

Sustainable Manufacturing of Aircraft (SUMAC)

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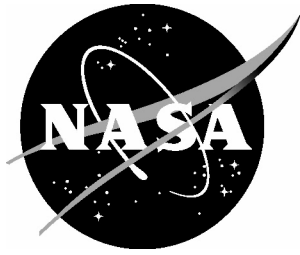
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Convergent Aeronautics Solutions (CAS) Project

Closeout Report

Sustainable Manufacturing of Aircraft (SUMAC)

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4QFY24 - 4QFY25

Activity Name: Sustainable Manufacturing of Aircraft (SUMAC)	
Title: CAS SUMAC Closeout Report	Closeout Date: 9/30/2025

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Principal Investigator (PI)/Co-PI Name(s):	Sang-Hyon Chu (LaRC)/Cheol Park (LaRC), Sandi Miller (GRC), and Andrew Santos (ARC)
Execution Duration:	4QFY24 – 4QFY25 (September '24 - September '25)

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1. Executive Summary

The CAS SUMAC (Sustainable Manufacturing of Aircraft) project aims to develop and demonstrate advanced composite technologies that combine exceptional performance with environmental responsibility. At its core, SUMAC leverages the synergistic benefits of hollow-core natural fibers and sustainably derived thermoplastic resins to create next-generation aerospace materials tailored for interior and secondary structure applications in Advanced Air Mobility (AAM) and, in the long term, commercial aviation. This application focus is carefully adjusted, reflecting the inherent performance characteristics of natural fiber reinforced bio-sourced composite systems, which are ideally suited for non-load-bearing structural components where their weight savings, vibration damping, noise mitigation, interference-free communication, and sustainability benefits can be maximized without compromising safety-critical primary structure requirements.

The hollow core and hierarchical microfibrillar structure of the natural fibers used in SUMAC composites are central to their exceptional performance. These fibers deliver significant weight reduction while providing superior vibration damping and noise mitigation—up to 250 percent better damping than conventional carbon fiber composites. Such characteristics directly support AAM’s unique operation environment that demands lightweight aircraft, quiet operation, passenger comfort, and safe communication in urban flight environments. In parallel, the project’s sustainably derived thermoplastic resins, specifically polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), and polyamide-11 (PA11) are bio-sourced, either plant-based or microbially produced, and offer recyclability, high-throughput fabrication, reduced carbon footprint, and compatibility with sustainable manufacturing systems that reuse and recycle materials in closed loops. Together, the fibers and resins form fully recyclable composite systems that can be processed efficiently, reshaped, if necessary, and repurposed at end-of-life, aligning with NASA’s sustainability objectives and global climate goals.

Use Case Highlight: Natural Fibers

Hemp and flax natural fibers offer multifunctional advantages that enhance **performance, safety, and comfort** for future aerospace systems:

- **Weight Reduction:** Up to 20% weight savings compared with carbon fibers, improving energy efficiency and payload capacity.
- **Vibration Damping:** Dissipate vibration up to 250% more effectively than carbon fibers, enhancing ride comfort and reducing structural fatigue.
- **Acoustic Noise Abatement:** Scatter and absorb sound, reducing external and cabin noise without added insulation.
- **Safe Communication:** Enable safe, interference-free communications critical for Advanced Air Mobility.

The SUMAC project focuses on six interconnected technical areas: sustainable thermoplastic resins, natural fibers, sustainable manufacturing, integrated sensing, computational modeling, and life cycle analysis (LCA). This integrated approach ensures

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that advances in one domain reinforce progress in the others, enabling optimized material systems, scalable manufacturing, and robust performance verification. Since the beginning of the execution phase in September 2024, the team has made substantial progress across these areas, supported by close collaborations among three NASA centers – Langley, Glenn, and Ames research centers, and with industry partners, academic institutions, and other government agencies.

A key milestone during the execution phase is the down-selection of natural fibers and bio-sourced thermoplastic resin systems. This effort has been guided by extensive testing of mechanical properties, vibration damping, environmental durability, and manufacturability. In parallel, the composite design has been optimized by computational modeling of natural fiber fabric patterns and mechanical property predictions. The project’s LCA work has focused on a detailed case study for a bulkhead application in Joby Aviation’s AAM vehicle. This bulkhead, located behind the passenger seats, offers an ideal technology demonstration opportunity, showcasing SUMAC composites’ ability to reduce weight, absorb vibrations, and mitigate cabin noise—properties that directly enhance passenger experience and operational efficiency. As part of this technical demonstration effort, the project successfully fabricated Joby’s propeller blades and c-channel seat brace prototypes using flax-PA11 composites, validating both the material’s processability and its application potential in representative aerospace components.

Throughout the entire project schedule, engagement with industry partners remained a cornerstone of SUMAC’s transition strategy. Biweekly technical exchanges with Joby Aviation have deepened the team’s understanding of AAM design criteria, operational environments, and potential component applications for SUMAC composites in interior and secondary structures. NASA Space Act Agreement (SAA) with Joby Aviation was focused on formalizing this collaboration, enabling direct exchange of data, joint evaluations, and the exploration of near-term integration opportunities. Engagements with Missouri University of Science and Technology via SAA are expanding capabilities in structural health monitoring, while collaborations with the U.S. Army are advancing sensor integration for aerospace structures. The project also explored lessons from the automotive sector that have successfully deployed natural fiber composites in high-performance and mass-production settings. These examples underscore the scalability and versatility of such materials and inform potential pathways for AAM adoption.

In addition, the project has built close relationships with Boeing Research & Technology (R&T). In a tag-up meeting on April 30, 2025, Boeing Vice President, structure engineers and materials specialists expressed particular interest in SUMAC’s vibration damping and acoustic attenuation capabilities, recyclability, and mechanical performance metrics. Discussions explored potential applications ranging from helicopter rotor blades and wind turbine blades to fuselage noise abatement, transformer noise control, and space launch pad structures. Boeing also highlighted the importance of measuring damping properties across temperature and amplitude ranges, identifying relevant noise frequency targets, and

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engaging their internal noise team for future collaboration. The meeting also opened opportunities for cross-sector applications, including sustainable packaging solutions in coordination with Amazon. Follow-up actions include deeper acoustic property characterization, targeted frequency analysis for rotorcraft and transformer applications, and coordination with Boeing’s sustainability leadership for potential joint efforts.

The project has also expanded industrial collaboration to strengthen the domestic natural fiber supply chain—critical for the scalability and resilience of SUMAC technology. In particular, SUMAC is supporting EnviroTextiles LLC, a domestic hemp fiber supplier, in the development of hemp fibers tailored for aerospace-grade composites. EnviroTextiles provided multiple hemp fiber samples that have undergone mechanical, chemical, and morphological analysis at NASA Langley facilities. These evaluations are aimed at improving fiber consistency, mechanical performance, and compatibility with thermoplastic resin systems, ultimately enhancing the performance of SUMAC composites while reinforcing domestic manufacturing capabilities.

Outreach and workforce development are integral to the SUMAC mission. The SUMAC Working Group hosted monthly technical sessions on topics such as sustainable materials, manufacturing processes, inspection methods, and modeling. These sessions regularly drew over 60 participants, with more than 120 stakeholders engaged. The project has also been featured in Composites World magazine and in numerous technical publications and conference presentations. Over the course of the project, 26 intern students have made solid contributions to research and development, reinforcing NASA’s role in cultivating the next generation of aerospace engineers and scientists.

In summary, CAS SUMAC has made decisive progress toward delivering a new class of aerospace composites that unite weight savings, vibration and noise control, safe communication, recyclability, and sustainability. By aligning cutting-edge material science with environmental stewardship, and by focusing on applications where natural fiber composites provide optimal benefits in interior and secondary structures, the project is poised to contribute significantly to NASA’s vision for sustainable aviation and to influence the next generation of both AAM and commercial aircraft design.



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2. Background

Through the “Synthesis” phase of this project, the CAS SUMAC team researched a myriad of topics related to sustainability in aeronautics applications. This ranged from integration of infrastructure to support electric aircraft in airports to life cycle analysis of rare earth elements in superalloys utilized in jet engine components. Three primary objectives were identified as a result of a technical interchange meeting (TIM) held at NASA Glenn Research Center in April, 2023: sustainably-derived thermoplastic composite materials, dispersion-strengthened metal alloys, and integrated sensing. An opportunity concept report (OCR) was generated for each of these areas and presented to a roundtable of subject matter experts in August, 2023. The recommendations from the roundtable were to pursue sustainably-derived thermoplastic composites and shift the emphasis from transport aircraft to AAM applications. With this recommendation and transitioning of the CAS SUMAC project from “Synthesis” to “X1,” the team transitioned all efforts toward sustainably-derived thermoplastic composites with consideration of the entire life cycle of the composite materials (Figure 2.1).

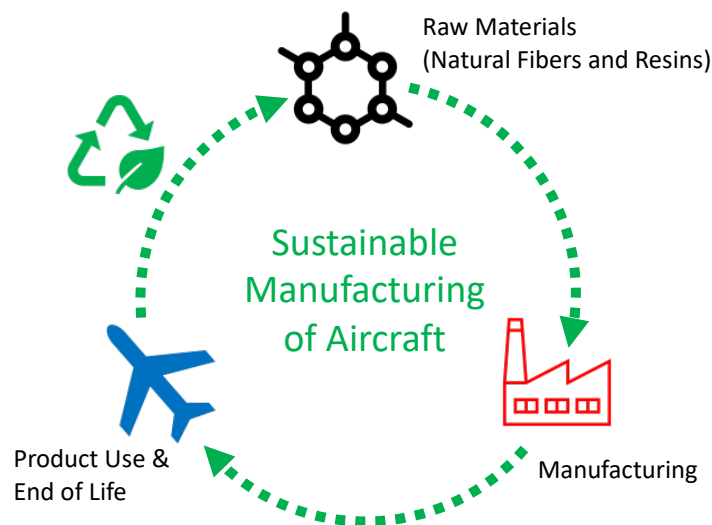


Figure 2.1 Sustainable manufacturing of aircraft.

The bio-sourced composite market, specifically those based on natural fibers, has seen significant growth due to increasing public awareness. The demand for natural fiber composites is high in industries, such as automotive and construction, due to their weight-saving properties, reduced CO₂ emissions, and low environmental burden. Likewise, the thermoplastic composites market is experiencing rapid growth due to their toughness, fatigue resistance, rapid production, easy repair, recyclability, and cost-effectiveness. The market is projected to reach \$465 million by 2026.

