

Mechanical performance of 3D-printed honeycomb structures fabricated from shredded E-glass reinforced polylactic acid composites

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ABSTRACT

This study investigates the effect of incorporating shredded E-glass fibers into polylactic acid (PLA) on the tensile strength, and flexural performance of honeycomb structures fabricated using fused deposition modeling. In addition, the study evaluates the relationship between fiber-reinforced composite materials and honeycomb cell-pitch geometry in determining the mechanical characteristics of the fabricated structures, while assessing the effectiveness of additive manufacturing in producing PLA-based composites. Composite filaments containing PLA and shredded E-glass fibers were manufactured through a twin-screw extrusion process using an 85:15 weight ratio, followed by the fabrication of honeycomb specimens via fused deposition modeling (FDM). Honeycomb structures with cell pitches of 3, 4, and 5 mm were prepared and evaluated through tensile and three-point bending tests in accordance with ASTM D638 and ASTM D790, respectively. The experimental results demonstrate that the shredded E-glass-reinforced PLA composite exhibited mechanical performance comparable to that of commercial PLA reinforced with carbon fiber. In particular, the honeycomb specimen with a 5 mm cell pitch achieved an ultimate tensile strength of 9.01 MPa, which was comparable to the 9.34 MPa obtained by the corresponding PLA/carbon fiber specimen. Furthermore, the 5 mm cell-pitch specimen reinforced with shredded E-glass exhibited superior flexural behavior, achieving a flexural strength of 42.83 MPa and a flexural modulus of 5.18 GPa. These findings demonstrate the potential of shredded E-glass-reinforced PLA manufactured by 3D printing as a composite material with potential cost advantages over carbon-fiber-reinforced PLA for lightweight semi-structural applications under quasi-static loading conditions.

Keywords: shredded e-glass fiber, polylactic acid (PLA) composite, honeycomb structure, additive manufacturing, 3D printing.

INTRODUCTION

Among the reinforcement materials available for FDM-fabricated PLA composites, carbon fibers have been extensively investigated because of their ability to improve stiffness and specific strength. Maqsood and Rimasauskas [1] characterized carbon-fiber-reinforced PLA processed by fused deposition modeling and reported substantial increases in flexural strength and flexural

modulus relative to unreinforced PLA. Ning et al. [2] showed that short carbon fibers raise the tensile and flexural properties of FDM-processed thermoplastics, but simultaneously reduce toughness and ductility. Alkabbanie et al. [3] further demonstrated that the mechanical benefit obtained from short carbon fibers in PLA depends strongly on the selected printing parameters. Consistent with these observations, carbon-fiber-filled PLA is generally reported to fail in a more brittle manner than

the unreinforced polymer, exhibiting higher stiffness together with reduced ductility and toughness [4], while carbon fiber raw material carries a substantially higher cost than E-glass fiber [5]. These characteristics can restrict its applicability in cost-sensitive engineering components. Unlike continuous fiber systems, shredded E-glass reinforcement can be uniformly dispersed throughout the polymer matrix using conventional twin-screw extrusion [6], enabling the production of customized composite filaments compatible with standard FDM printers [7].

Despite these advances, most published studies have focused on commercially available carbon fiber-reinforced PLA filaments or continuous/chopped glass fiber systems [8], whereas investigations involving self-fabricated shredded E-glass reinforced PLA filaments remain scarce [9]. In particular, honeycomb architectures are particularly well suited to fabrication by fused deposition modeling, since the process reproduces the cell walls directly without dedicated tooling. Nayana et al. [10] designed, fabricated, and tested 3D-printed honeycomb structures for a specific functional application, while Irfan et al. [11] examined the thermal and morphological characteristics of several 3D-printed composite honeycomb cores. The combined influence of shredded fiber morphology and honeycomb cell-pitch geometry on the flexural response of FDM-fabricated lightweight cellular structures has not yet been systematically investigated. Addressing this gap is important because customized reinforced honeycomb composites have considerable potential for lightweight engineering applications.

Such lightweight composite structures have significant potential for engineering applications requiring high stiffness-to-weight ratios. Wannarong and Singhanart [12] reviewed sandwich structures incorporating 3D-printed honeycomb cores and identified aerospace panels and lightweight energy-absorbing components as their principal application domains. Ilyas et al. [13] similarly surveyed the mechanical properties and engineering applications of fiber-reinforced polymer composites across the automotive and aerospace sectors. Marsono et al. [14] evaluated fibreglass honeycomb sandwich panels at defined cell-pitch and cell-height dimensions, demonstrating that cellular geometry is a controllable design parameter in such structures. Recent studies on FDM composite filaments have highlighted the growing interest in

developing customized reinforced filaments to overcome the limitations of commercially available materials and to tailor mechanical performance for specific engineering applications.

Although numerous studies have investigated commercially available carbon fiber-reinforced PLA filaments and short glass fiber composites fabricated by FDM, studies addressing self-fabricated shredded E-glass reinforced PLA filaments integrated with honeycomb structures of different cell-pitch geometries remain extremely limited. Moreover, the interaction between shredded fiber morphology and honeycomb architecture in governing flexural load transfer has not yet been systematically investigated. Therefore, this study proposes a novel approach by integrating self-fabricated shredded E-glass reinforced PLA filament produced through twin-screw extrusion with additively manufactured honeycomb structures featuring different cell-pitch configurations. Unlike previous studies, this work evaluates the flexural behavior of lightweight honeycomb structures and directly compares their performance with commercially available PLA/carbon fiber composites. The findings provide new insights into the combined effect of shredded fiber reinforcement, honeycomb geometry, and the 3D-printing process on the mechanical performance of lightweight structures, thereby offering an alternative strategy for developing lightweight polymer composite structures with enhanced mechanical efficiency.

MATERIALS AND METHODS

Materials

An experimental investigation was conducted to evaluate the mechanical performance of 3D-printed honeycomb structures fabricated from shredded E-glass-reinforced polylactic acid (PLA) composites (Figure 1). Commercial carbon fiber-reinforced PLA (PLA/CF) filament was employed as the reference material, while PLA reinforced with shredded E-glass fibers (PLA/E-glass) was developed as the proposed composite. The study primarily aimed to investigate the effects of shredded E-glass reinforcement and honeycomb cell-pitch variation on the tensile and flexural behavior of lightweight honeycomb structures fabricated by fused deposition modeling (FDM).

