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(Research Article)

Evaluation of Shear Modulus of Lotus Root and Beetle Wing Inspired Particulate Hemp-PLA Cores Using ASTM E756

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Abstract

This study investigates the mechanical characterization of bio-inspired cellular cores utilizing polylactic acid (PLA) reinforced with hemp powder. Two distinct core geometries lotus root inspired and beetle wing inspired—were fabricated using fused deposition modeling with varying hemp content (0%, 2.5% and 5% by weight). Sandwich beam specimens with galvanized iron facings were evaluated using ASTM E756 standards for damping properties. Results demonstrated that lotus root-inspired cores achieved superior shear modulus values of 4.32 MPa for pure PLA representing a 20.7% advantage over beetle wing designs (3.58 MPa). Lotus root cores provided enhanced damping characteristics with loss factors up to 0.1497, while beetle wing cores showed optimal damping at 2.5% hemp content (0.1165 loss factor). Hemp reinforcement at 2.5% weight content emerged as the optimal composition for balanced performance, reducing core density by 31.9% while maintaining mechanical integrity. The 5% hemp composition achieved maximum weight reduction (37.2% density decrease) with superior damping characteristics but significant stiffness reduction. The bio-inspired geometries demonstrated 15-20% superior specific strength compared to conventional honeycomb designs, validating the feasibility of sustainable composite production through additive manufacturing with natural fiber reinforcement.

Keywords: Bio-Inspired Design; Transverse Shear Modulus; ASTM E756; Cellular Cores; Additive Manufacturing; PLA Composites

1. Introduction

Bio-inspired design principles have emerged as a transformative approach in developing advanced structural materials, drawing inspiration from nature's evolutionary optimization processes [1, 28]. Natural structures demonstrate remarkable efficiency in achieving multiple functional requirements simultaneously, including load-bearing capacity, weight minimization and energy dissipation [2]. The translation of these biological principles into engineered systems has led to significant advances in lightweight composite structures. Cellular solids represent a fundamental class of materials that combine low density with desirable mechanical properties through geometric optimization [3]. The structural efficiency of cellular materials depends critically on cell topology, with different geometries providing distinct advantages for specific applications [4]. Conventional honeycomb structures have dominated sandwich construction due to their predictable behavior and manufacturing simplicity [5, 29].

Recent advances in additive manufacturing have enabled the fabrication of complex bio-inspired geometries previously impossible through conventional processing methods [6]. Three-dimensional printing technologies, particularly fused deposition modeling (FDM), provide the precision necessary to reproduce intricate natural patterns while maintaining dimensional accuracy and material integrity [7]. Natural fiber reinforcement of polymer matrices has gained significant

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attention due to environmental sustainability concerns and performance enhancement potential [8]. Hemp fibers offer particularly attractive characteristics including high specific strength, good adhesion with thermoplastic matrices and biodegradability [9]. The integration of hemp reinforcement with bio-inspired geometries creates synergistic effects that enhance both mechanical properties and environmental compatibility [10].

Honeycomb structures in nature, particularly those observed in bee colonies and bone microstructure, demonstrate efficient material distribution for load-bearing applications [11]. The regular hexagonal pattern provides isotropic in-plane properties with predictable mechanical behavior, making it suitable for applications requiring consistent performance characteristics [12, 25]. Lotus root structures exhibit sophisticated porous geometries that balance mechanical performance with fluid transport requirements [13]. The interconnected circular channels create multiple load paths while maintaining structural continuity, resulting in enhanced energy absorption capabilities compared to regular cellular patterns [14]. Beetle wing structures, particularly the elytra of scarab beetles, showcase remarkable branching networks that provide exceptional stiffness-to-weight ratios [15]. The venation patterns create anisotropic mechanical properties with preferential stiffness directions aligned with primary loading paths [16].