Multifunctional sustainably-derived thermoplastic composites have the potential to make a significant impact in the aviation industry. Weight reduction achieved with lightweight

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composites leads to improved fuel efficiency, reduced greenhouse gas emissions, and enhanced aircraft performance. The durability and high strength-to-weight ratios of these composites result in longer service life and reduced maintenance requirements. Furthermore, the research activities for sustainable composites and manufacturing processes help to reduce environmental impact, build robust supply chains, and support the circular economy. The use cases for sustainable thermoplastic composites include the utilization of natural fibers and bio-thermoplastic resins for non-structural aircraft parts. These composites, made from fibers such as flax, hemp, and ramie, and resins like poly-lactic acid and poly-hydroxy-butyrate, are candidates for use in components such as cabin panels, seat backs, fairings, and winglets.

2.1 Topic areas of SUMAC project

The CAS SUMAC team will seek to advance the material readiness level (MRL) of sustainable composites with efforts focused on several topic areas:

- Evaluation and characterization of sustainably-derived thermoplastic resins
- Determination of natural fiber material candidates
- Fabrication of test articles and a demonstration article using sustainable composite materials and manufacturing methods
- Acceleration of experimental results using computational materials modeling methods
- Integration of distributed sensing capabilities to enable vehicle health monitoring with an emphasis on materials properties unique to natural systems
- Identification of the highest impact applications for sustainable composite materials on AAM platforms using systems analysis
- Evaluation of scalability and life cycle assessment across a fleet of AAM vehicles

2.1.1 Sustainably-derived Thermoplastic Resins

Thermoplastic resins are increasingly gaining attention within aerospace and automotive sectors as a result of their high impact-resistance, shorter processing times, and recyclability over their thermoset composite counterparts which have been predominantly utilized as high-performance aerospace composite materials. Their ability to withstand repeated processing, enhanced mechanical properties, and cost-effective and sustainable manufacturing processes make thermoplastic resins a highly desirable choice for future composite applications in the aerospace industry.

While thermoplastic resin has already been adopted by NASA programs, thermoplastic resins derived from bio-based resources can maximize the sustainability of SUMAC composites. As shown in Figure 2.2., the bio-based or sustainably-derived resins can reduce the environmental impact in comparison to the petroleum-based synthetic resins [1]. Currently-available bio-based resins usually show limitations, including lack of high-temperature stability and poor mechanical properties, as indicated in Figure 2.3 [1]. Therefore, it is necessary to identify promising candidates and further improve their material properties by tailoring their chemical formulation if possible.

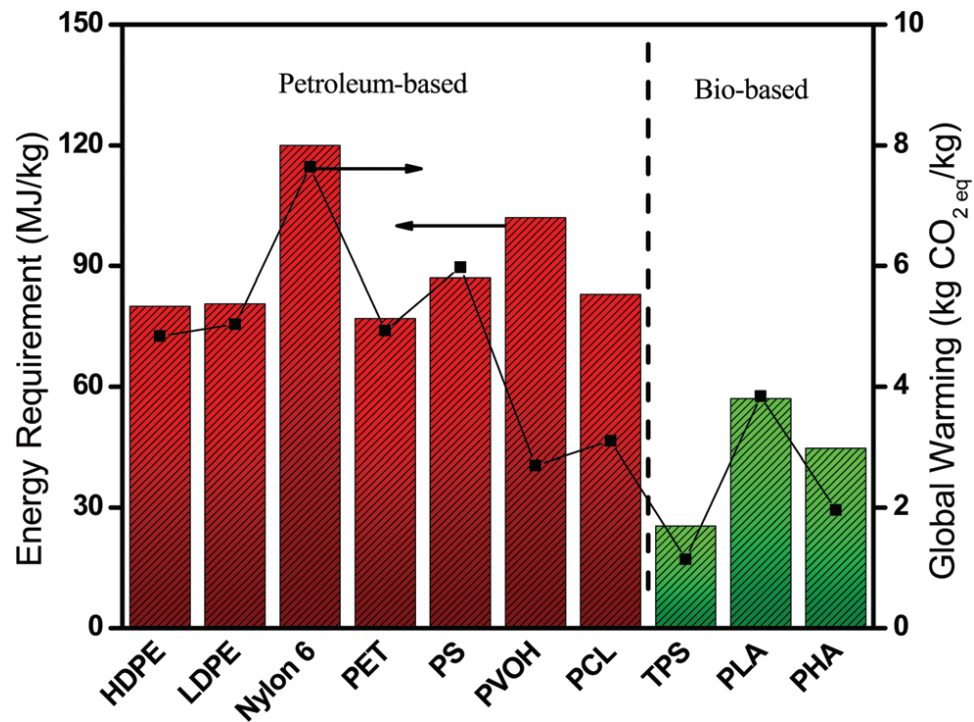


Figure 2.2 Production energy and CO₂ emission from petroleum-based and bio-based resins [1]. (HDPE: high density polyethylene, LDPE: low density polyethylene, PET: polyethylene terephthalate, PS: polystyrene, PVOH: polyvinyl alcohol, PCL: polycaprolactone, TPS: thermoplastic starch, PLA: polylactic acid, and PHA: polyhydroxyalkanoates).

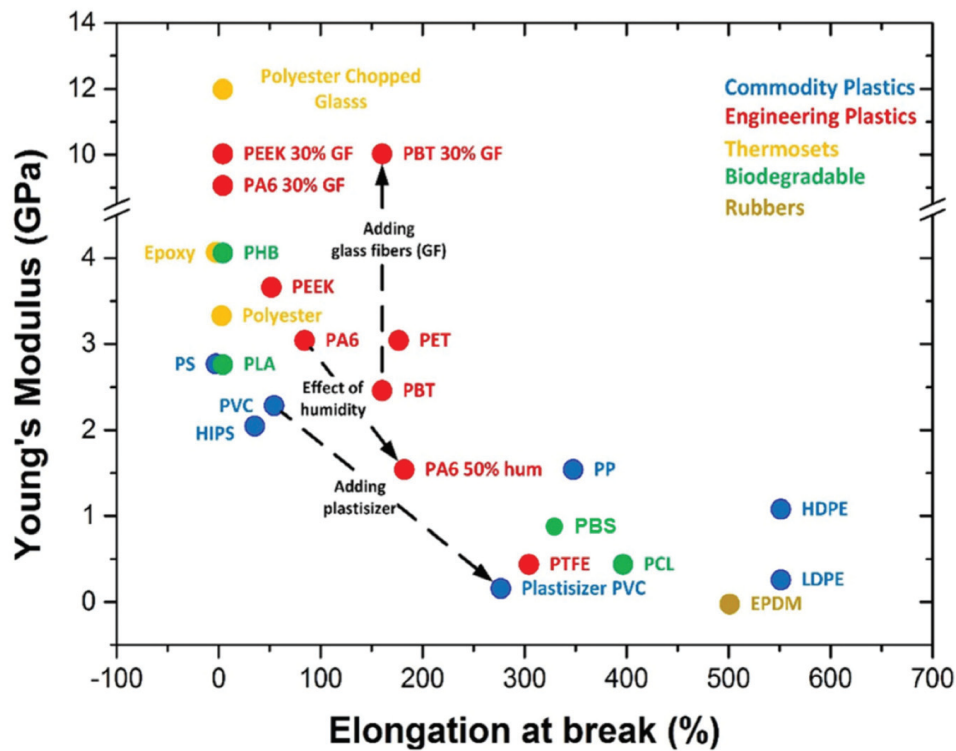


Figure 2.3 Ashby plot of tensile properties for natural and synthetic resins [1]. (PS: polystyrene, PVC: polyvinyl chloride, HIPS: high impact polystyrene, PP: polypropylene, HDPE: high density polyethylene, LDPE: low density polyethylene; PEEK: polyetheretherketone, PBT: polybutylene terephthalate, PA: polyamide, PTFE: polytetra-fluoroethylene; PHB: polyhydroxybutyrate, PLA: polylactic acid, PCL: polycaprolactone, PBS: polybutylene succinate; EPDM: ethylene propylene diene monomer).

Market analysis performed by PreScouter provided additional insights regarding the availability, scalability, and current research/evaluation efforts involving sustainably-derived resins. Polylactic acid (PLA) was one of several resins identified in the PreScouter report as showing promise as a scalable resin that has a high technology readiness level, TRL 8. The company identified in the PreScouter report utilized greenhouse gases as a feedstock. Polyhydroxyalkanoates (PHA)s can also be fabricated using greenhouse gases. Additionally, several resins were identified that were not sustainably-derived but were designed to be recyclable which would reduce the carbon footprint for the use of these materials. Based on these results, both PLA and PHA resin systems were identified as candidates for the work described here.

2.1.2 Natural Fibers

Natural fibers, such as cotton, hemp, jute, flax, kenaf, ramie, and sisal, are also experiencing a notable and increasing demand as sustainable structural materials. They are favored over

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synthetic fibers due to their low cost, weight savings, renewable sourcing, biodegradability, and lower environmental impact. These trends of the natural fiber market reflect the increasing demand for sustainable and eco-friendly materials, advancements in technology, evolving consumer preferences, and market dynamics. While textiles and apparel have traditionally been the primary sectors for natural fibers, they are now being utilized in automotive components, construction materials, packaging, furniture, consumer goods, and even in high-performance applications such as aerospace.

The range of materials properties varies considerably for natural fiber systems [2]. For aerospace applications, materials that provide the greatest mechanical properties at the lowest density are preferred. This has likely influenced the focus of recent research efforts toward flax, hemp, jute, ramie, and cellulose fibers. Many of these systems exhibit superior properties relative to steel wire, although they all exhibited reduced materials properties relative to Kevlar and carbon fiber systems which could influence the potential application space for these material systems.

Table 2.1 provides additional comparisons between natural fibers, glass fibers, and carbon fibers. The annual global production values are notable with natural fibers being produced at a level that is three orders of magnitude greater than carbon fiber. Likewise, the density of these fibers is significantly lower than that of glass fibers. Natural fiber materials exhibit less mechanical wear on processing equipment relative to both glass and carbon fibers. The ecological impacts identified in Table 2.1 all strongly favor the use of natural fibers.

Table 2.1 Properties for natural fibers, glass fibers, and carbon fibers [2].

Properties		Plant Fibers ^a	Glass Fibers ^b	Carbon Fibers ^c
Economy	Annual global production [tons] ^d	31,000,000	4,000,000	55,000
	Distribution in EU [tons] ^d	Moderate (~60,000)	Wide (600,000)	Low (15,000)
	Cost of raw fiber	Low	Low	High
Technical	Density [gcm ⁻³]	Low (~1.35-1.55)	High (2.50-2.70)	Low (1.70-2.20)
	Specific tensile stiffness [GPa/gcm ⁻³]	Moderate (~20-60)	Low (27-34)	High (68-290)
	Specific tensile strength [GPa/gcm ⁻³]	Moderate (~0.3-1.1)	Moderate (0.7-1.5)	High (0.6-3.7)
	Abrasive to machines	No	Yes	Yes
Ecological	Energy demand of raw fiber [MJ/kg]	Low (4-15) ^e	Moderate (30-50)	High (>130)
	Renewable/Biodegradable	Yes	No	No
	Recyclable	Yes	Partly	Partly
	Toxic	No	Yes	Yes

^a Includes bast, leaf and seed fibers, but does not include wood and grass/reed fibers.