Shredded E-glass fibers with an average length of 3–4 mm were selected as the reinforcing phase. Bhaskar and Srinivas [15] characterized chopped-strand E-glass reinforcement and reported an effective balance between mechanical performance and processability at comparable fiber lengths, while Akhyar et al. [16] demonstrated that fiber size directly governs the flexural strength attainable in fiber-reinforced polymer composites. Ismail et al. [7] further showed that fiber length is a decisive parameter in FDM-processed composites, since excessively long fibers impair extrusion while very short fibers provide limited reinforcement.

The nominal diameter of the commercially available E-glass fibers was approximately 10–13 μm according to the supplier specification, corresponding to an estimated aspect ratio of approximately 300 for the as-received fibers. This value represents an upper bound, since the effective fiber length is reduced during compounding, as noted below. An aspect ratio of this order is generally considered sufficient to promote effective stress transfer between the reinforcement and the PLA matrix while maintaining acceptable filament processability. During twin-screw extrusion and subsequent FDM printing, the fibers were expected to be randomly dispersed within the filament before deposition and to become partially aligned along the extrusion direction as a result of shear-induced flow through the printer nozzle. Tóth et al. [17] reported in a meta-analysis of short fiber reinforcement in material extrusion processes that fiber orientation is generally parallel to the printing direction, consistent with this mechanism. Z. Wang et al. [18] additionally

reported that the same extrusion process induces fiber-length attrition, so that the effective fiber length within the deposited strand is generally shorter than the nominal length of the feedstock fibers. Since quantitative characterization of fiber orientation (e.g., SEM image analysis or X-ray micro-computed tomography) was beyond the scope of the present study, no statistical orientation analysis was performed.

Composite filaments were prepared by blending PLA pellets with shredded E-glass fibers at a weight ratio of 85:15 (PLA:E-glass, wt.%). The selected composition was adopted based on literature recommendations. Mohankumar et al. [19] reported that short glass fiber additions in this range improved the flexural and impact behavior of 3D-printed polymer composites. Chicos et al. [20] demonstrated stable processing and enhanced mechanical performance for short glass fiber-reinforced PLA produced by fused filament fabrication, while Rashia et al. [21] confirmed that glass fiber-reinforced PLA filaments in this loading range remain printable under conventional FDM conditions. Conversely, excessive fiber loading may increase melt viscosity and reduce extrusion stability, whereas lower fiber contents generally provide less effective reinforcement. An 85:15 (PLA:E-glass, wt.%) weight ratio was therefore selected as a literature-supported composition.

The PLA pellets and shredded E-glass fibers were compounded using a Wellzoom Type B twin-screw extruder (Figure 2). The PLA was processed within a temperature range of 190–210 $^{\circ}\text{C}$, selected to remain within the range recommended for stable melt processing while limiting

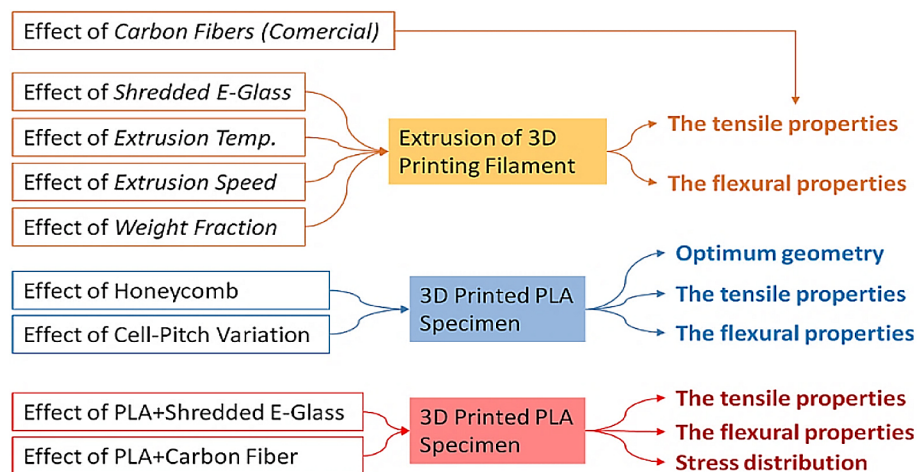


Figure 1. Experimental workflow illustrating the overall research aims and methodology

thermal degradation of the polymer [22]. The processing temperature was well below the softening range of E-glass fiber, so that no degradation of the reinforcing phase was expected during extrusion. The resulting composite filament was subsequently used for specimen fabrication. The diameter of the extruded composite filament was continuously monitored using a digital caliper and maintained at a target value of 1.75 mm within a tolerance of ± 0.02 mm, indicating satisfactory dimensional consistency of the twin-screw extrusion process. No nozzle clogging was observed at either the extrusion die or the FDM printer nozzle throughout filament production and specimen fabrication. This is attributed to the fiber-length attrition occurring during twin-screw compounding [17], which reduces the effective fiber length within the filament well below the nominal 3–4 mm length of the feedstock fibers and thereby limits fiber entanglement at the nozzle.

Honeycomb specimen design

Honeycomb specimens were designed using SolidWorks with three cell-pitch variations. In this study, the term cell pitch refers to the honeycomb cell-wall thickness, which was varied at 3, 4, and 5 mm while the cell size was held constant at 6.68 mm (Figure 3). Keeping the cell size constant enabled the influence of cell pitch on the mechanical behavior of the honeycomb structures to be evaluated independently without interference from other geometric parameters.

Tensile specimens were designed following ASTM D638 Type III [23], whereas flexural specimens were prepared in accordance with

ASTM D790 [24]. ASTM D638 Type III was selected because it is widely recommended for molded and semi-rigid polymeric materials, providing reliable tensile characterization for additively manufactured PLA composites.

Figure 3(a) shows tensile specimens had overall dimensions of $246 \times 29 \times 7$ mm, with a gauge length of 50 mm and a narrow section width of 19 mm. Flexural specimens were fabricated with dimensions of $127 \times 12.7 \times 3.2$ mm following ASTM D790 (Figure 3.b). Three identical specimens were fabricated for each material and cell-pitch configuration, resulting in a total of 18 specimens to ensure statistical consistency and repeatability that shown in Table 1.

