancement of materials engineering and additive manufacturing.

2. EXPERIMENTAL SET-UP AND MEASUREMENT PROCEDURE

The experimental materials encompassed CFPLA, CFPETG, PETG, and recycled PLA (rPLA) filaments with a diameter of 1.75 mm, sourced from reputable suppliers. The PETG and rPLA filaments were acquired from 3Djake, while CFPLA and CFPETG filaments were obtained from Spectrum. These filaments were reinforced with fibers with 10 wt.% carbon fibers, each with a fiber length of 100 μm. The inclusion of carbon fibers significantly augmented stiffness, hardness, and tensile strength, all while maintaining low shrinkage and excellent adhesion. Furthermore, the 10% carbon fiber addition provided the models with a matte finish.

The test specimens were fabricated utilizing a commercial FDM 3D printer, specifically the “Geetech A20M,” offering a working area of 255 × 255 × 255 mm. Process parameter variations were facilitated through the slicing software “Cura Ultimaker.” Sample designs were created using “SolidWorks 2021” CAD software and subsequently exported as STL files. These STL files were used by Ultimaker Cura 5.2.1 to generate G-codes, incorporating the chosen process parameters. Printing of the test pieces took place using a 0.4 mm nozzle diameter on the Geetech A20M printer situated in the additive manufacturing laboratory at Szent Istvan Campus, MATE University, Hungary. Tabulated in Table 1 are the mechanical and physical properties of the employed materials, as provided by the manufacturers, while Table 2 presents the specific printing parameters for each material.

Tensile test specimens, conforming to the ASTM D3039 rectangular shape (165 × 20 × 3 mm), were 3D-printed. For each material, samples were produced in two orientations: flat and on-edge. A total of 24 tensile test samples were printed (three from each orientation, utilizing identical print settings). Compressive test samples, adhering to ASTM

### Table 1. Mechanical properties of the materials used

<table>
<thead>
<tr>
<th>Properties</th>
<th>PETG</th>
<th>CFPETG</th>
<th>CFPLA</th>
<th>rPLA</th>
<th>Unit</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.3</td>
<td>1.32</td>
<td>1.3</td>
<td>1.24</td>
<td>g cm⁻³</td>
<td>ISO 1183</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>42</td>
<td>45</td>
<td>65</td>
<td>63</td>
<td>MPa</td>
<td>ISO 527-1</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>5,250</td>
<td>4,250</td>
<td>12,500</td>
<td>3,251</td>
<td>MPa</td>
<td>ISO 527-1</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>7.4</td>
<td>4.90</td>
<td>0.5</td>
<td>4</td>
<td>%</td>
<td>ISO 527-1</td>
</tr>
<tr>
<td>Heat resistance</td>
<td>75</td>
<td>80</td>
<td>60</td>
<td>–</td>
<td>°C</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 2. Printing parameters employed for each material

<table>
<thead>
<tr>
<th>Printing parameters</th>
<th>PETG</th>
<th>CFPETG</th>
<th>CFPLA</th>
<th>rPLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer thickness</td>
<td>0.2 mm</td>
<td>0.2 mm</td>
<td>0.2 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Initial layer height</td>
<td>0.24 mm</td>
<td>0.24 mm</td>
<td>0.24 mm</td>
<td>0.24 mm</td>
</tr>
<tr>
<td>Print speed</td>
<td>60 mm s⁻¹</td>
<td>60 mm s⁻¹</td>
<td>60 mm s⁻¹</td>
<td>60 mm s⁻¹</td>
</tr>
<tr>
<td>Infill density</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Platform temperature</td>
<td>70 °C</td>
<td>75 °C</td>
<td>60 °C</td>
<td>45 °C</td>
</tr>
<tr>
<td>Printing temperature</td>
<td>230 °C</td>
<td>240 °C</td>
<td>210 °C</td>
<td>200 °C</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
</tr>
</tbody>
</table>
D695, were created with a diameter of 13 mm and length of 20 mm. The total count of compressive test samples reached 12. The design of these specimens was executed using SolidWorks software. Figure 1 depicts the designed compressive and tensile specimens with distinct building orientations.

Tensile tests were carried out according to the ASTM D3039 standard, while compressive tests adhered to ASTM D695, utilizing a Zwick/Roell Z100 test machine equipped with a 10 kN force transducer. Tensile testing involved the use of fixed and movable grips to secure the specimen, with a similar setup employed for the compressive test but with the movable grip opposing the tensile direction, exerting pressure on the samples. The tests were conducted at a displacement rate of 5 mm min\(^{-1}\), and the grip-to-grip distance was maintained at 99.8 mm. The force-displacement data were collected via computer using data acquisition software. Tensile properties assessed included tensile strength, tensile Young’s modulus, and failure modes under prescribed conditions. The modulus of elasticity was experimentally determined within the elastic range, employing an extensometer to evaluate strain rate sensitivity (viscoelasticity). For each material, three specimens underwent tensile strength testing.