^b Includes E- and S-glass fibers.

^c Includes polyacrylonitrile (PAN)- and pitch-based carbon fibers.

^d Estimated values for the year 2010 for global fiber production values and for values on the distribution of fibers for composites in EU.

^e While the energy required in the cultivation of plant fibres is low (4-15 MJ/kg), further processing steps (e.g. retting and spinning) can significantly increase the cumulative energy demand, for instance, to up to 146 MJ/kg for flax yarn.

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Market analysis performed by PreScouter identified several important aspects regarding the different natural fiber systems being considered (Table 2.2). Flax was identified as having one of the largest market shares regarding natural fiber systems with a significant compound annual growth rate (CAGR). Of further interest is that flax fibers have already begun to see significant interest regarding non-traditional applications, such as in composite materials (Figure 2.4). One challenge for this material is that the primary, almost exclusive, exporter is France.

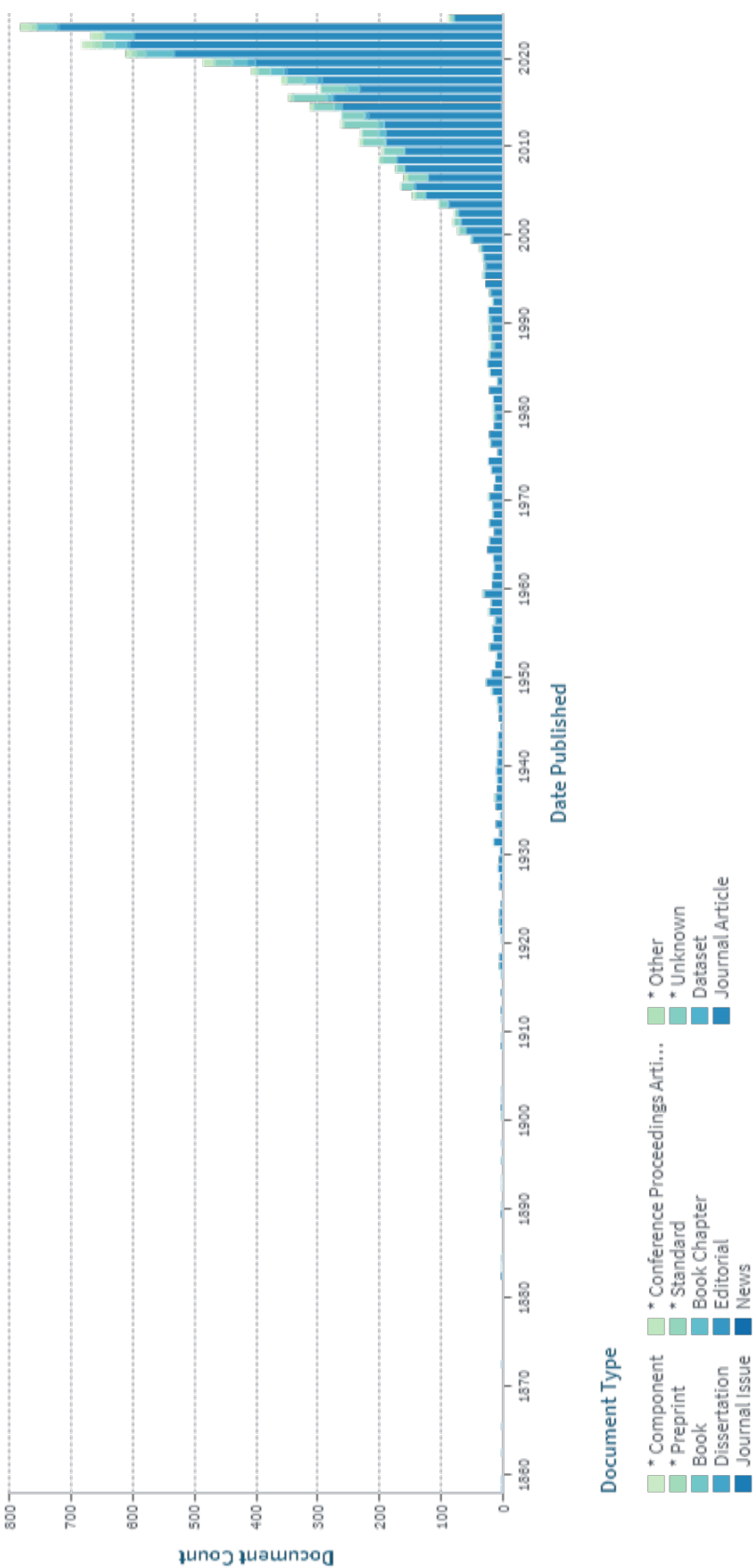
Hemp fibers were also identified as a promising candidate regarding aerospace composite applications. Although the market share for this natural fiber system is lower and the 2021 CAGR rate was negative (Table 2.2), the research interest has been growing significantly with the number of publications doubling in the last five years (Figure 2.4). Additionally, there is growing interest in increasing the production volume of hemp fibers which will result in an increasing CAGR in years to come.

Table 2.2 Natural fiber agro-economic considerations identified by PreScouter market analysis.

Fiber	2021 World Trade (\$M)	2021 Export Growth (CAGR) ^a	Primary Exporter	Primary Importer	Market Consideration
Flax	\$985	35.8%	France	China	Break even prices range from \$0.21 to \$0.47 per pound
Hemp	\$67.2	-18.8%	Italy ^b	Germany	Average price for hemp fiber was \$1.50 per pound in 2021
Coir	\$621	4.7%	India	China	Revenue for one hectare of Malaysia Tall Coconut is \$96.15 per month
Ramie	\$355	3.9%	China	Japan	Ramie market expected to grow 27% by 2030
Kenaf		6.1%	India		Kenaf market project to grow significantly by 2029

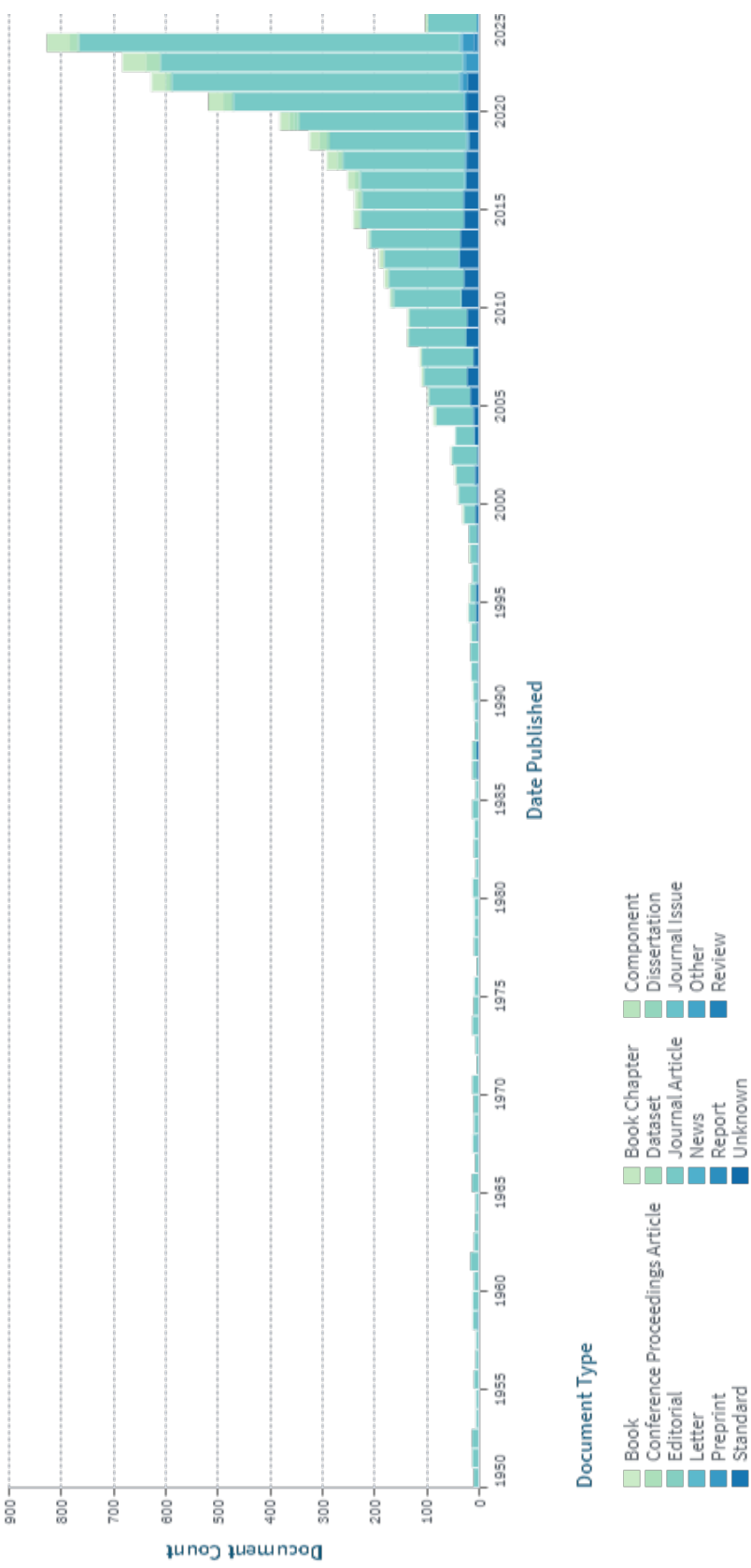
^aCompound Annual Growth Rate

^bThe United States has become the 3rd highest producer of hemp fiber.



(a)

Figure 2.4 Number of publications involving (a) flax fibers and (b) hemp fibers.



(b)

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2.1.3 Sustainable Manufacturing

Another pivotal aspect of the sustainable manufacturing of future aircraft involves the adaptation of design and analysis methodologies to effectively accommodate the durability and lifespan of eco-friendly materials and manufacturing approaches (Figure 2.5). This requires integrating considerations for the unique characteristics and behavior of these materials, ensuring their long-term performance and sustainability within the aircraft's operational lifespan. By proactively addressing the specific requirements and challenges associated with these environmentally conscious alternatives, NASA can contribute to the development of sustainably-derived thermoplastic composites for future aircraft.