Fabrication of honeycomb specimens

The FDM processing conditions were adopted from the experimental procedure reported by Reverte et al. [25] rather than being independently optimized in the present study. The selected parameters included a printing temperature of 210 °C, a printing speed of 50 mm/s, a volumetric flow rate of 4.8 mm³/s, a layer height of 0.16 mm, a nozzle diameter of 0.4 mm, a line width of 0.35 mm, five top and bottom layers, a concentric deposition pattern, and an infill density of 100%. Reverte et al. [25] maintained these processing conditions constant to isolate the effects of material reinforcement and build orientation on the mechanical and geometric performance of PLA-based composites. Accordingly, the same parameter set was adopted in the present work to provide stable and reproducible deposition conditions and to minimize variations associated with

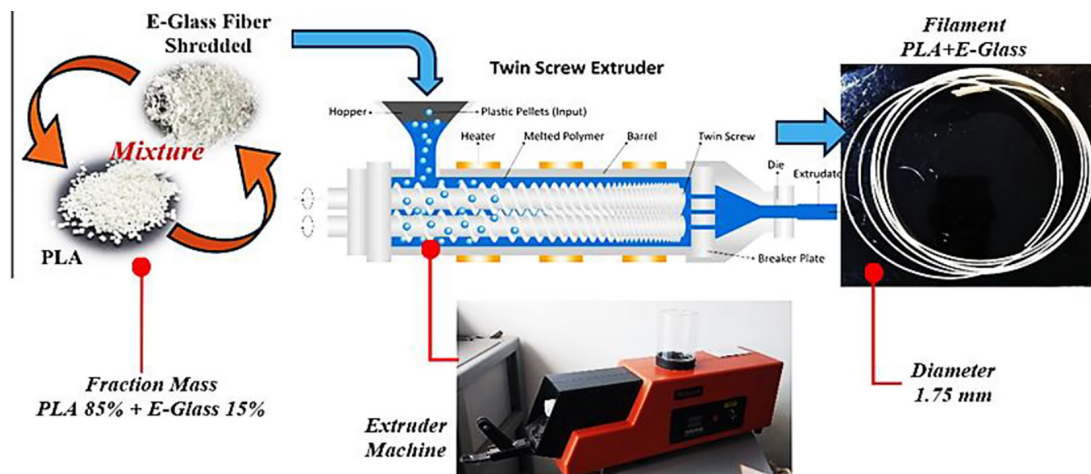


Figure 2. Fabrication of shredded E-glass-reinforced PLA composite filaments

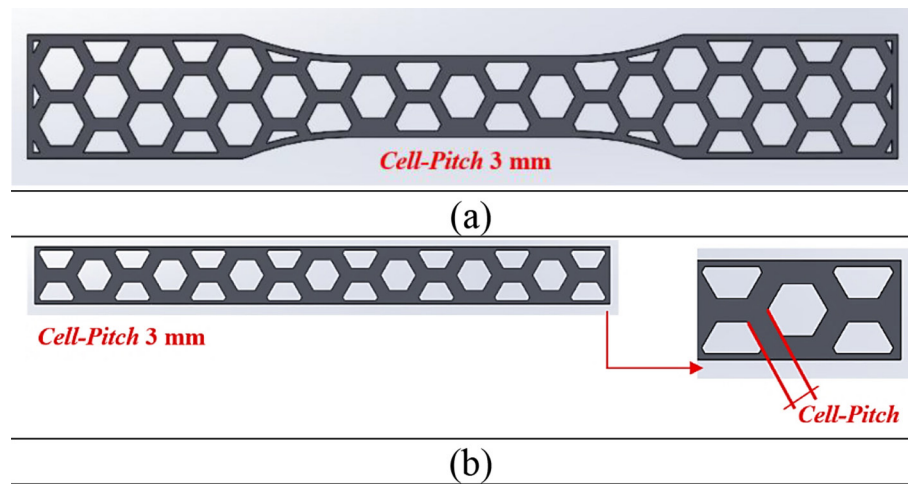


Figure 3. Specimen model designed according to; (a) ASTM D638 Type III (Tensile); (b) ASTM D790

Table 1. Experimental matrix of the investigated materials and honeycomb cell-pitch configurations

Material	Category	Cell-Pitch (in-mm)	No. Specimen	Category code	Total
PLA+Carbon Fiber (CF)	I / A	3	1 / 2 / 3	Variation CF – I -1/2/3	3
	II / B	4		Variation CF – II -1/2/3	3
	III / C	5		Variation CF – III -1/2/3	3
PLA+E-Glass (EG)	I / A	3	1 / 2 / 3	Variation EG – I -1/2/3	3
	II / B	4		Variation EG – II -1/2/3	3
	III / C	5		Variation EG – III -1/2/3	3

Note: Category code (I / II / III) for tensile specimen; (A / B / C) for bending specimen.

the printing process [26]. The printing temperature of 210 °C was selected to provide adequate melting and continuous extrusion of the PLA-based filaments, whereas the moderate printing speed of 50 mm/s was used to balance deposition stability, geometric accuracy, and manufacturing time. The combination of a 0.16 mm layer height, a 0.4 mm nozzle diameter, and a 0.35 mm line width was intended to maintain consistent strand geometry and sufficient interlayer contact. Moreover, the 100% infill setting was applied to minimize internal voids arising from the slicer-defined infill density and to ensure that the measured mechanical response was primarily governed by the material composition and honeycomb cell-pitch variation. The concentric deposition strategy was maintained consistently for all specimens to reduce processing-related variability. No separate experimental optimization of the FDM parameters was conducted in this study; instead, the literature-established conditions were applied uniformly to both PLA–carbon-fiber and PLA–shredded-E-glass specimens to enable a controlled comparison between the investigated

materials. Each specimen required approximately 1–2 h of printing time depending on its geometry. The complete printing parameters are summarized in Table 2.

The fabricated tensile and flexural honeycomb specimens are shown in Figure 4(a) and Figure 4(b), respectively. Following the fabrication process, all honeycomb specimens were visually and dimensionally inspected prior to mechanical testing. The printed specimens exhibited well-defined honeycomb geometries and satisfactory interlayer adhesion, with no visible delamination, warping, stringing, or under-extrusion observed during general inspection. Only the initial calibration print required parameter adjustment; all subsequently fabricated specimens ($n = 18$) were successfully printed on the first attempt without failure or repetition, indicating a reproducible fabrication process. It should be noted that porosity was not quantitatively assessed in this study, as density measurement and cross-sectional microscopy were beyond its scope; this is recognized as a limitation and is recommended for future investigation.

Table 2. FDM printing parameters used for the fabrication of all honeycomb specimens

Parameters	Value
Print speed (%)	100
Flow rate (mm ³ /s)	4.8
Layer height (mm)	0.16
Printing temperature (°C)	210
Bed temperature (°C)	40–65
Nozzle diameter (mm)	0.4
Filament diameter (mm)	1.75
Infill pattern	Concentric
Infill density (%)	100%

Mechanical testing and statistical analysis

Mechanical characterization consisted of tensile and three-point bending tests conducted in accordance with ASTM D638 Type III and ASTM D790, respectively. For each experimental condition, three identical specimens were tested to improve the repeatability and reliability of the experimental measurements.