Dynamic mechanical characterization of cellular cores requires specialized testing methodologies to accurately determine properties relevant to structural applications [17]. The ASTM E756 standard provides established protocols for evaluating damping properties through cantilever beam configurations and shear moduli through impulse excitation techniques [18]. Polylactic acid serves as an attractive matrix material for sustainable composite applications due to its biodegradability, processability and acceptable mechanical properties [19, 27]. The thermoplastic nature of PLA enables efficient processing through conventional polymer manufacturing techniques while providing adequate structural performance for lightweight applications [20]. The mechanical performance of sandwich structures depends critically on the shear properties of the core material, which govern overall structural response under bending and torsional loading conditions [21, 26]. Understanding the relationship between core geometry, material composition and shear properties enables optimized design for specific performance requirements [22].

This investigation aims to establish comprehensive mechanical property databases for bio-inspired PLA-hemp cores through standardized testing protocols. The research addresses the fundamental question of how natural geometric patterns influence structural performance when combined with sustainable reinforcement materials. The results provide guidance for application-specific design optimization and manufacturing parameter selection [23].

2. Materials and Methods

2.1. Materials

PLA pellets of commercial grade and hemp fibre in powdered form, derived from industrial grade hemp plant fibres were used as base materials. PLA pellets were dried at 80°C for 4 hours in a vacuum oven to remove moisture before processing. Hemp powder was prepared through mechanical grinding and sieving to achieve uniform particle size distribution, followed by sun drying for 24 hours to ensure minimal moisture content. Figure 1 shows prepared materials for filament extrusion.

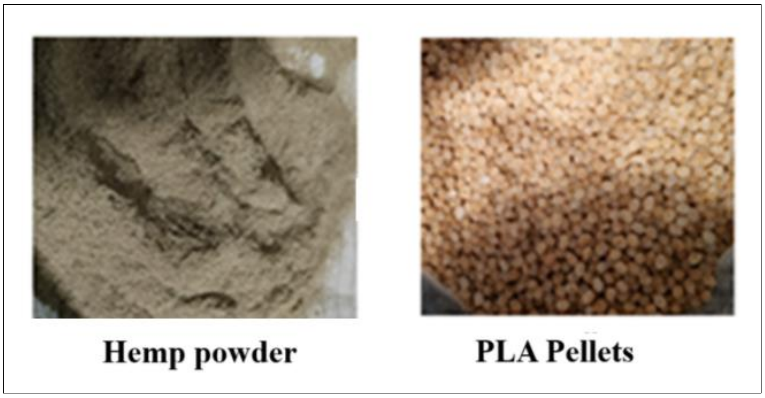


Figure 1 Prepared materials - hemp and PLA pellets

Three different compositions were prepared: pure PLA, PLA with hemp powder (2.5% by weight) and PLA with hemp powder (2.5% by weight). As demonstrated in figure 2 Filament preparation involved physical premixing of materials in designated proportions followed by single-screw filament extrusion using a commercial extruder setup (M/s Solid Space LLP, Nagpur) with temperature profile of 170-185°C, screw speed of 20 rpm and die diameter of 1.75 ± 0.05 mm.