Compressive strength was computed by dividing the compressive load by the specimen’s cross-sectional area. Compressive strain was determined using equation (1), and compressive modulus was calculated using equation (2).

\[
\varepsilon = \frac{\Delta l}{l_0},
\]

(1)

where \(\Delta l\) is the elongation and \(l_0\) is the length of the sample.

\[
E = \frac{\sigma}{\varepsilon}.
\]

(2)

Figure 2 shows the group of samples before the tensile and compressive tests.

The fracture interfaces of the specimens were examined post-mechanical testing utilizing the Axio Lab A1 Microscope, situated in the additive manufacturing laboratory at Szent Istvan Campus, MATE University, Hungary. The imaging software, operating at 50\(\times\) magnification, was employed to capture and process data, facilitating the analysis of interfaces between deposited lines and the isolation of fractured fibers within the matrix subsequent to the tensile test. A single specimen, selected from the three tested samples, was scrutinized to study the fracture interface in detail.

3. RESULTS AND DISCUSSION

The investigation aimed to enhance stiffness and strength through various parameters, as highlighted in the literature. Tensile and compressive property graphs were constructed by averaging the values from three replicate samples for each condition.

3.1. Tensile properties

Figure 3 portrays the tensile force-elongation curves for the four materials across distinct building orientations. Notably, the 3D printing building orientation and the material composition distinctly influenced the force-elongation profiles. The results were segregated into two curves based on the building orientation, each delineating the material’s behavior in relation to the orientation. Discrepancies among the materials may be attributed to distinct material properties and the interlayer adhesion generated during FDM-based specimen construction.

![Fig. 1. Samples design by SolidWorks software (a) the compressive sample, (b) tensile specimens built with two different orientations; on-edge and flat](image)

![Fig. 2. Samples before testing: (a) tensile specimens, (b) compressive specimens](image)
The rPLA exhibited a maximum force load of 3393 N and 3202 N for flat and on-edge orientations, respectively, surpassing the carbon fiber reinforced PLA. Moreover, PETG and CFPETG exhibited differential responses based on orientation. In the flat orientation, CFPETG demonstrated superior force load due to aligned fibers, displaying 20% higher force than PETG. Conversely, in the on-edge orientation, CFPETG recorded 37% lower force than PETG.

Figure 4 summarizes the average tensile test results. In terms of tensile strength, rPLA outperformed other materials with both building orientations. Specifically, rPLA exceeded CFPLA, PETG, and CFPETG by 30, 100, and 65.7% for flat orientation, and by 39.2, 21, and 77.6% for on-edge orientation, respectively. For tensile modulus, CFPLA displayed superior values for both orientations, indicating lower elasticity in rPLA compared to CFPLA. The comparison between CFPLA and CFPETG revealed CFPLA’s tensile strength to be 26.6 and 27.6% higher for flat and on-edge orientations, respectively. Concerning tensile modulus, CFPLA exceeded CFPETG twofold for flat orientation and threefold for on-edge orientation, aligning with the results reported by [46]. rPLA and CFPLA exhibited tensile strengths of around 54 and 38 MPa, respectively, alongside elastic moduli of 3,152 MPa and 14,677 MPa. These values aligned with the literature’s reported range for thermoplastic filaments (36.5–70 MPa and 1.07–4.0 GPa, respectively) [47, 48]. The results also indicate that adding 10% carbon fiber to PLA achieved a higher tensile strength than adding 15% carbon fiber to PLA, as noted by [49]. PETG’s average tensile strength and Young’s modulus also fell within the scope of other studies (σ_max between 25 and 52.4 MPa and E between 1.5 and 2.02 GPa) [47, 50, 51].

Principal failure scenarios during tensile tests are depicted in Fig. 5. The fracture location differed across loading points, with better performance observed in flat orientation specimens.