During tensile testing, the applied load and displacement were continuously recorded until specimen failure. The resulting load–displacement data were subsequently processed to determine the ultimate tensile strength (UTS), yield strength, and Young’s modulus. Likewise, the flexural test data were analyzed to determine the flexural strength, maximum deflection, and flexural modulus according to Equation 1 and 2.

Equation 1, was used to calculate the flexural strength of the honeycomb specimens:

$$\sigma_f = \frac{3FL}{2bd^2} \quad (1)$$

Equation 2, was used to determine the flexural modulus of the honeycomb specimens:

$$E_f = \frac{L^3m}{4bd^3} \quad (2)$$

where: σ_f – flexural strength (MPa), E_f – flexural modulus (MPa), F – maximum applied load (N), L – support span (mm), b – specimen width (mm), d – specimen thickness (mm), m – slope of the initial linear region of the load–deflection curve (N/mm).

The average values obtained from the three repeated tests were used for subsequent analysis, while the replicated measurements minimized experimental uncertainty and improved the reliability of the reported mechanical properties. The mechanical performance of each honeycomb configuration was then compared to evaluate the combined influence of reinforcement material and cell-pitch variation on the structural response under tensile and flexural loading.

Three independent specimens were tested for each combination of material type, honeycomb cell pitch, and mechanical test. The results are reported as the mean $\pm$ standard deviation. A two-way analysis of variance (ANOVA) was performed separately for ultimate tensile strength, yield strength, Young’s modulus, deflection at

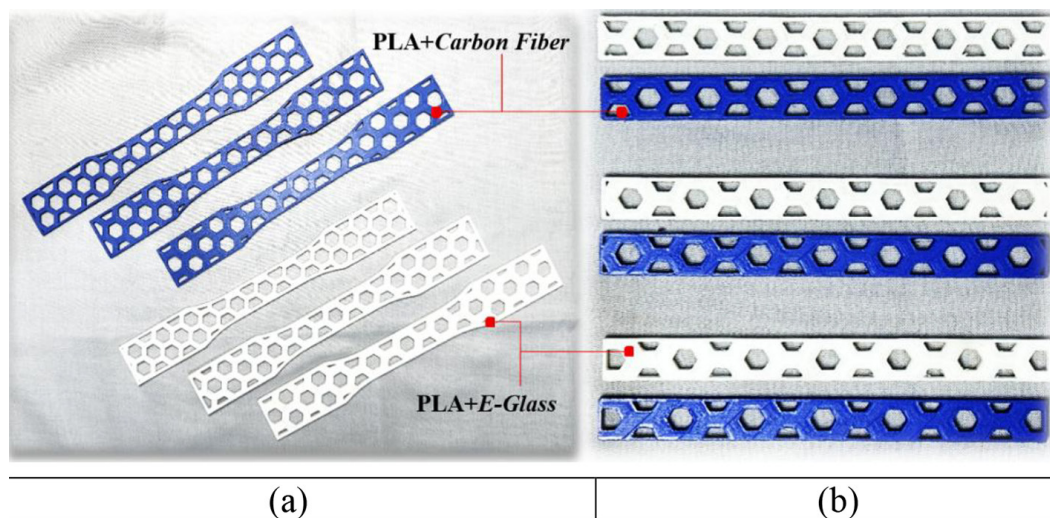


Figure 4. Specimen model fabricated according to ASTM; (a) Tensile; (b) Flexural

maximum flexural load, flexural strength, and flexural modulus. Material type (PLA/carbon fiber and PLA/shredded E-glass) and cell pitch (3, 4, and 5 mm) were treated as fixed factors, and the material $\times$ cell-pitch interaction was also evaluated. When a statistically significant effect was identified, Tukey's honestly significant difference test was applied for multiple pairwise comparisons among the six material–geometry groups. Statistical significance was defined at $p < 0.05$. Homogeneity of variance was evaluated using Levene's test. Error bars in the relevant figures represent one standard deviation from the corresponding mean ($n = 3$).

RESULTS

Tensile test result

The tensile test results for the PLA/carbon-fiber and PLA/shredded-E-glass honeycomb specimens with cell pitches of 3, 4, and 5 mm are presented in Figures 5, 6 and 7. As shown in Figure 5, the 5 mm cell-pitch configuration exhibited the highest ultimate tensile strength (UTS) for both investigated materials. The maximum UTS values were 9.39 MPa for the PLA/carbon-fiber composite and 9.15 MPa for the PLA/shredded-E-glass composite. A similar trend was observed for yield strength, with the highest values of 7.19 MPa and 6.93 MPa, respectively, also being obtained from the 5 mm cell-pitch specimens.

In contrast, the lowest tensile performance was recorded for the 3 mm cell-pitch configuration. The corresponding UTS values were 6.35 MPa for PLA/carbon fiber and 6.57 MPa for PLA/

shredded E-glass. Thus, increasing the cell pitch from 3 to 5 mm resulted in an increase in both UTS and yield strength for the two material systems. Nevertheless, the differences in UTS among the investigated cell-pitch configurations remained relatively limited, generally within approximately 1–2 MPa. The specimen mass also varied with the honeycomb cell pitch. For the PLA/carbon-fiber system, the average mass of the tensile specimens increased from 26.0 g at a cell pitch of 3 mm to 28.5 g at 4 mm and 33.5 g at 5 mm. The corresponding values for the PLA/shredded-E-glass system were 28.5, 30.5, and 35.5 g. This trend is consistent with the greater volume of deposited material associated with the thicker cell walls.

The tensile properties of the PLA/carbon-fiber and PLA/shredded-E-glass honeycomb specimens are presented as the mean $\pm$ standard deviation of three independent tests. As shown in Figure 5, the mean ultimate tensile strength of the PLA/carbon-fiber specimens increased from 6.28 ± 0.08 MPa for the 3 mm cell pitch to 8.19 ± 0.17 MPa for the 4 mm cell pitch and 9.34 ± 0.06 MPa for the 5 mm cell pitch. The corresponding values for the PLA/shredded-E-glass specimens were 6.48 ± 0.14 , 8.06 ± 0.07 , and 9.01 ± 0.17 MPa, respectively. Two-way ANOVA showed that cell pitch had a statistically significant effect on ultimate tensile strength ($p < 0.001$), whereas the main effect of material type was not statistically significant ($p = 0.165$). A significant material $\times$ cell-pitch interaction was identified ($p = 0.010$), indicating that the variation in ultimate tensile strength with cell pitch was not identical for the two material systems. The corresponding yield strength and Young's modulus values for all material and cell-pitch configurations are presented in