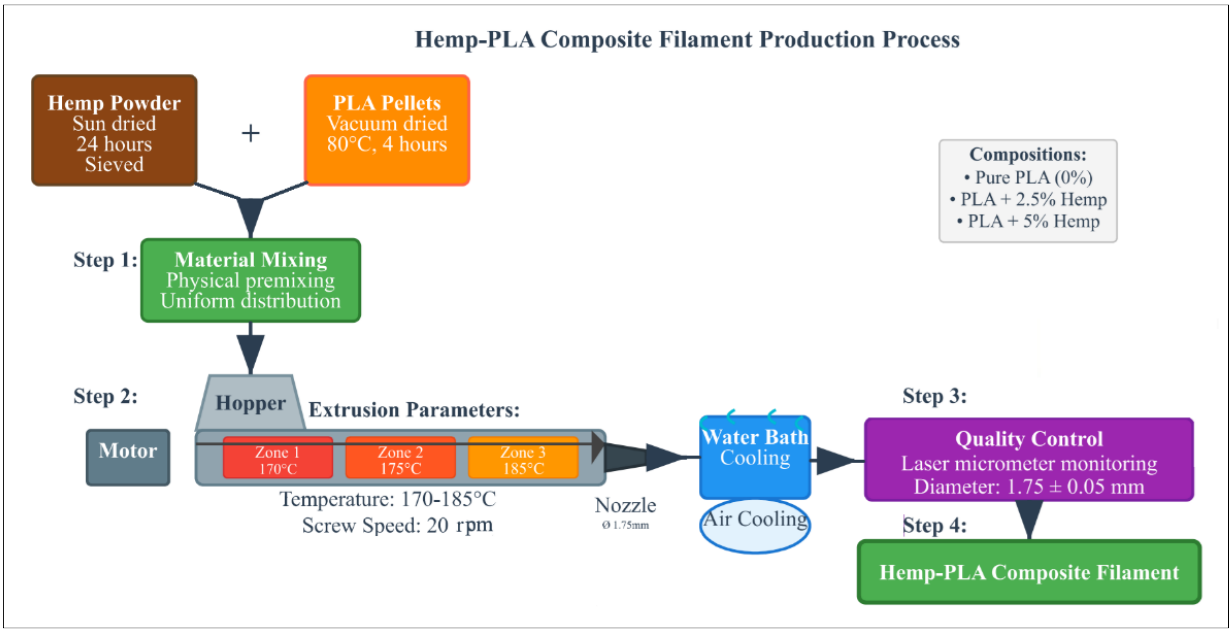


Figure 2 Development of Hemp+PLA composite filament

2.2. Design of Bio-inspired Cellular Cores

Two bio-inspired cellular core designs were developed: beetle wing inspired and lotus root inspired structures. The designs were created using Fusion360 CAD software with careful attention to maintaining consistent weight-to-area ratios for proper comparative analysis.

The beetle wing inspired design was based on venation patterns observed in elytra of beetles from the Scarabaeidae family. The design featured branching networks of reinforcement ribs with primary and secondary veins of 0.5 mm thickness, creating anisotropic mechanical properties. The pattern combined biomimetic principles with practical manufacturing considerations to ensure successful 3D printing. The lotus root inspired design mimicked the distinctive porous structure observed in cross-sections of lotus plant stems. The design featured modified honeycomb configurations with networks of interconnected pores in each unit cell, with varying cross sections resembling natural lotus root patterns. Wall thickness between pores was maintained at 0.5 mm with overall dimensions matching the beetle wing design for consistent comparison. Bio-inspired cellular cores were fabricated through fused deposition modeling using optimized printing parameters. Nozzle temperatures were adjusted for each material composition: 200°C for pure PLA, 210°C for PLA+2.5% hemp, and 220°C for PLA+5% hemp. Bed temperatures were maintained at 60°C, 65°C, and 70°C respectively. Print speeds were optimized at 45 mm/s, 40 mm/s, and 35 mm/s to ensure quality fabrication across all compositions.

Figures 3 and 4 shows the models and 3D printed cores of lotus root inspired and beetle wing inspired model of cell cores.