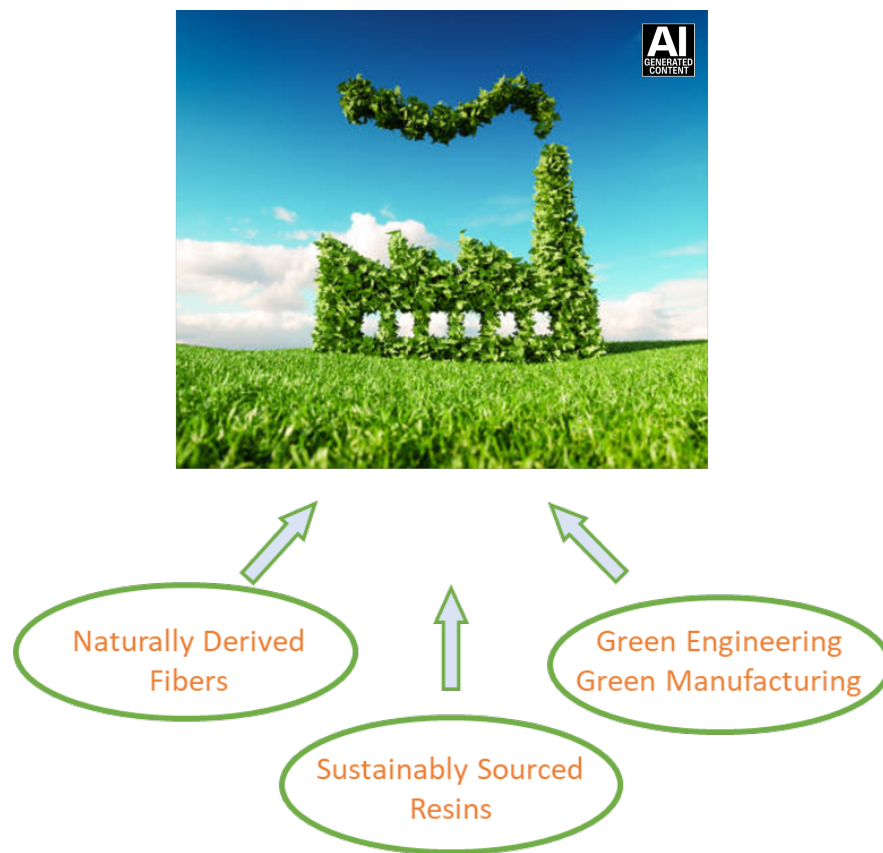


Figure 2.5 SUMAC project aspects being leveraged to enable sustainable manufacturing.

2.1.4 Integrated Sensing

Sensor-based health monitoring is essential for understanding the performance of sustainable natural-fiber composites. Moisture uptake, elastic properties, and dynamic strain events (e.g., from operational loads, impacts, or vibration) can be assessed using a variety of sensors, including strain gauges and accelerometers, piezoelectric acoustic sensors, and wireless electromagnetic sensors. In early applications of sustainable

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materials, integrated sensing is critical for understanding the material's response in the operating environment. In future applications where sustainable materials are fully deployed, sensing will provide feedback for guiding maintenance actions and responding to damage or degradation events that could impact integrity and safety. In both cases, the data from the integrated sensing suite provides a real-time view of the material state, giving operators the information needed to extend the lifespan of sustainably-derived aircraft components (Figure 2.6).

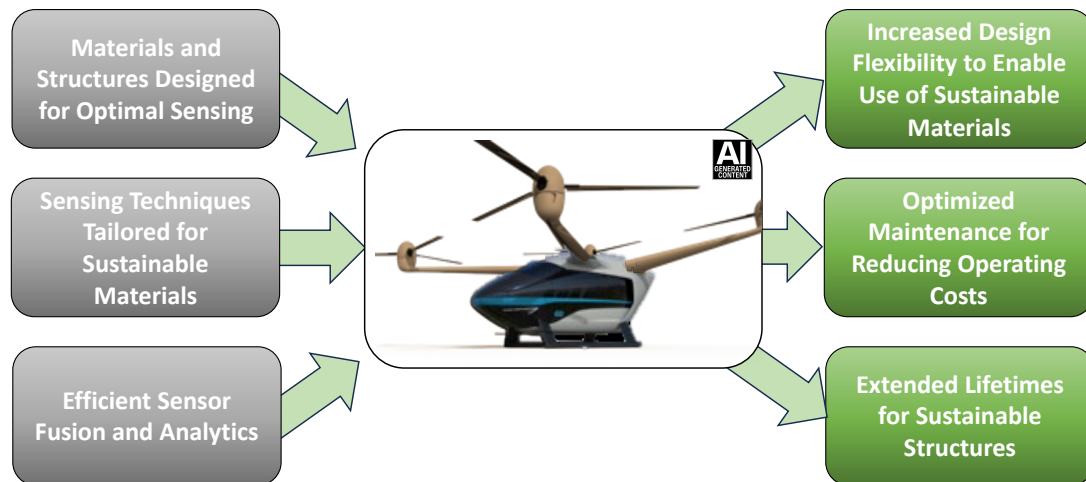


Figure 2.6 Schematic of the approach and benefits to using integrating sensing to enable sustainable materials in AAM vehicle structures.

2.1.5 Computational Materials

To maximize the benefits of thermoplastic composites with natural fibers, the design and analysis processes can be accelerated, utilizing advanced modeling and simulation techniques to predict the behavior and performance of the composite structures. Engineers can achieve lightweight and structurally efficient components by modeling each component in the composite (see Figure 2.7). Analysis of each component's role in composite mechanical performance and structure can improve processing design. Optimized design and analysis methodologies play a crucial role in achieving manufacturing of safe, efficient, and reliable aircraft structures.

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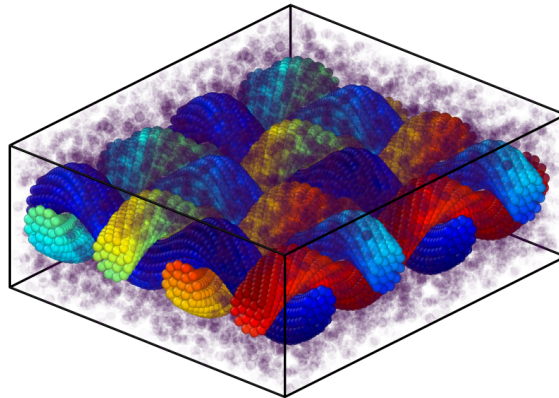


Figure 2.7 Simulation cell of woven natural fiber (opaque) infused in a bio-based polymer resin (transparent). Modeling each component can predict composite properties and analyze the role of microstructure, even during mechanical testing.

2.1.6 Life Cycle Analysis

In the development of sustainable aircraft manufacturing, it is essential to consider the entire lifecycle of the thermoplastic composites with natural fibers including their synthesis, use, and end of life, as shown in Figure 2.8. Designing components with ease of disassembly and separation of materials facilitates efficient reuse and recycling. Thermoplastic matrices can be melted and reprocessed multiple times without significant degradation, allowing for the recycling of the composite materials. Furthermore, the incorporation of natural fibers offers additional environmental benefits. During plant growth, natural fibers facilitate the removal of CO₂ from the atmosphere, contributing to carbon sequestration. The use phase of the aircraft must also be considered. Material systems that add weight to the aircraft are likely to have an overall negative impact on the environment given the extra energy requirements to power the aircraft over the vehicles life. As a result, it will be important to perform a systems analysis to identify applications of natural material systems that minimize environmental impact during the entire lifecycle of the aircraft. The systems and lifecycle analysis will ensure this project aligns with industry's goals of sustainability and environmental stewardship while maintaining structural integrity, safety, and efficiency in aircraft manufacturing and operations.

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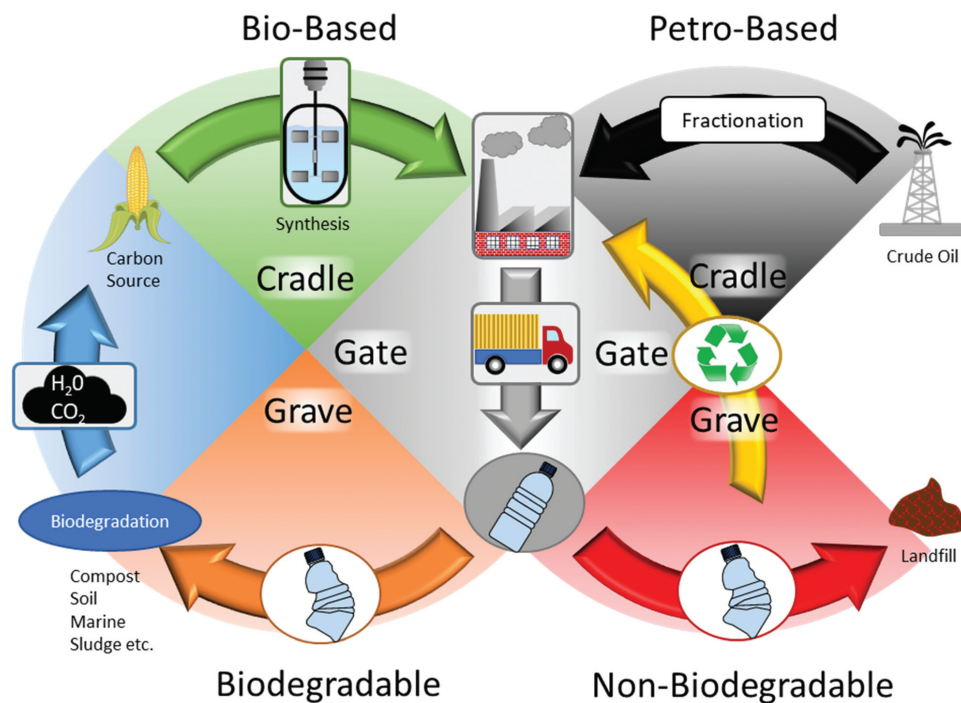


Figure 2.8 Life cycle of bio-based and petroleum-based materials [1].

2.2 ARMD Strategic Thrust Alignment

The proposed research directly aligns with the ARMD Strategic Thrust 3: Ultraefficient Subsonic Transport as well as a key ARMD priority to realize and improve technologies enabling Advance Air Mobility (AAM) platforms. The work proposed here would make a clear impact on the environmental impact of aircraft through integration of natural and sustainably-derived materials with environmentally conscious manufacturing methods to reduce the carbon footprint for manufacturing vehicles. Integrated sensing for vehicle health monitoring will provide greater insights regarding the status of vehicle components which can lead to a paradigm shift in vehicle operation and maintenance. Computational activities will reduce the timeline and required material consumption to advance the research objectives outlined here. Determination of the highest impact components amenable to replacement with sustainably-derived composite materials will enable the greatest increase in inertia across the aerospace community to move toward ever-increasing sustainable practices. Life cycle analysis will be utilized to determine the true environmental impact of the implementation of sustainably-derived thermoplastic composite materials and manufacturing from a cradle-to-cradle perspective.