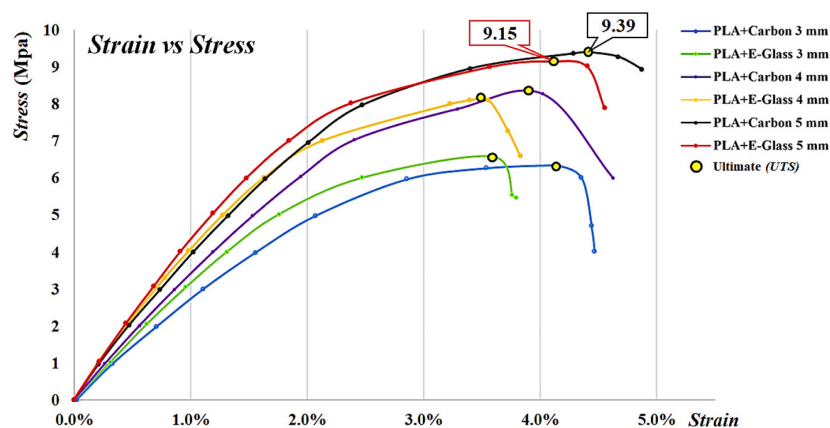


Figure 5. Representative stress–strain curves of PLA/carbon fiber and PLA reinforced with shredded E-glass honeycomb

Figure 6. These results indicate that the influence of cell-pitch variation on UTS was relatively limited, with differences of only approximately 1–2 MPa despite the variation in specimen mass.

The tensile fracture surfaces of both composite systems are shown in Figure 7. Macroscopic examination of the PLA/shredded-E-glass specimens revealed a comparatively rough, irregular, and fibrous fracture surface. These observations suggest that the improved tensile response of Category III specimens resulted from the combined contribution of the reinforcement material and the optimized honeycomb geometry.

Values are presented as the mean $\pm$ standard deviation of three independent specimens ($n = 3$); error bars represent one standard deviation.

Flexural test result

The flexural behavior of the honeycomb specimens was evaluated using a three-point bending test. The maximum flexural load, deflection, flexural strength, and flexural modulus were determined for each material and cell-pitch configuration. The bending test demonstrated that the PLA/E-glass honeycomb structures consistently exhibited higher maximum flexural loads than the commercial PLA/carbon fiber specimens, particularly for the 3 mm and 4 mm cell-pitch configurations.

The flexural results are reported as the mean $\pm$ standard deviation of three independent specimens. The mean deflection at maximum flexural load for the PLA/carbon-fiber specimens decreased from 3.10 ± 0.02 mm at a cell pitch of 3 mm to 2.50 ± 0.02 mm at 4 mm and 1.64 ± 0.05

mm at 5 mm. In comparison, the PLA/shredded-E-glass specimens exhibited mean deflections of 1.45 ± 0.03 , 1.91 ± 0.03 , and 1.72 ± 0.04 mm at cell pitches of 3, 4, and 5 mm, respectively. Two-way ANOVA showed significant effects of material type, cell pitch, and their interaction on deflection at maximum flexural load ($p < 0.001$). The mean flexural strengths of the PLA/carbon-fiber specimens were 29.45 ± 1.01 , 22.56 ± 1.50 , and 23.47 ± 1.16 MPa for the 3, 4, and 5 mm cell-pitch configurations, respectively. The corresponding values for the PLA/shredded-E-glass specimens were 37.06 ± 1.23 , 32.68 ± 1.13 , and 42.83 ± 1.27 MPa. Material type, cell pitch, and the material $\times$ cell-pitch interaction had statistically significant effects on flexural strength ($p < 0.001$). For PLA/carbon fiber, the mean flexural modulus values were 2733.64 ± 4.74 , 2694.54 ± 13.15 , and 3396.66 ± 9.41 MPa for cell pitches of 3, 4, and 5 mm, respectively. The corresponding values for PLA/shredded E-glass were 3852.85 ± 39.16 , 3840.67 ± 2.72 , and 5177.69 ± 22.56 MPa. Two-way ANOVA demonstrated statistically significant effects of material type, cell pitch, and their interaction on flexural modulus ($p < 0.001$).

The complete ANOVA results for tensile and flexural properties are summarized in Table 3. The significant interaction effects observed for the flexural properties indicate that the response to cell-pitch variation depended on the investigated material system.

Values are presented as the mean $\pm$ standard deviation of three independent specimens ($n = 3$); error bars represent one standard deviation.

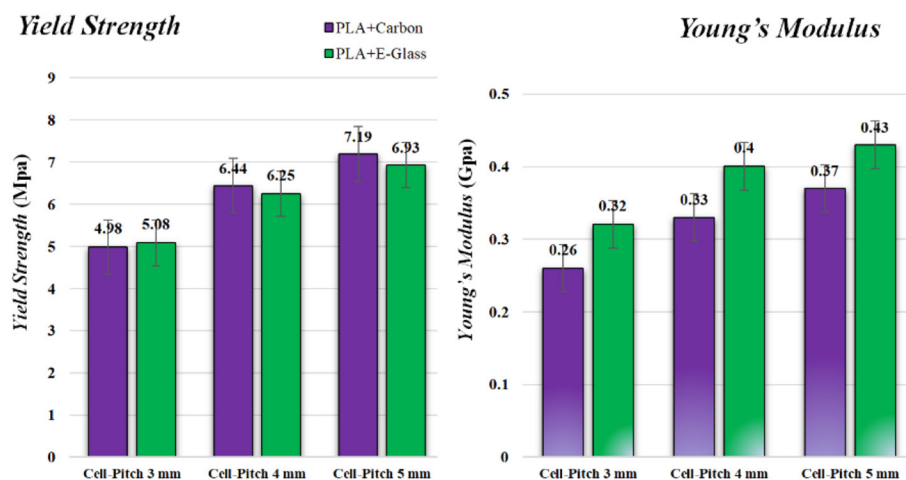


Figure 6. Yield strength and Young's modulus of the PLA/carbon-fiber and PLA/shredded-E-glass honeycomb specimens at cell pitches of 3, 4, and 5 mm

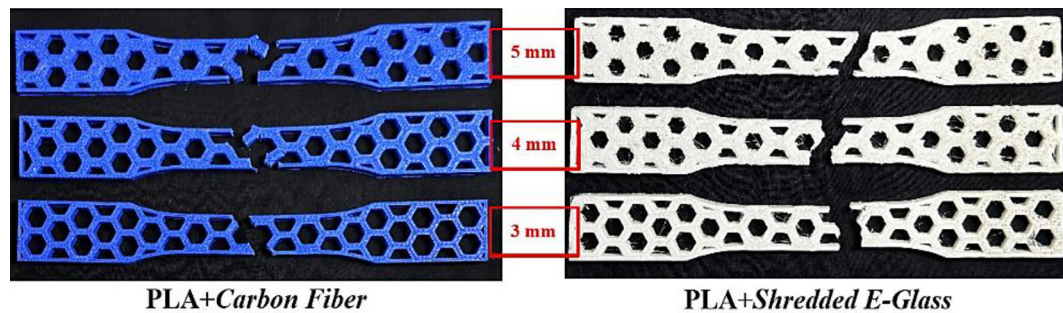


Figure 7. Tensile fracture morphology of PLA/carbon fiber and PLA/E-glass honeycomb specimens after failure