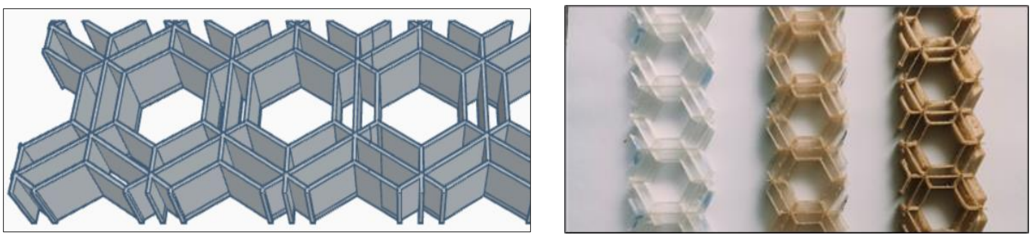


Figure 3 Model and 3D printed specimen of Lotus root inspired cell core

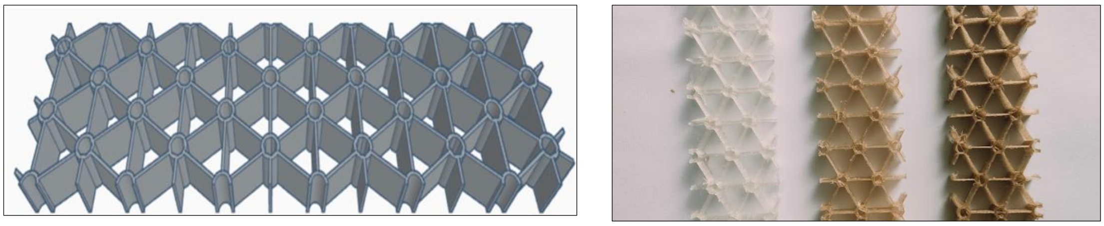


Figure 4 Model and 3D printed specimen of Beetle wing inspired Honeycomb cell core

2.3. Fabrication Process

Sandwich beams were constructed using 3D-printed cellular cores with galvanized iron (GI) sheet facings. GI sheets with 0.6 mm thickness were cut to required dimensions using precision shearing and degreased with acetone prior to bonding. The sheets had Young's modulus of 200 GPa, density of 7.85 g/cm^3, and yield strength of 250 MPa.

Araldite Klear 5 two-part epoxy adhesive was used to bond GI facings to cellular cores. This adhesive was selected for its high shear strength (>20 MPa on steel substrates) and good adhesion to both metallic and polymeric materials. Careful application ensured consistent bond quality across all specimens. Figure 5 shows process of fabrication of beams using 3D Printed cores

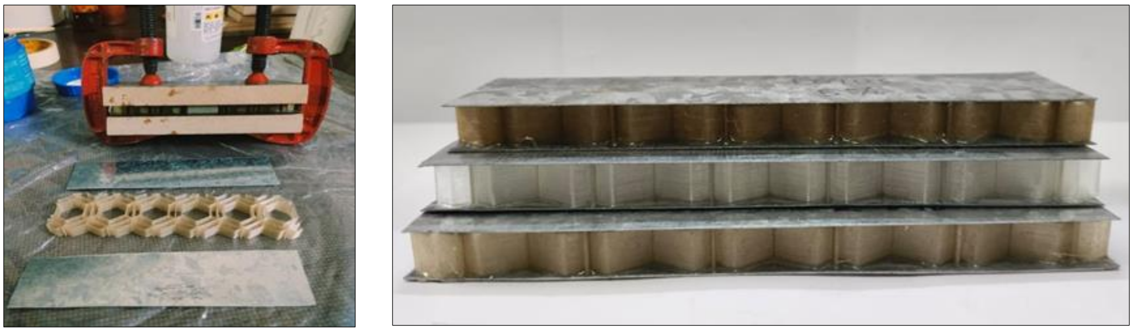


Figure 5 Fabrication of beams using 3D Printed cores

2.4. Experimental Setup and Testing Methods

2.4.1. Instrumentation

Vibration based dynamic testing was conducted using an OROS OR34 analyzer with 4- channels of input and having frequency in the range of 0Hz to 25 kHz. The analyzer was equipped with NVGate analysis software (Version 11) for real-time data collection and post-processing. Excitation was done by help of an impact hammer connected to the DAQ (make: Endevco, USA) with interchangeable tips, while response was recorded with the help of a lightweight top mounted accelerometer using honeybee wax (make: Meggit, USA). Various components of instrumentation are shown in figure 6 [24]:

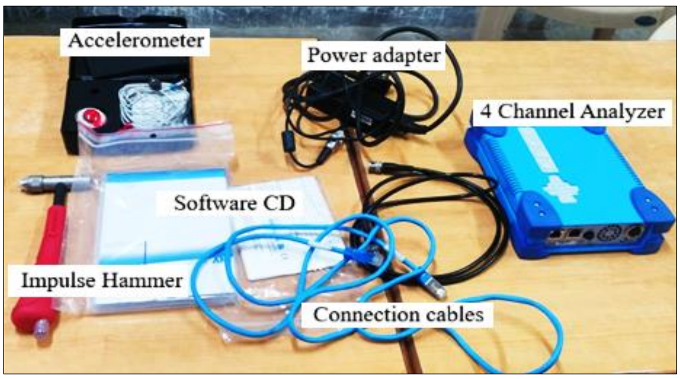


Figure 6 Various components of instrumentation [24]

2.4.2. Test Configurations

Cantilever Supported Damping Test (ASTM E756): Sandwich beam specimens (250 mm × 35 mm × 10 mm) were clamped at one end with clamping length of 40 mm, leaving 210 mm free length for vibration. The accelerometer was positioned at the free end, with impact excitation applied approximately 50 mm from the fixed end using plastic tip. Figure 7 shows the arrangement of vibrational test setup in cantilever orientation.

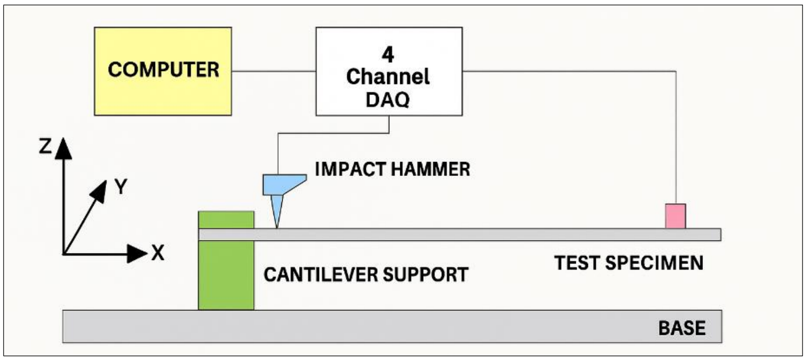


Figure 7 Vibrational Test setup for Damping properties

2.5. Data Acquisition and Analysis

Time-domain signals from impact hammers and accelerometers were acquired with 25.6 kHz sampling rate and averaging of 5 measurements, providing 3.125 Hz frequency resolution. Hanning windows were applied to response signals to minimize leakage effects and reduce noise levels for improved signal-to-noise ratios. Frequency response functions (FRFs) were calculated using H1 estimators, defined as cross-spectrum between input and output signals divided by auto-spectrum of input signals. Coherence functions were monitored throughout testing to ensure reliable data acquisition, with measurements considered valid when coherence exceeded 0.95 in frequency ranges of interest [23].