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2.3 Team Structure

SUMAC consists of six task teams: bio-sourced thermoplastic resins (R), sustainable fibers (F), sustainable manufacturing (M), integrated sensing (S), computational materials (CM), and systems analysis (SA). All the focus area teams seamlessly work together to develop SUMAC composites and manufacturing processes. The resin, fiber, and manufacturing teams work together to optimize material properties and fabrication parameters. The optimization processes are guided by computational modeling and sensing teams, while the systems analysis team identifies the highest impact parts of aircraft and completes life cycle analysis (LCA) work.

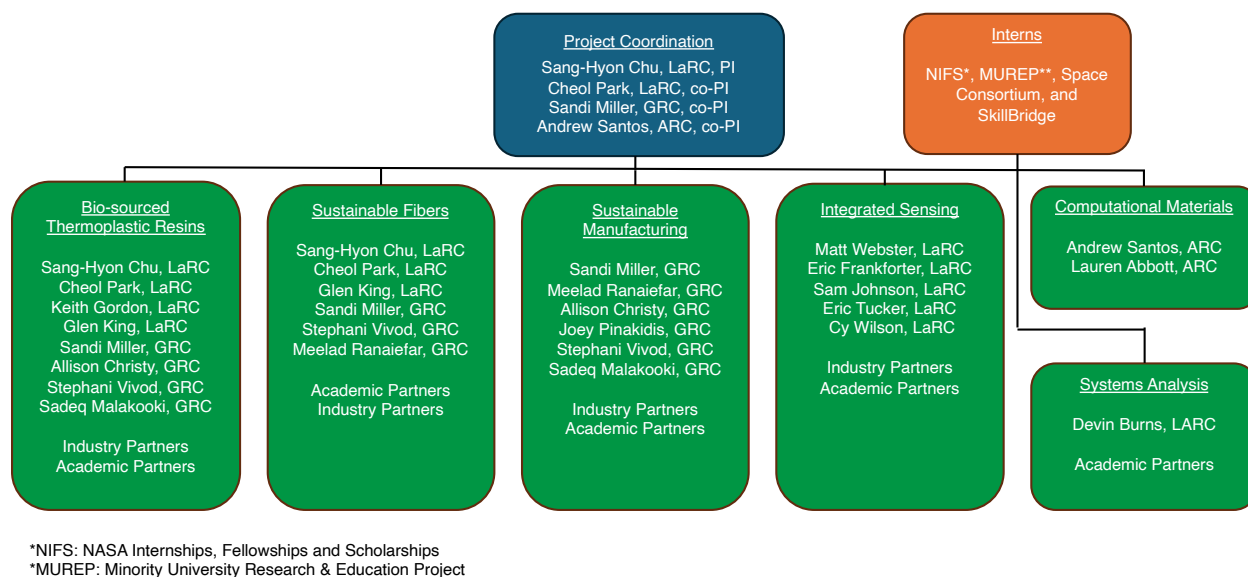


Figure 2.9 Team structure of SUMAC.

2.4 References

- [1] Meereboer, Kjeld W., Manjusri Misra, and Amar K. Mohanty. "Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites." *Green Chemistry* 22, no. 17 (2020): 5519-5558.
- [2] Shah, Darshil Upendra. "Characterisation and optimisation of the mechanical performance of plant fibre composites for structural applications." PhD diss., University of Nottingham, 2013.

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3. Partnerships and Outreach

3.1 OEM Engagement

The SUMAC project has emphasized close engagement with original OEMs and material suppliers to align sustainable composite development with industry priorities. These interactions span three key perspectives: emerging AAM companies seeking lightweight, multifunctional materials for next-generation aircraft; established aerospace OEMs leveraging decades of certification and manufacturing expertise; and material suppliers advancing bio-sourced materials to strengthen domestic supply chains.

Through targeted technical exchanges, SUMAC has worked with Joby Aviation, Boeing Research & Technology, and EnviroTextiles to identify opportunities for weight reduction, vibration and acoustic performance, recyclability, and U.S.-sourced natural fibers. Together, these partnerships have provided a pathway for transitioning SUMAC technologies from research to industry-relevant applications, supporting both performance demands and long-term sustainability goals.

3.1.1 Joby Aviation

The SUMAC project has actively engaged with Joby Aviation (Joby) to explore applications of SUMAC sustainable composite technologies for advanced air mobility platforms. The collaboration was initially pursued through the development of a NASA Space Act Agreement (SAA) annex focused on sensing technologies and sustainable composites. This partnership was expected to provide insight into Joby's design criteria and identify the most suitable application components for SUMAC composites, while offering integrated sensing technology to Joby aircraft.

Regular technical exchanges have taken place through biweekly meetings co-led by Matthew Webster (NASA Langley Research Center) and John Geriguis (Joby). On February 11, 2025, six members of the CAS SUMAC team, accompanied by CAS execution manager Todd Stinchfield, conducted a site visit to Joby's headquarters in Santa Cruz, CA, and its manufacturing facility in Marina, CA. Discussions during the visit included potential demonstrations of SUMAC composites for a bulkhead located behind passenger seats, where weight savings, vibration absorption, and noise mitigation are critical. Subsequent biweekly meetings continued to refine technical directions. NASA received a revised draft of Non-reimbursable SAA annex with Joby with plans for full execution. However, in June, 2025, the decision was made not to proceed with the Joby SAA due to the scheduled closeout of the CAS program.

Despite this outcome, several technical collaboration areas were advanced. Joby expressed strong interest in integrated sensing technology during Joby aircraft shipping to test facility and SUMAC composites for vibration suppression and noise mitigation. Specific

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opportunities included demonstrating a bulkhead application, where composites could provide lightweight structural performance with damping and acoustic attenuation added. Current aircraft weight constraints limit noise mitigation strategies to pilot and passenger headsets, making lightweight multifunctional composite material-based solutions particularly effective. Testing opportunities were identified on the NASA GRC vibration rig (500 Hz to 5 kHz frequency range). Additional Joby testing activities—including cold testing on the dovetail structure and bird strike testing, were also noted as opportunities to integrate sensors for structural health monitoring.

In terms of design integration, Joby recommended using HyperX (formerly HyperSizer) for composite structural analysis, stress evaluation, and sizing optimization. Material property inputs for SUMAC composites would be required for HyperX system analysis. Further coordination included Joby's interest in landing test evaluations at NASA Langley's Landing and Impact Research Facility (LandIR). Plans were also discussed to involve the Federal Aviation Administration (FAA) in upcoming Joby meetings to address structural health monitoring and sensing technologies.

Through these collaborative efforts, NASA and Joby have laid important groundwork for advancing sustainable natural fiber composites in advanced air mobility. While the formal SAA did not proceed, the technical exchanges have identified clear pathways for integrating SUMAC composites into weight-sensitive, vibration-damping, and noise-mitigation applications, with additional opportunities in testing, sensing, and certification support.

3.1.2 Boeing Research & Technology (BR&T)

The CAS SUMAC team has also initiated collaboration with Boeing Research & Technology (BR&T) to explore the potential of sustainable natural fiber composites developed under the current project for application to commercial airliners. The main engagement began during the NASA-Boeing BR&T Leadership Meeting hosted by NASA ARMD on November 20–21, 2024, where Sang-Hyon Chu, the SUMAC PI, provided an overview presentation. Following the leadership meeting, NASA Langley coordinated with Boeing representatives, which led to a technical tag-up meeting on April 30, 2025 during the NASA HiCAM (Hi-Rate Composite Aircraft Manufacturing) Spring review meeting.

The April 30, 2025 meeting included Mitch Petervary (Structures and Technology, Boeing), Bill Carter (Materials and Manufacturing Technology, Boeing), Keith Young (Materials, Boeing), additional Boeing researchers, and SUMAC representatives, Sang-Hyon Chu and Cheol Park. Boeing asked several technical questions regarding the evaluation of SUMAC natural fiber composites, focusing on:

- Availability of material property data (toughness, specific strength, specific stiffness, damping properties).
- Recyclability of SUMAC thermoplastic resins.

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- Variability in natural fibers and mitigation strategies, such as transitioning from single fibers to yarns and woven fabrics.
- Flame, smoke, and toxicity (FST) performance.
- Natural fiber/resin sourcing (flax largely from Europe, hemp increasingly available from U.S. suppliers).

Boeing expressed strong interest in applications where SUMAC composites could provide value, including vibration damping, acoustic attenuation, and electromagnetic (EM) signal transparency. Specific areas identified include:

- Vibration damping/absorption: space launch pads, helicopter rotor blades, and wind turbine blades (where recyclability and large volume needs are critical).
- Acoustic attenuation/abatement: external open rotor noise with large acoustic footprints, and internal noise sources such as fuselage, transformer, and cockpit noise.
- Additional applications: sustainable automotive parts, impact-resistant delivery packaging (with potential collaboration with Amazon), and mechanical damping components.

Boeing's ongoing projects in sustainable aviation materials are currently limited, with activities focused on interior components using repurposed carpet, alternative fuels, and the elimination of hazardous chemicals. As such, SUMAC composites offer a new pathway aligned with Boeing's long-term sustainability goals.

Action items and next steps identified from this Boeing tag-up meeting include:

- Conducting damping property characterization of SUMAC composites as a function of temperature and amplitude.
- Performing noise frequency identification relevant to aerospace and rotorcraft applications.
- Engaging with Boeing's noise team to advance acoustic applications.
- Connecting with Tia Benson-Tolle (Boeing Commercial Airplanes, Product Development and Sustainability) for technical and strategic discussions.
- Engaging with Amazon's sustainability research team, led by Alan Jacobsen, regarding impact-resistant packaging applications.

Through these discussions and follow-up actions, SUMAC has been working together with Boeing to identify pathways for integrating SUMAC composites into aerospace and related industries. These efforts not only address technical challenges such as vibration damping, acoustic noise mitigation, recyclability, and FST performance, but also align with broader sustainability objectives, supporting decarbonization across transportation sectors.

3.1.3 EnviroTextiles LLC: Supporting the U.S. Domestic Hemp Fiber Supply Chain

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EnviroTextiles LLC (<https://www.envirotextiles.com/>) is a key U.S.-based hemp fiber supplier supporting the Environmental Life Institute (ELI) and the Hemp Alliance of Tennessee. Represented by Summer Haeske and Barbara Filippone, the company has actively engaged in technical discussions aimed at advancing the standardization, processing, and application of hemp fibers to strengthen the domestic hemp fiber supply chain. While flax fiber markets are currently dominated by European suppliers such as Bcomp (Switzerland), hemp presents significant potential as a leading natural fiber for reinforced composites. The United States has an opportunity to establish global leadership in natural fiber–reinforced composites, particularly for advanced applications in the automotive and aviation sectors and other important manufacturing sectors, e.g., automotive.