Table 3. Two-way ANOVA results for the tensile and flexural properties of the investigated honeycomb composites

Mechanical properties	Statistical factor	F-value	P-value	Significance
Ultimate tensile strength	Material type	2.182	0.165	Not significant
	Cell-pitch	774.772	<0.001	Significant
	Material x cell pitch	6.874	0.010	Significant
Yield strength	Material type	4.302	0.060	Not significant
	Cell-pitch	173.009	<0.001	Significant
	Material x cell pitch	5.732	0.018	Significant
Young's modulus	Material type	952.614	<0.001	Significant
	Cell-pitch	1050.015	<0.001	Significant
	Material x cell pitch	3.377	0.069	Not significant
Flexural strength	Material type	457.894	<0.001	Significant
	Cell-pitch	41.560	<0.001	Significant
	Material x cell pitch	38.288	<0.001	Significant
Flexural modulus	Material type	21050.218	<0.001	Significant
	Cell-pitch	5214.818	<0.001	Significant
	Material x cell pitch	541.147	<0.001	Significant

The flexural strength and flexural modulus, calculated from the bending test results (Figure 8), showed that the 5 mm cell-pitch PLA/Carbon Fiber specimens did not achieve the highest flexural strength (24.26 MPa), whereas the corresponding PLA/E-glass specimens exhibited a simultaneous increase in both flexural strength and flexural modulus.

DISCUSSION

Scope and interpretive framework of the present study

The experimental work reported in this study characterized the tensile and flexural behavior of the honeycomb specimens at the macroscopic scale only. Microstructural characterization such

as scanning electron microscopy (SEM), X-ray micro-computed tomography, digital image correlation, and numerical simulation, was beyond the scope of the present investigation, and the discussion presented below is explicitly bounded by this limitation.

In the absence of direct microstructural evidence, the possible role of fiber–matrix interaction in the observed mechanical response is discussed qualitatively by drawing on fractographic and SEM-based studies of comparable PLA/glass-fiber and PLA/carbon-fiber composite systems reported elsewhere in the literature [27, 28]. Such studies commonly report that fiber breakage and fiber–matrix debonding observed at fracture surfaces reflect effective stress transfer from the polymer matrix to the reinforcing fibers prior to failure, with fractured fibers indicating active load-sharing by the reinforcement rather than an

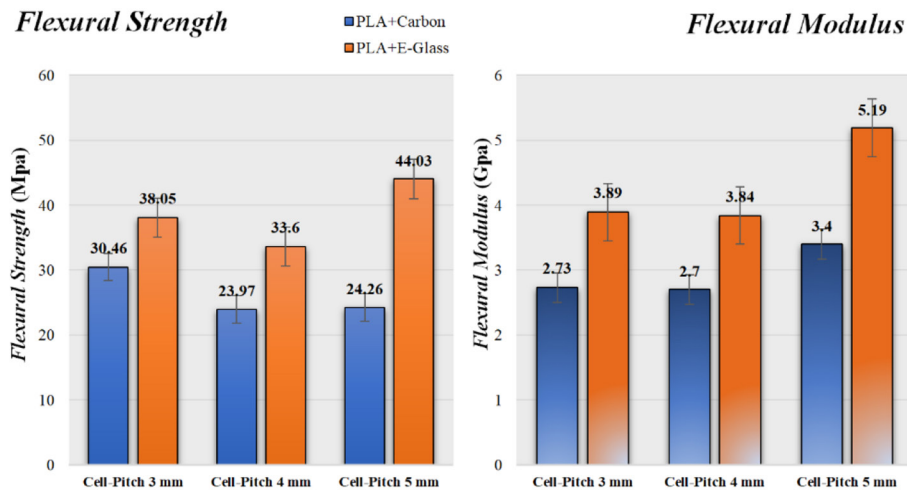


Figure 8. Flexural strength and flexural modulus of the PLA/carbon-fiber and PLA/shredded-E-glass honeycomb specimens at cell pitches of 3, 4, and 5 mm

unfavorable failure mode. These published observations are employed here strictly as an interpretive framework; the mechanisms discussed in the following subsections are not direct observations of the specimens examined in this study.

Accordingly, a distinction is maintained throughout the discussion between two categories of interpretation: macroscopic, geometry-related effects associated with honeycomb cell pitch, which are supported directly by the measured tensile and flexural data and by the accompanying two-way analysis of variance; and microscopic fiber–matrix stress-transfer mechanisms, which remain inferences drawn from analogous composite systems reported in the literature rather than mechanisms verified within the present work.

Effect of cell-pitch on tensile behavior

The 5 mm cell-pitch configuration exhibited the highest ultimate tensile strength and yield strength among the investigated geometries for both composite systems. The measured results therefore indicate a numerical improvement in tensile performance with increasing cell pitch within the range examined. The increase in ultimate tensile strength observed for the 5 mm configuration was accompanied by a corresponding improvement in yield strength and by delayed plastic deformation relative to the 3 mm and 4 mm configurations. However, the physical mechanism responsible for this trend was not directly characterized in the present study.

The ANOVA results demonstrate that honeycomb cell pitch was a significant factor governing

the tensile response, whereas material type did not exert a statistically significant overall effect on UTS or yield strength. These results indicate that the tensile-strength differences between the two composite systems were relatively small compared with the effect associated with cell-pitch variation. In contrast, both material type and cell pitch significantly affected Young’s modulus, indicating that the stiffness response depended on both the reinforcement system and cellular configuration. The tensile behavior of the two composite systems was otherwise generally comparable: although PLA/carbon fiber exhibited the highest overall ultimate tensile strength and yield strength at a cell pitch of 5 mm, the differences between the PLA/carbon-fiber and PLA/shredded-E-glass specimens remained small across all investigated configurations.