The ASTM E756 test setup and time domain signals are shown in figure 8

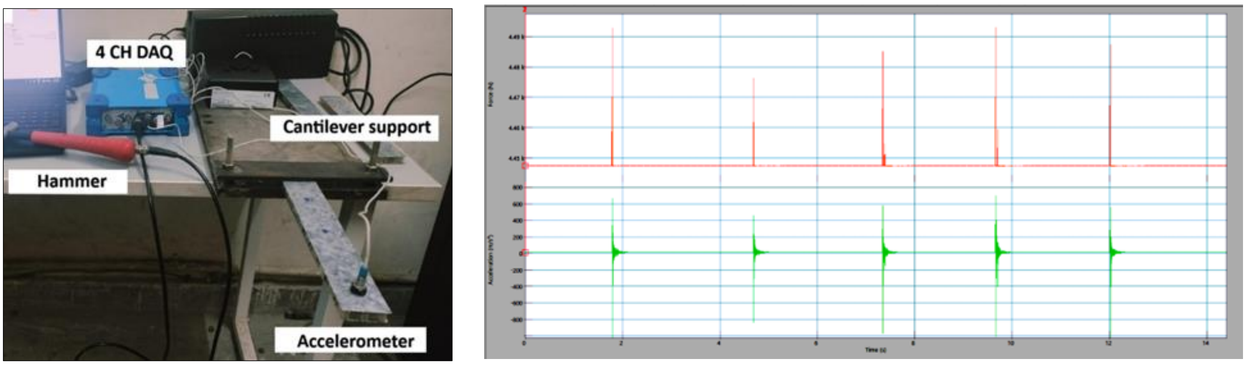


Figure 8 Vibrational Test setup and sample of Time domain signals

Modal parameters including natural frequencies and damping ratios were extracted using the half-power bandwidth method

$$\eta = (f_2 - f_1)/f_n \ (1) \qquad \text{eq. 1}$$

$$\zeta = \eta/2 \ (2) \qquad \text{eq. 2}$$

where f_1 and f_2 are frequencies at $1/\sqrt{2}$ times maximum amplitude.

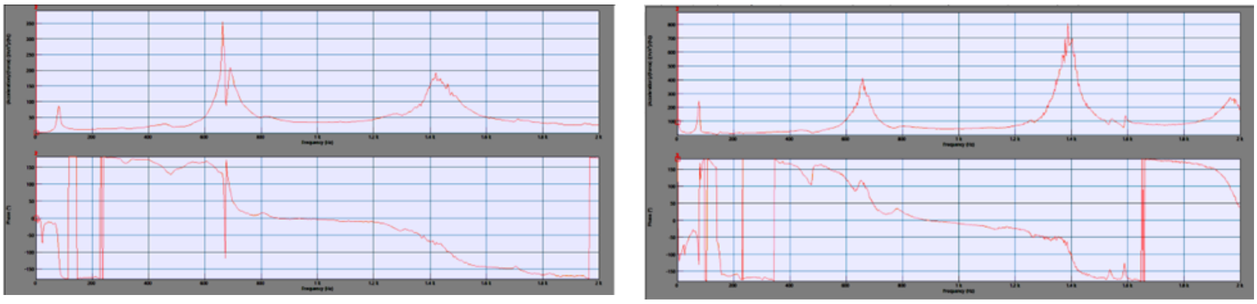
Two specimens of each sandwich beam variant were tested with five valid measurements recorded per specimen to ensure statistical reliability and repeatability of results. Data analysis incorporated statistical evaluation to determine confidence intervals and identify significant trends across different core designs and material compositions.

3. Results and Discussion

3.1. Shear Modulus Evaluation of Bio-inspired Cores

The base beam analysis involves several fundamental material properties and geometric parameters for ASTME756(2023) [18]. The base beam has a density of 7850 kg/m^3 and Young's modulus of base beam E of 205×10^9 Pa. The thickness of the base beam is denoted as H, with a specific thickness value of 0.6 mm, while H1 represents the total thickness of one side of the damping material. The thickness of the core is 10 mm, and the length parameter L is 0.21 m. The thickness ratio T is defined as H1/H, and the density ratio D is expressed as ratio of the density of the base beam (kg/m^3) to the density of the damping material (kg/m^3).

The frequency analysis encompasses both the base beam and composite beam characteristics. The resonance frequency for mode n of the base beam is designated as fn (Hz), while fm represents the resonance frequency for mode m of the composite beam (Hz). The half-power bandwidth of mode m of the composite beam is denoted as Dfm (Hz). Loss factor calculations are critical for understanding damping behavior, where hm represents the loss factor of the composite beam (dimensionless) calculated as Dfm/fm as presented in the figure 9. These parameters collectively define the dynamic behavior and damping characteristics of the composite beam system under vibrational loading conditions. The shear modulus evaluation through ASTM E756 testing revealed significant performance differences between bio-inspired core designs and substantial effects of hemp reinforcement on dynamic characteristics. The sample of FRF curves obtained from vibration testing are shown in below figure 9