During technical meetings with the SUMAC team, the importance of standardization and scale-up of hemp fiber products was emphasized. Retting (separating natural fibers using microbes) was identified as a critical step, with winter retting determined to yield the highest-quality fibers. Additional key processing methods include semi-bleaching with hydrogen peroxide and the application of starch-based sizing on warp yarns to reduce friction. The fibers typically consist of 1.5–5 cm staples, with yields currently below 15%. All fibers are degummed prior to use.

EnviroTextiles produces a range of B-series hemp fabrics, which include semi-bleached and preshrunk fabrics, with selected products offered in prepared-for-dyeing (PFD) form. Notable examples include:

- B601 and B602 – semi-bleached, preshrunk.
- B605, B607, and B608 – semi-bleached, preshrunk, PFD (available in heavy, medium, and light weights).
- B610 – semi-bleached, preshrunk.

In addition, hemp twill fabrics are under evaluation in a raw, unfinished form, woven with potato starch sizing on the fiber without bleaching. The best tensile properties to date have been measured in 100% hemp twill fabric.

The company also provided several new fiber series for evaluation. These include Colorado winter-retted bast hemp, Colorado bast hemp roving processed locally, washed and yarn forms of Fiber C (a non-hemp control fiber), Fiber P#2, and Fiber X (agave-based byproduct fibers). Detailed material property data for these fibers have not yet been reported. Based on recent single-fiber tensile testing, the Colorado winter-retted bast hemp sample exhibited the highest tensile performance among the materials evaluated.

Potential applications for EnviroTextiles' hemp fibers are expanding into structural and performance-driven markets. Ongoing discussions have considered the use of B608 hemp fabric for aircraft interior components (e.g., interior panels, sidewalls, overhead bins,

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luggage racks, seat backs, trays, acoustic panels, and cabin liners) along with opportunities in prosthetic limbs, ice hockey helmets, surfboards, and skateboards. Tailoring of yarn structures has also been explored, with B601 produced as a 1- or 2-ply yarn, B602 as a 3-ply yarn, and B605 as a single-ply yarn.

Through these efforts, the SUMAC project has supported the advancement of the U.S. domestic hemp fiber supply chain by providing technical expertise, developing reliable evaluation methods, and enabling pathways for structural, functional, and performance-based applications. Furthermore, by establishing a robust domestic hemp fiber supply, EnviroTextiles, LLC can contribute to reducing reliance on European flax suppliers, lowering the carbon footprint associated with imports, and advancing sustainable material solutions. These initiatives position the United States to compete globally in the natural fiber composites market, enabling innovations in aerospace, automotive, sporting goods, and other industries while aligning with broader sustainability and energy efficiency goals.

3.2 Space Act Agreement and Research Agreement

Under the CAS SUMAC project, the team established and pursued a number of SAAs and collaborative research partnerships to advance sustainable composites and multifunctional sensing technologies. These partnerships provided opportunities to align SUMAC's research focus with both industry needs and broader government missions, while also leveraging external expertise and facilities.

As noted in the previous section, **the SAA with Joby Aviation** facilitated technical exchanges on integrated sensing technology and most suitable applications, including the demonstration of SUMAC composites for a bulkhead located behind passenger seats. A final version of the non-reimbursable SAA annex was submitted to NASA in June 2025. However, due to the planned closeout of the CAS program, the decision was made not to proceed with final execution. While the agreement itself was not completed, the interactions with Joby provided valuable insights into design considerations and potential pathways for SUMAC composite applications in future advanced air mobility platforms.

An SAA with Missouri University of Science and Technology was established to develop frequency-selective surface (FSS) sensors through advanced 3D printing approaches. Led by Cy Wilson at NASA LaRC, this collaboration aimed to integrate novel FSS designs into composite structures, enabling multifunctional capabilities such as electromagnetic filtering and embedded sensing. This research supports SUMAC's objective of advancing sustainable composite technologies that not only reduce weight and enhance multifunctional performance, but also approach the limits of material capability by incorporating integrated sensing functionalities for improved material state awareness.

In parallel, NASA established a **Collaborative Research Agreement with the U.S. Army Ground Vehicle Systems Center (GVSC)**, led by Eric Tucker (LaRC). This partnership

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explored novel designs of frequency selective surfaces (FSS) as sensors for structural health monitoring and for other applications, including applications in defense-related ground vehicles. One aim of the collaboration was to build upon SUMAC's sensor development work to extend its impact beyond aerospace, highlighting the potential for dual-use technologies that enhance safety and reliability in military ground platforms. The GVSC engagement also emphasized cross-agency coordination and technology transfer, aligning SUMAC's sensing research with Department of Defense interests.

Collaborations with Oak Ridge National Laboratory (ORNL) extended the SUMAC project into sustainable materials and industrial applications. Discussions with ORNL staff members, Amber Hubbard and Katie Copenhaver, focused on various bio-sourced materials and manufacturing strategies. Specific research interests included the evaluation of bio-based polymers such as PLA and PHB, hemp-based reinforcements through the Hemp Alliance Tennessee, additive manufacturing of sustainable materials, and their potential use in automotive interior parts. Mechanical and environmental tests were identified as a critical step, including flexural and impact performance, heat deflection, thermal stability, and water uptake studies. The University of Tennessee's Fibers and Composites Manufacturing Facility (FCMF) was also highlighted as a key resource, including availability of tooling such as a car seat back mold for part fabrication.

In addition to technical collaboration, discussions with ORNL explored potential partnership mechanisms. In the short term, user agreements funded through department of energy (DOE) could enable ORNL staff contributions to ongoing NASA SUMAC efforts, while long-term opportunities may involve strategic partnership projects with larger scope and budget, potentially funded through NASA mechanisms such as a Military Interdepartmental Purchase Request (MIPR). Collaborative development could also be facilitated through in-kind cost sharing. Travel plans were arranged to visit ORNL's Manufacturing Demonstration Facility (MDF) and the University of Tennessee's composite manufacturing facility to assess available equipment and identify joint research opportunities. However, the trip was ultimately not carried out due to the project closeout schedule.

These SAAs and research agreements allowed SUMAC to establish strong connections with industry, academia, and government partners. While not all agreements were executed to completion due to program timelines, the activities generated valuable technical exchanges, opened pathways for future collaborations, and broadened the impact of SUMAC research across aerospace, automotive, and defense applications.

3.3 SUMAC Working Group Activity – Monthly Meeting Series

The SUMAC Working Group, led by Sandi Miller at NASA Glenn Research Center, was established in January 2025 as an outreach initiative to promote sustainable composites in aerospace and to foster multidisciplinary collaborations across industry, academia, and

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government agencies. The CAS SUMAC team served as the central hub, coordinating activities and guiding the development of sustainable composite initiatives.

As part of this outreach, the group hosted a monthly meeting series focused on sustainable materials, manufacturing, inspection, and modeling, featuring two technical presentations at each session. These meetings consistently attracted over 60 participants, providing a dynamic platform for cross-sector knowledge exchange and promoting broad awareness of sustainable composite technologies among stakeholders (see Table 3.1). The list of speakers and presentation titles from January through August 2025 is summarized in Table 3.2, highlighting the diversity of expertise and topics covered.

As the SUMAC project concludes, these outreach efforts will continue under the “Emerging Technologies Working Group” monthly meeting series, led by Allison Christy at GRC. This transition ensures that the technical knowledge, collaborations, and momentum established by SUMAC are sustained and expanded, supporting continued advancement of sustainable aerospace materials.

3.4 Future Workforce Development

A central pillar of the SUMAC project has been the cultivation of a diverse and skilled future workforce prepared to advance sustainable aerospace technologies. Over the course of the project, 25 interns were engaged through NASA Office of STEM Engagement (OSTEM), NASA internships, fellowships and scholarships (NIFS), NASA Minority University Research & Education Project (MUREP), NASA-Chabot High School Learning Experience (CHSLE), and NASA Space Grant Consortium programs, representing a wide range of institutions from research universities to community colleges and high schools (see Table 3.3). These internships provided hands-on experience in composite development, life-cycle analysis, and advanced manufacturing while fostering pathways into the aerospace field for students from underrepresented backgrounds. In FY25 only, 17 interns contributed to SUMAC activities, with 13 students during the summer term alone. These included participants from Penn State, Boise State, the University of Idaho, UC Santa Barbara, the University of Puerto Rico, and the University of Nebraska-Lincoln, among others. Notably, the summer group also included high school students engaged through the NASA-CHSLE program, broadening early STEM exposure.

Beyond formal internships, SUMAC actively expanded its educational impact through outreach and curriculum development. In July 2024, SUMAC researchers introduced project activities to University of Virginia students in collaboration with the LaRC Aeronautics Research Directorate (ARD) and HiCAM leadership. In parallel, discussions with professor Sean McGinnis, Virginia Tech’s Green Engineering Program, are laying the groundwork to integrate SUMAC’s life-cycle analysis research into senior project courses, ensuring continued educational benefits beyond the project’s duration. These workforce development activities not only advanced the immediate goals of SUMAC but also invested

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in the long-term talent pipeline needed to sustain innovation in sustainable aerospace technologies.

Table 3.1 List of participating stakeholders: industry, academia and government.

Industry	Academia	OGAs
Boeing, Airbus, Lockheed Martin, ATI, Volkswagen America, Rad Tech, Material supply companies	Penn State, Univ. of Delaware, Old Dominion, Texas A&M, Univ. of Texas Arlington, Northwest Nazarene, Univ. of Maine, Boise State, Alabama State, Montana State, UC-Davis	Oak Ridge NL, ONR, DARPA, USDA, Sandia NL, NASA (ARC, GRC, LaRC, KSC, MSFC/HQ), Army Research Lab

Table 3.2 List of speakers who presented in the SUMAC monthly meeting series (Jan–Aug, 2025).