Variation in cell pitch also altered the amount of deposited material within the cellular structure and, consequently, the overall specimen mass. Increasing the cell-wall thickness from 3 to 5 mm at a constant cell size increased the average mass of the tensile specimens from 26.0 to 33.5 g for the PLA/carbon-fiber system and from 28.5 to 35.5 g for the PLA/shredded-E-glass system, corresponding to increases of approximately 28.8% and 24.6%, respectively. Over the same geometric range, the mean ultimate tensile strength increased by approximately 48.7% and 39.0%, respectively. The gain in load-bearing capacity therefore exceeded the accompanying increase in deposited material for both composite systems, indicating that the 5 mm configuration provided the highest absolute tensile and yield strengths

among the geometries investigated while also improving the mass-normalized tensile strength relative to the 3 mm configuration. The differences in ultimate tensile strength between adjacent cell-pitch configurations nevertheless remained limited to approximately 1–2 MPa.

Previous investigations of cellular structures have shown that cell geometry can influence local stress concentration, deformation mode, and load transmission under tensile loading. Khan et al. [29] reported that the tensile response of 3D-printed PLA prismatic cellular structures depends directly on cell geometry, while Hao et al. [30] demonstrated through a novel hexagonal cell-body topology that modifying the cell architecture alters the resulting mechanical properties. Yang et al. [31] similarly showed that varying wall thickness within a honeycomb changes its deformation behavior under load. Accordingly, the improved tensile response of the 5 mm configuration may be associated with a more favorable structural arrangement. Nevertheless, because no finite-element simulation, full-field strain measurement, or internal structural characterization was performed, improved stress redistribution should be regarded as a literature-based hypothesis rather than an experimentally verified mechanism.

The influence of honeycomb wall thickness (cell pitch) on the tensile response can further be considered in relation to classical cellular solids theory. According to the framework established by Gibson and Ashby for periodic hexagonal honeycombs [32], the relative density of a honeycomb scales with the wall-thickness-to-cell-size ratio (t/l), and for in-plane, bending-dominated deformation of the cell walls, this framework predicts that modulus scales approximately with $(t/l)^3$ and strength with $(t/l)^2$. Increasing the wall thickness from 3 to 5 mm at the fixed 6.68 mm cell size investigated in this study corresponds to an increase in t/l of approximately 67% (from 0.449 to 0.749), which under this idealized bending-dominated scaling would nominally predict an increase in modulus on the order of 4-fold and in strength on the order of 2.8-fold. This scaling relationship has since been verified numerically for periodic hexagonal honeycombs by Malek and Gibson [33].

The measured increase in specimen mass reported above confirms that the relative density of the structures increased with cell-wall thickness, although the measured increase of approximately 25–29% is smaller than the proportional increase in t/l , in part because the ASTM D638

specimen geometry also includes non-cellular regions that do not scale with cell-wall thickness. The experimental data therefore follow the direction predicted by this scaling, but not its magnitude. Over the same geometric range, the measured mean ultimate tensile strength increased by a factor of approximately 1.49 for the PLA/carbon-fiber system (from 6.28 to 9.34 MPa) and 1.39 for the PLA/shredded-E-glass system (from 6.48 to 9.01 MPa), while the mean flexural modulus increased by factors of approximately 1.24 (from 2733.64 to 3396.66 MPa) and 1.34 (from 3852.85 to 5177.69 MPa), respectively. The measured improvements are therefore substantially smaller than the idealized predictions. This discrepancy is not unexpected, since the Gibson–Ashby scaling laws are formulated for slender cell walls ($t/l \ll 1$) deforming predominantly by bending, whereas the configurations examined here operate at t/l values between approximately 0.45 and 0.75. In this thick-walled regime, axial and shear deformation of the cell walls contribute increasingly to the overall response, and the idealized bending-dominated scaling would be expected to overestimate the sensitivity of both modulus and strength to changes in t/l . The non-monotonic variation of flexural strength with cell pitch observed for both material systems provides further indication that the response of the present structures is not governed by relative density alone. Finite-element modeling that resolves the actual printed cell-wall geometry is recommended to quantify the relative contributions of bending, axial, and shear deformation in this regime.

Beyond the effect of cellular geometry, the observed mechanical trends can also be considered in relation to expected outcomes derived from established fiber-reinforced composite theory. According to the rule of mixtures and related micromechanical models such as the Halpin–Tsai formulation, the longitudinal stiffness of a fiber-reinforced composite is expected to scale, among other factors, with the intrinsic elastic modulus of the reinforcing fiber. Standard-modulus carbon fibers typically exhibit an elastic modulus on the order of 230 GPa, considerably higher than that of E-glass fibers, which is on the order of 70–86 GPa [34]. On this basis, a composite reinforced with carbon fiber would conventionally be expected to exhibit a higher Young’s modulus than an equivalent composite reinforced with E-glass fiber.

The present tensile results show the opposite trend: the PLA/E-glass honeycomb exhibited a

higher Young's modulus than the PLA/carbon-fiber honeycomb at every investigated cell-pitch configuration, reaching 430.95 MPa compared with 374.87 MPa at the 5 mm cell pitch. This deviation from the expected fiber-modulus-driven trend suggests that factors other than the intrinsic fiber modulus played a more dominant role in governing the overall composite stiffness in this study. Plausible contributing factors include the undisclosed fiber content of the commercial PLA/carbon-fiber filament, which may differ from the precisely controlled 15 wt.% E-glass content of the self-fabricated filament; differences in fiber dispersion, orientation, and effective aspect ratio resulting from the twin-screw extrusion process relative to the commercial compounding route; and differences in fiber–matrix interfacial adhesion between the two systems, which is known to govern the efficiency of stress transfer in fiber-reinforced polymer composites [35]. Clarifying the relative contribution of these factors would require additional characterization, such as thermogravimetric analysis or ash-content testing to verify the actual fiber content of the reference PLA/carbon-fiber filament, and is recommended as a direction for future work.

Flexural response and possible reinforcement mechanisms

The three-point bending results showed that the PLA/E-glass honeycomb structures consistently sustained higher maximum flexural loads than the commercial PLA/carbon-fiber specimens, particularly for the 3 mm and 4 mm cell-pitch configurations. This behavior is consistent with more effective load transfer contributed by the shredded E-glass reinforcement within the honeycomb structure during bending, although direct verification of this interfacial mechanism through SEM fractography or interfacial characterization was beyond the scope of the present study, as stated in Section: Scope and interpretive framework of the present study.

The deflection behavior further distinguishes the two composite systems. The PLA/carbon-fiber specimens became progressively stiffer with increasing cell pitch, yet this was accompanied by a reduction in maximum bending load, whereas the PLA/E-glass honeycombs maintained relatively low deflection while achieving higher maximum flexural loads. This indicates that structural stiffness alone does not govern flexural resistance,

consistent with Yang et al. [31], who reported that optimized honeycomb geometries improve the mechanical efficiency of cellular structures through more uniform stress distribution.