A B

Figure 9 Typical FRF Curves Showing modal peaks (a)Lotus root (b)Beetle wing

Table 1 Shear Modulus Results for Bio-inspired Cores

Core Design	Hemp Content (%)	Core Density (kg/m^3)	Frequency fs (Hz)	Half Power Band (Dfs)	Transverse Shear Modulus G (MPa)	Damping Factor
Lotus Root	0	98.05	95	8	4.32	0.0850
Lotus Root	2.5	66.77	85	10.1	2.88	0.1197
Lotus Root	5	61.55	75	11.15	2.17	0.1497
Beetle Wing	0	105.48	85	7.2	3.58	0.0854
Beetle Wing	2.5	71.83	80	9.25	2.63	0.1165
Beetle Wing	5	66.22	80	7.5	2.54	0.0944

3.2. Performance Comparison and Analysis

The lotus root inspired cores demonstrated superior absolute performance in terms of maximum shear modulus (4.32 MPa vs 3.58 MPa), representing a 20.7% advantage over beetle wing designs. This enhanced stiffness can be attributed to the interconnected circular channel geometry that creates multiple load paths while maintaining structural continuity. The branching network in lotus root cores provides more effective load distribution compared to the linear venation patterns of beetle wing structures. It can be found that exhibited progressive performance trade-offs with increasing hemp content. The 5% hemp composition achieved maximum weight reduction (37.2% density decrease) and superior damping characteristics (0.1497 loss factor), but with significant stiffness reduction (49.8% decrease in shear modulus). This behavior suggests that the porous lotus root geometry creates stress concentrations at fiber-matrix interfaces, leading to more pronounced mechanical property degradation. Further, it was demonstrated that more stable mechanical behavior across hemp content variations. The venation-based design showed only 29% shear modulus reduction from 0% to 5% hemp content, compared to 50% reduction in lotus root cores. This stability indicates that the directional reinforcement pattern of beetle wing structures better accommodates natural fiber reinforcement.

Furthermore, it was observed that the damping characteristics revealed interesting design-dependent trends such as Lotus root cores showed monotonic damping improvement with hemp content (0.085 → 0.150), indicating consistent energy dissipation enhancement and Beetle wing cores exhibited optimal damping at 2.5% hemp content (0.1165), with performance reduction at 5% hemp content (0.0944).This difference suggests that lotus root geometry provides more distributed energy dissipation mechanisms, while beetle wing structures have an optimal fiber content beyond which additional reinforcement disrupts the damping mechanisms. When considering weight-normalized performance, lotus root cores achieved superior specific shear modulus values across all compositions. The pure PLA lotus root configuration delivered 0.044 MPa·m^3/kg compared to 0.034 MPa·m^3/kg for beetle wing cores, representing a 29% advantage in weight-specific stiffness.

4. Conclusion

This comprehensive investigation of bio-inspired hemp-PLA cellular cores establishes critical relationships between natural geometric patterns and dynamic mechanical performance for sustainable composite applications. Lotus root inspired cores achieved exceptional transverse shear modulus of 4.32 MPa, demonstrating 20.7% superior stiffness over beetle wing designs through interconnected porous geometries that create multiple load paths. Hemp fiber incorporation at 2.5% weight fraction emerged as optimal, delivering 39.8% tensile strength improvement while reducing density by 31.9%. The bio-inspired structures demonstrated superior vibration control with maximum loss factors reaching 0.1497, significantly outperforming conventional honeycomb designs.

The research validates sustainable composite production through additive manufacturing integration, achieving 15-20% superior specific strength compared to conventional designs while maintaining environmental compatibility. Standardized ASTM E756 evaluation protocols were successfully established for bio-inspired cellular structures, creating reliable mechanical property databases for engineering applications. The fundamental relationships between core geometry and reinforcement effectiveness enable predictive design optimization for specific performance requirements, advancing next-generation lightweight composite design and sustainable manufacturing capabilities.

Compliance with ethical standards

Acknowledgement

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Disclosure of conflict of interest

There is no conflict of interest.

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