Date	Presenter	Affiliation	Title
Jan 2025	Katie Copenhaver	Oak Ridge National Lab	Sustainable Composites Manufacturing at ORNL
	Allison Christy	NASA Glenn	Evaluation of Hydrolytic Degradation of PLA Matrices in Flax/PLA Composites
Feb 2025	Tyler Roberts	Arkema	Advanced Bio-Circular Materials: The Circle of Life Meets the Circular Economy
	Matthew Webster	NASA Langley	SUMAC Integrated Sensing for Natural Fiber Composites
Mar 2025	Vitaliano Dattilo / Michael Bozlar	Univ. of Texas Arlington	Recycled PET Reinforced With Graphene
	Larry Perko	RBT Biocomposites	Commercializing Sustainable Composites
May 2025	Anne Schauer-Gimenez	Mango Materials	Using PHAs to Create a Sustainable Future
Jun 2025	Derrick Dean	Alabama State Univ.	Pectic/Cellulose Nanocomposites for Packaging
	Carolyn Westmark	US Army DEVCOM	Harnessing Microbe-Sourced Cellulose for Advanced Fiber Manufacturing
Jul 2025	Jacob Clark	Univ. of Maine	Continuous Forming Machine
	Sandi Miller	NASA Glenn	Overview of NASA's SUMAC Project
Aug 2025	Cara Bommarito	RadTech	Coating Sustainability Predictions
	Sean Reymond & Hiral Jani	Concordia Fibers	Commingled Fiber Prepregs in Tailored Fiber Placement

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Table 3.3 A list of SUMAC intern students

Name	School	Funding Program	NASA Center
FY25 Summer (13)			
Katie Blyler	Penn State University	NASA Space Grant	GRC
Tyler Klinchuch	Boise State University	NASA Space Grant	GRC
Chase Long	University of Idaho	NASA Space Grant	GRC
Aliah Colobong	Passaic County Community College	NASA MUREP-MCA	LaRC
Khadeejah Jenkins	Passaic County Community College	NASA MUREP-MCA	LaRC
Nerika Hernandez-Santiago	University of Puerto Rico Río Piedras	NASA Space Grant	LaRC
Pearl Yoon	UC Santa Barbara	NASA MUREP	LaRC
Leo Alvelais	California Polytechnic State University	NASA Space Grant	LaRC
Gael Perez Alvarez	University of Nebraska–Lincoln	NASA Space Grant	LaRC
Elizabeth Suehr	UC Davis	NASA NIFS/OSTEM	ARC
Mathew Wilson	Hunter College	NASA MUREP	ARC
Frederic Strommen	High School Student	NASA CHSLE	ARC
Melanie Rodriguez	High School Student	NASA CHSLE	ARC
FY25 Spring (4)			
Francisco de Jesus	Polytechnic University of Puerto Rico	NASA MUREP	LaRC
Enoch Kim	UC Irvine	NASA MUREP	LaRC
Nour Hakim	University of Nevada–Las Vegas	NASA NIFS/OSTEM	LaRC
Luke Post	Iowa State University	NASA NIFS/OSTEM	LaRC
FY24 Fall (3)			
Izzy Cowan	Cornell University	NASA NIFS/OSTEM	LaRC
Karina Hafeez	University of Maryland	NASA NIFS/OSTEM	LaRC
Julia Hand	Grand Canyon University	NASA NIFS/OSTEM	GRC
FY24 Summer (4)			
John Sturm	University of North Dakota	NASA NIFS/OSTEM	LaRC
David Warren	Elizabeth City State University	NASA NIFS/OSTEM	LaRC
Mason Clobes	University of North Dakota	NASA NIFS/OSTEM	GRC
Ana Mata	University of Texas at El Paso	NASA NIFS/OSTEM	GRC
FY24 Spring (1)			
Finnian Day	Virginia Tech	NASA NIFS/OSTEM	LaRC

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3.5 SUMAC Project Publications

The following publications from the SUMAC project have communicated its vision, goals, technical progress, and key accomplishments through multiple outlets, including Composites World magazine and technical conferences, thereby advancing visibility, credibility, and collaboration in aerospace communities.

1. Christopher Wohl et al., "Opportunity Concepts Developed from the Sustainable Manufacturing of Aircraft (SUMAC) Project," WAMS 2024, Orlando, FL, February 19-23, 2024.
2. Sadeq Malakooti et al., "Sustainable Manufacturing of Aircraft for Greener Aviation," Science Night at Ohio Aerospace Institute, Great Lakes Biomimicry, Cleveland, OH, June 27, 2024
3. Meelad Ranaiefar et al., "Toward Greener Aviation Through Sustainable Manufacturing of Aircraft", Invited Presentation, MS&T Conference, Pittsburgh, PA. October 2024
4. Sang-Hyon Chu et al., "Sustainable Manufacturing of Aircraft," NASA/Boeing BR&T Leadership Meeting, November 20-21, 2024, Virtual Presentation
5. Composites World Press Release, "NASA launches sustainable aircraft project CAS SUMAC," Composites World, January 3, 2025.
(<https://www.compositesworld.com/news/nasa-launches-sustainable-aircraft-project-cas-sumac>)
6. Allison J. Christy, "Evaluation of Hydrolytic Degradation of Poly(lactic acid)(PLA) matrices in Compression Molded Flax/PLA Composites" Meeting Series on Sustainable Composites, January 21, 2025, Virtual Presentation
7. Sandi G. Miller et al., "Overview of SUMAC Project", Joint Defense Manufacturing Technology Panel (JDMTP), Spring Portfolio Review, March 25, 2025, Virtual Presentation
8. Sandi G. Miller, Paula J. Heimann, Allison J. Christy and Meelad Ranaiefar, "Evaluation of Braided Flax/Polyamide-11 Composites By Material Characterization and Mechanical Testing", International Committee on Composite Materials (ICCM 24), Baltimore, MD. August 4-8, 2025.
9. Allison Christy et al., "Manufacture and Characterization of Bio-based Thermoplastic Composites to Improve Efficiency of Advanced Air Mobility Vehicles," ACS Fall Meeting, Washington, D.C., August 17-21, 2025.
10. Matthew Webster et al., "Developing Sensing Techniques for Material State Awareness in Natural Fiber Composites," The 15th International Workshop on Structural Health Monitoring (IWSHM) Meeting at Stanford University, September 9-11, 2025.
11. Sam Johnson et al., "THz Inspection as a Unique Enabler for Characterizing Sustainably Derived Composites," The 15th International Workshop on Structural Health Monitoring (IWSHM) Meeting at Stanford University, September 9-11, 2025.
12. Meelad Ranaiefar et al., "Manufacture and Mechanical Performance of Bio-Based Thermoplastic Composites for Advanced Air Mobility Vehicles", Invited Presentation, [MS&T 2025](#), Columbus, OH, September 28, 2025.

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4. Technical Accomplishment

4.1 Sustainably Derived Thermoplastic Resins

4.1.1 SUMAC Thermoplastic Resins

4.1.1.1 Introduction

Next-generation air travel increasingly leverages from emerging advanced air mobility (AAM) technologies to provide safe, efficient, and sustainable services for urban and rural areas [1]. However, AAM vehicles are currently not manufactured sustainably, leading to even more environmental degradation as production rates rise. The Sustainable Manufacturing of Aircraft (SUMAC) project, a part of the NASA Convergent Aeronautics Solutions (CAS) portfolio, seeks to reduce the environmental impact of aircraft manufacturing through advancing sustainably derived composite technologies relevant to the aerospace industry.

Traditional composite materials typically are thermoset polymers [2]. These resins offer the advantage of low viscosity and high thermal and mechanical performance; however, they cannot be remolded after curing. As a result, mechanical fasteners must be used at joints and interfaces, which can alter structural performance and add unnecessary mass to the structure [3]. In contrast, thermoplastic polymers are highly processable, allowing them to be reheated, remolded, and cooled on demand with minimal changes to their chemical backbones, making them more recyclable [4]. Additionally, from a sustainability point of view, synthesized thermoplastic polymers from biobased precursors degrade slowly in nature, making biomass-derived thermoplastic polymers a more sustainable and recyclable alternative for manufacturing environmentally friendly parts and structures in AAM technologies. Moreover, it should be mentioned that biomass-derived resins present a compelling alternative to conventional thermosets and thermoplastics, reducing dependence on fossil fuels and often offering improved environmental benefits, such as lower toxicity and greater biodegradability.

This report investigated three biomass-derived thermoplastics including polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), and polyamide-11 (PA11). Various thermomechanical properties such as melting point, glass transition temperature (T_g), and decomposition onset temperature, were analyzed alongside their temperature-dependent viscoelastic behavior. Additionally, their potential advantages for different aerospace applications are also briefly discussed.

4.1.1.2 Experimental Section

4.1.1.2.1 Materials

Polylactic acid (IMF101 from Pond Global Ltd., Denmark), poly-3-hydroxybutyrate (YOPP ST-101 from Mango Materials Inc., Oakland, CA), and polyamide-11 (RILSAN PA11 from

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Arkema Inc., France) were investigated in this work. Materials were received in pellet form. Pellets were vacuum-dried overnight at 80 °C before testing.

4.1.1.2.2 Compression Molding

Dried resin pellets were compression molded in a 4 in x 4 in steel picture frame tool (Figure 4.1A). The pellets were laminated between Kapton films coated with a mold release compound before pressing. The amount of resin was determined based on a desired final panel thickness.

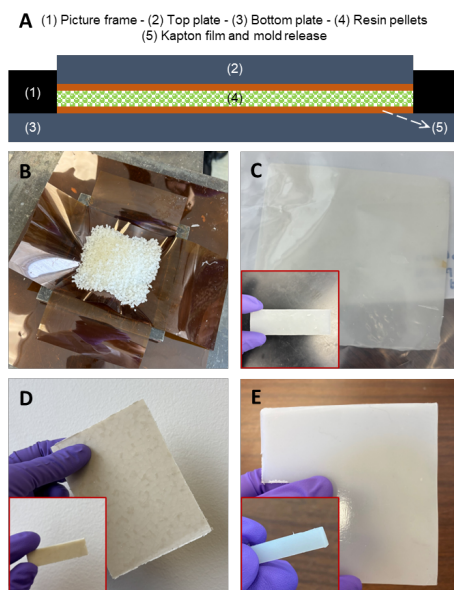


Figure 4.1 Compression molded resins: (A) The schematic for resin compression molding; (B) Top view image of PLA pellets placed on the coated Kapton films inside the steel picture frame tool part of the compression molding process; (C) Hot-pressed PLA panel of 2.72 mm thickness; (D) Hot-pressed PHB panel of 2.79 mm thickness; and (E) Hot-pressed PA11 panel of 2.56 mm thickness. The picture of a rectangular test bar of each resin is also shown in the inset of figures C to E, bounded with red color line.

The compression molding procedure including the compression molding parameters (listed in Table 4.1) is as follows:

- Heat the picture frame in the press to temperature T1.
- Place the dried resin pellets into the picture frame.
- Hold at temperature T1 with no pressure for time Δt_1 .
- Place the top plate and apply pressure P.
- Hold at temperature T1 and pressure P for time Δt_2 , then heat to temperature T2 and pressure P for time Δt_3 .
- Air cool to room temperature.

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Table 4.1 The compression molding parameters for each resin.