The same distinction is reflected in the calculated flexural strength and flexural modulus. The 5 mm cell-pitch PLA/carbon-fiber specimens did not achieve the highest flexural strength among the carbon-fiber configurations, whereas the corresponding PLA/E-glass specimens exhibited a simultaneous increase in both flexural strength and flexural modulus. The 5 mm configuration therefore achieved a more favorable balance between stiffness and load-bearing capacity than the other configurations, since an increase in stiffness does not necessarily translate into higher strength when failure is governed by local stress concentrations. These observations are consistent with reports [36] that optimized honeycomb geometries enhance stress redistribution and mechanical performance in additively manufactured cellular structures, suggesting that geometric optimization may be as important as material selection when designing lightweight composite structures for flexural loading [37].

Within the interpretive framework established in Section: Scope and interpretive framework of the present study, published fractographic studies offer a plausible, though indirect, basis for interpreting these macroscopic trends. Javadian et al. [38] reported that fiber breakage and fiber–matrix debonding observed in PLA/glass-fiber composites indicate effective stress transfer between matrix and reinforcement prior to failure, while void formation acts as a local stress concentrator promoting crack initiation. Keshavamurthy et al. [39] similarly observed that short carbon fibers in PLA function not merely as inert fillers but as active structural reinforcements that carry a significant proportion of the applied flexural load, with stress initially concentrated within the matrix progressively redistributed to the stiffer reinforcing fibers as loading proceeds. This mechanism was reflected in flexural-strength improvements of approximately 45% and 88% for composites containing 3 wt.% and 6 wt.% carbon fibers, respectively, relative to neat PLA. By analogy, the superior flexural strength and modulus of the PLA/E-glass honeycomb at the 5 mm cell-pitch configuration may plausibly reflect a similarly efficient stress-transfer mechanism between the shredded E-glass fibers and the PLA matrix.

Macroscopic examination of the fractured PLA/shredded-E-glass specimens revealed a comparatively rough and fibrous fracture surface, which is qualitatively consistent with the fiber-dominated failure modes described in these studies. However, fiber orientation, the fiber–matrix interface, fiber pull-out, and internal void distribution could not be quantitatively determined, as microscopic characterization was not performed in the present study. This interpretation therefore requires confirmation by future microstructural investigation.

Engineering significance, cost considerations, and limitations

The flexural performance achieved by the PLA/E-glass honeycomb structures is particularly relevant because cellular structures are generally designed to minimize weight, often at the expense of mechanical strength. The ability of the proposed material system to maintain high flexural resistance while preserving the advantages of lightweight honeycomb geometry highlights its potential for semi-structural applications requiring both mechanical efficiency and weight reduction. More broadly, the results emphasize that improvements in flexural performance are not governed solely by reinforcement type, but also by the combined influence of reinforcement morphology, cellular architecture, and additive manufacturing parameters.

This outcome is also relevant from an economic perspective, since carbon fiber raw material is generally reported to be considerably more expensive than E-glass fiber, whereas glass-fiber composites are widely recognized for their relatively low cost and favorable corrosion resistance [5]. Based on this established cost differential reported in the literature, shredded E-glass reinforcement is expected to offer a more economical alternative to carbon-fiber-reinforced PLA for the development of lightweight semi-structural components manufactured by fused filament fabrication, within the quasi-static tensile and flexural performance range evaluated in this study. It should be noted, however, that a dedicated cost analysis encompassing raw material, processing, and fabrication costs was not performed in the present work and is recommended as a direction for future investigation to quantitatively substantiate this potential economic advantage.

The present investigation was further limited to quasi-static tensile and three-point bending tests conducted at room temperature. Properties

that govern long-term or service-representative structural performance, including fatigue resistance, impact tolerance, creep behavior, fracture toughness, thermal stability, and environmental durability, were not evaluated. Accordingly, the potential suitability of the developed PLA/E-glass composite discussed throughout this work should be interpreted strictly within the scope of the quasi-static loading conditions examined here, and further investigation of these properties is required before the material can be considered validated for load-bearing structural applications.

CONCLUSIONS

This study evaluated the tensile and flexural performance of 3D-printed honeycomb structures fabricated from a self-produced shredded E-glass reinforced PLA filament and compared them with a commercial PLA/carbon-fiber composite at cell pitches of 3, 4, and 5 mm. The principal findings are as follows:

- Cell pitch governed the tensile response of both composite systems. Ultimate tensile strength and yield strength increased with cell pitch for both materials, and the two-way ANOVA confirmed cell pitch as a statistically significant factor, whereas material type did not exert a significant effect on ultimate tensile strength.
- The two material systems differed in flexural behavior. For PLA/carbon fiber, the 3 mm cell pitch provided the highest flexural load-bearing capacity, while the 5 mm configuration was stiffer without a corresponding gain in flexural strength. PLA/shredded E-glass exhibited a more consistent response, with the 5 mm configuration achieving the highest values of all measured tensile and flexural properties.
- The gain in tensile strength from the 3 to the 5 mm cell pitch (approximately 48.7% for PLA/carbon fiber and 39.0% for PLA/shredded E-glass) exceeded the corresponding increase in specimen mass (28.8% and 24.6%), indicating that the improvement was not obtained solely through the addition of material.
- At the 5 mm cell pitch, the PLA/shredded-E-glass honeycomb reached an ultimate tensile strength and yield strength within approximately 3.5% and 3.6% of the PLA/carbon-fiber reference, while exceeding it by approximately 15.0% in Young's modulus, 82.5% in flexural strength, and 52.4% in flexural modulus.

- The principal contribution of this work is the demonstration that a self-fabricated shredded E-glass reinforced PLA filament, combined with an appropriate honeycomb cell pitch, can achieve tensile performance comparable to, and flexural performance exceeding, that of a commercial PLA/carbon-fiber composite under quasi-static loading, with potential cost advantages that remain to be quantified.

These findings are bounded by the scope of the present investigation. Three cell pitches at a fixed cell size and a single fiber ratio (85:15) were examined, all specimens were fabricated with a single infill pattern and a fixed set of FDM parameters, and no microstructural characterization was performed to verify the fiber–matrix stress-transfer mechanisms discussed. All testing was conducted under quasi-static loading at room temperature; fatigue resistance, impact tolerance, creep behavior, fracture toughness, thermal stability, and environmental durability were not evaluated, and no dedicated cost analysis was carried out. Systematic variation of fiber content, broader topology optimization, finite-element modeling, and microstructural investigation are therefore recommended before the developed composite can be considered validated for load-bearing structural applications.

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