3.2. Compressive properties

Figure 6 illustrates the compressive force-elongation curves for the four materials across three specimens. Notably, rPLA and CFPLA displayed the highest and
Fig. 5. Samples after tensile tests (a) PETG and CFPETG, (b) rPLA and CFPLA with different print orientations

Fig. 6. Force-elongation curves for compressive tests

Table 3. The compressive properties for the materials examined

<table>
<thead>
<tr>
<th>Compressive Properties</th>
<th>rPLA</th>
<th>CFPLA</th>
<th>PETG</th>
<th>CFPETG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>82.3</td>
<td>66.5</td>
<td>53.7</td>
<td>49.3</td>
</tr>
<tr>
<td>Compressive modulus (MPa)</td>
<td>358.1</td>
<td>290.4</td>
<td>241.8</td>
<td>221.8</td>
</tr>
<tr>
<td>Compressive strain (%)</td>
<td>2.30</td>
<td>2.29</td>
<td>2.23</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Fig. 7. Compressive properties (a) compressive strength, (b) compressive modulus, (c) compressive strain

Fig. 8. Compressive samples after testing (a) rPLA, (b) CFPLA, (c) PETG, (d) CFPETG
near-highest force loads at 10,880 N and 10,416 N, respectively. Conversely, CFPETG samples exhibited the lowest compressive force among the materials. Table 3 provides average compressive results for all tested materials. Figure 7 showcases average maximum compressive stress, Young’s modulus, and maximum compressive strain. rPLA demonstrated a maximum compressive stress of 82.3 MPa, surpassing CFPLA by 23.7%. PETG’s compressive strength (53.7 MPa) aligned with reported literature values, ranging from 41 to 98 MPa [48]. PETG and CFPETG exhibited lower compressive deformation, while rPLA demonstrated the largest maximum deformation, in accordance with Hsueh et al. [39]. The latter found that PLA’s mechanical properties surpassed those of PETG, except for thermal deformation.

Figure 8 highlights pre- and post-compressive test samples for the four materials. Notably, samples reinforced with carbon fibers, such as rPLA and PETG, exhibited significantly enhanced compressive resistance. The compressive deformation occurred primarily around the pressure application point. Notably, fiber-reinforced samples displayed pressure distribution toward the center, contributing to greater resistance against pressure force in CFPTG and CFPETG samples, compared to rPLA and pure PETG samples.

### 3.3. Interface characterization

The impact of incorporating fibers on tensile strength was further explored using an Axio Lab A1 Microscope to scrutinize the interfacial fusion of the diverse materials. The analysis revealed the dispersion of carbon fibers within PLA and PETG filaments, with noticeable carbon fiber agglomeration in the cross-section of CF-PLA and CF-PETG filaments. Optical microscope images of the fractured surfaces of rPLA, PETG, CF-PLA, and CF-PETG specimens are presented in Fig. 9. The fractured surfaces of rPLA and PETG specimens appeared smooth and flat (Fig. 9a and b). In contrast, Fig. 9c and d showcases various orientations of CFs dispersed in the PLA and PETG substrate, with evident tiny pores and some broken carbon fibers in the CF specimen’s fractured surface. Moreover, distinct gaps between the carbon fibers and PLA substrate indicated a suboptimal bonding interface.

### 4. CONCLUSIONS

In this study, the compressive and tensile properties of FDM-fabricated rPLA, 10% carbon fiber-reinforced PLA, PETG, and carbon fiber-reinforced PETG were investigated, with a focus on examining the influence of different building orientations. Valuable insights into the mechanical properties of the specimens were obtained through rigorous tensile and compression tests. The key findings of this investigation are summarized as follows:

- Superior performance over PETG and 10% carbon fiber-reinforced PETG in both tensile and compressive tests,

Fig. 9. Optical Microscope images of (a) rPLA, (b) PETG, (c) CF-PLA, (d) CF-PETG
across assessments of Young’s modulus and strength, was consistently demonstrated by rPLA and 10% carbon fiber-reinforced PLA.
- Distinct tensile and compression asymmetry, with compressive stress surpassing tensile stress, was observed in all four materials.
- Remarkably, superior tensile and compressive properties compared to the fiber-reinforced samples were exhibited by rPLA.
- Comparisons in flat orientation revealed that rPLA outperformed CFPLA by 30%, PETG by 100%, and CFPETG by 65.7% in terms of tensile strength. Similarly, in on-edge orientation, superiority over CFPLA, PETG, and CFPETG by 39.2, 21, and 77.6%, respectively, was demonstrated by rPLA.
- Regarding compressive strength assessment, margins of 23.7, 53, and 67%, respectively, were exceeded by rPLA compared to CFPLA, PETG, and CF-PETG.
- Notably, superior tensile and compressive properties compared to 10% carbon fiber-reinforced PETG were demonstrated by 10% carbon fiber-reinforced PLA.

These findings provide valuable insights for researchers involved in polymer-based endeavors and FDM technology, offering potential avenues for sustainable advancements. Looking ahead, future exploration could encompass novel material compositions, intricate geometries, and advanced manufacturing techniques to unlock new horizons in enhancing the mechanical properties of 3D-printed parts.

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