Resin	T ₁ (°C)	Δt ₁ (min)	P (kPa)	Δt ₂ (min)	T ₂ (°C)	Δt ₃ (min)
PLA	182	40	345	15	-	-
PHB	171	15	690	15	173	5
PA11	193	5	-	-	-	-

Typical images from the fabricated test coupons from the compression molding process are also shown in Figure 4.1C to Figure 4.1E. It is important to note that the compression molding process is relatively straightforward and repeatable, which is important for resin and composite manufacturing.

4.1.1.2.3 Characterization

Chemical compositions of the resins were studied with attenuated total reflectance (ATR) infrared spectroscopy using a Nicolet Nexus 470 FT-IR spectrometer at room temperature. Resins were also examined by Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) techniques to identify major transitions and any unusual weight loss events. TGA was performed using a TA Instruments (New Castle, DE) Thermogravimetric analyzer (TGA Q500). Sample size ranged from 1 to 10 mg. Samples were run at a temperature ramp rate of 10 °C/min from room temperature to at least 600 °C under air and nitrogen. DSC was performed on a modulated TA Instruments (New Castle, DE) DSC Q1000. Samples were 10 to 15 mg and were run under nitrogen at a temperature ramp rate of 5 °C/min from room temperature to 400 °C.

Viscoelastic material properties of the resins were investigated using Dynamic Mechanical Analysis (DMA) technique in 3-point bending mode. DMA was performed on a Mettler Toledo (Columbus, OH) DMA/SDTA861e. At 1-Hz frequency, the samples were heated to 200 °C at a rate of 5 °C/min. The deformation was force limited to 5 N, with a 200 μm offset (5% strain) and oscillating deformation amplitude of 20 μm (0.5% strain).

4.1.1.3 Results and discussion

Figure 4.2 shows the FTIR spectra of the biomass-derived thermoplastic resins studied in this work. Major peaks associated with PLA functional groups can be observed: C=O stretching (1751 cm⁻¹), CH₃ asymmetrical scissoring (1452 cm⁻¹), C–O asymmetrical stretching (1180 cm⁻¹), C–O–C symmetric (1073 cm⁻¹), and C–CH₃ symmetrical stretching (1040 cm⁻¹) [5]. The major peaks associated with PHB functional groups are also identified as: ester carbonyl stretch at 1725 cm⁻¹, as well as a group of peaks between 1450 and 1000

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cm^{-1} associated with methyl (CH_3) and methylene (CH_2) deformations and C–O stretches [6]. PA11 major peaks are also characterized as: N–H stretching at 3301 cm^{-1} and 2919 cm^{-1} , C–H vibration of the methylene groups 2851 cm^{-1} , amide I at 1638 cm^{-1} , amide II at 1546 cm^{-1} , and C–H bending vibration at 1467 cm^{-1} [7].

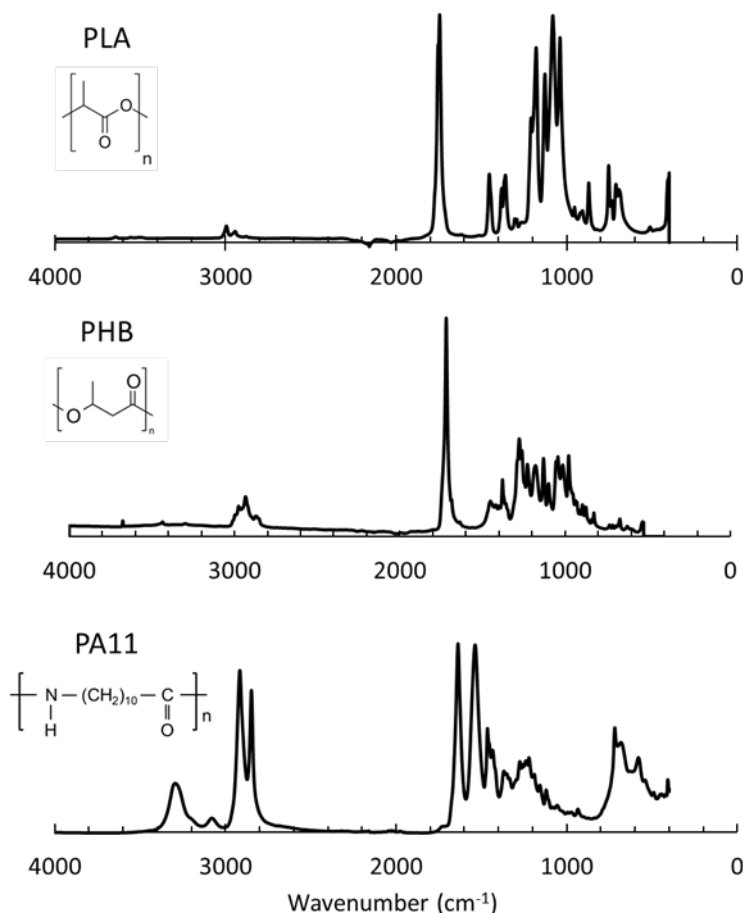


Figure 4.2 FTIR spectra of the biomass-derived thermoplastic resins studied in this work.

Figure 4.3 shows the DSC analysis of the hot-pressed thermoplastic samples in nitrogen environment. To ensure consistency and eliminate any thermal history from processing, a heat-cool-heat DSC experiment was conducted. Melting points (T_m) were measured from the endothermic peaks on the second heating ramp as $162\text{ }^\circ\text{C}$ for PHB, $192\text{ }^\circ\text{C}$ for PA11, and $169\text{ }^\circ\text{C}$ for PLA.

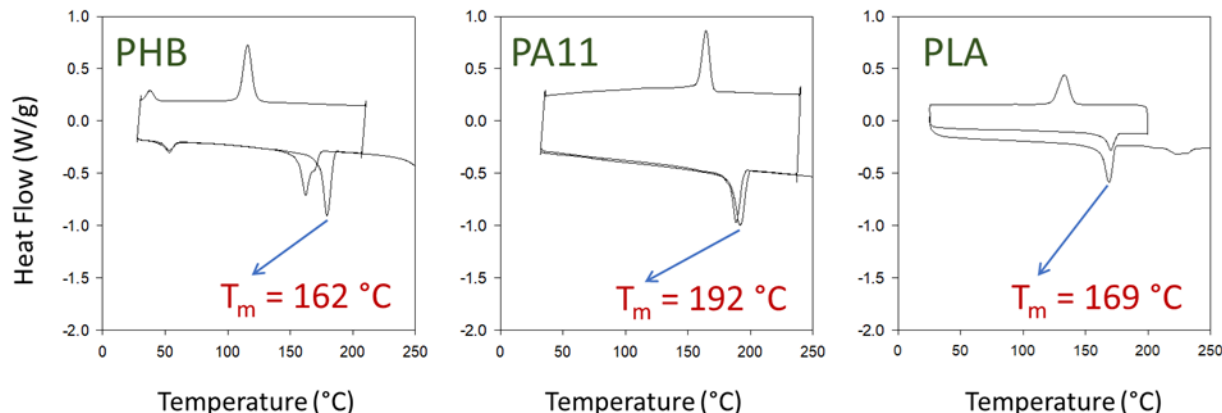


Figure 4.3 The heat-cool-heat DSC analysis of the hot-pressed PHB, PA11, and PLA samples measured at 5 °C/min in nitrogen environment. Melting points (T_m) for each material were measured from the second heat ramp.

The melting temperature endothermic peaks were also integrated in the TA Universal Analysis 2000 software for enthalpy of fusion (ΔH_m) values. Using the equilibrium enthalpy of fusion for a crystalline sample (obtained from literature), the degree of crystallinity was also estimated (equation 3.1).

$$\text{Crystallinity (\%)} = ((\Delta H_m)/(\Delta H_c)) \times 100, \quad (4.1)$$

where ΔH_m and ΔH_c are the enthalpy of fusion of the sample and a fully crystalline resin, respectively. The values of ΔH_m , ΔH_c , and degree of crystallinity for each thermoplastic sample are listed in Table 4.2. Compared to the state-of-the-art thermoplastic resins, the sustainably derived resins studied in this work are comparable regarding the degree of crystallinity of polyetheretherketone (PEEK, 28-37%) but a bit higher than the corresponding values for polyetherketoneketone (PEKK, 18-29%) and low-melt PAEK (LMPAEK, 15-21%) [8].

Table 4.2 Enthalpy of fusion and degree of crystallinity of the hot-pressed thermoplastic samples.

Resin	ΔH_m (J/g)	ΔH_c (J/g)	Crystallinity (%)
PLA	35.1	98.2 ^a	35.8
PHB	52.0	146 ^b	35.6
PA11	59.5	189 ^c	31.5
^a Ref [9], ^b Ref [10], and ^c Ref [11]			

Figure 4.4 displays the TGA analysis of the thermoplastic resins measured in air. PA11 shows the highest onset of decomposition among the resin materials. The onset of decomposition temperatures (measured at 5% mass loss point) for the PLA, PHB and PA11 resins are 297 °C, 289 °C, and 400 °C, respectively.

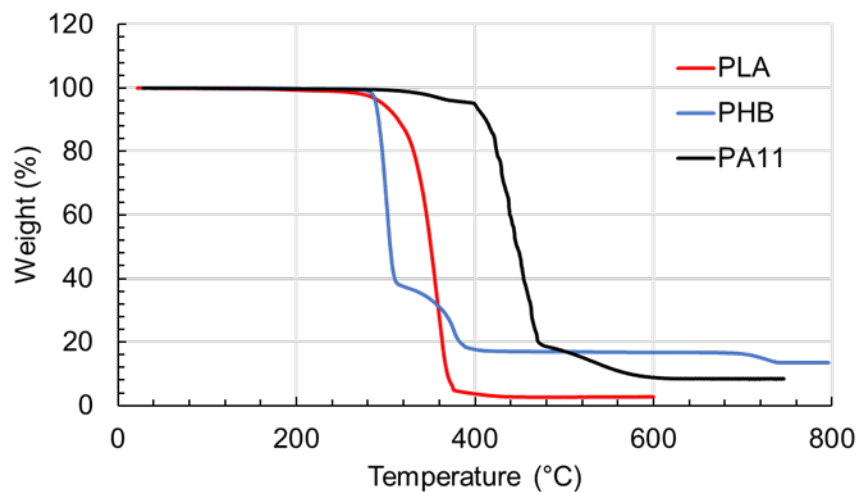


Figure 4.4 The TGA analysis of the resins in air. The onset of decomposition temperatures (measured at 5% mass loss point) for the PLA, PHB and PA11 resins are 297 °C, 289 °C, and 400 °C, respectively.

The PHB TGA shows that only approximately 80% mass loss occurred in air even up to 700 °C, suggesting the presence of a material filler mixed with the polymer. Figure 4.5 shows the FTIR spectrum from PHB material left after TGA decomposition. The material library associated to FTIR suggested a silicate-based filler primarily based on the peaks 3600 cm^{-1} and 980 cm^{-1} .

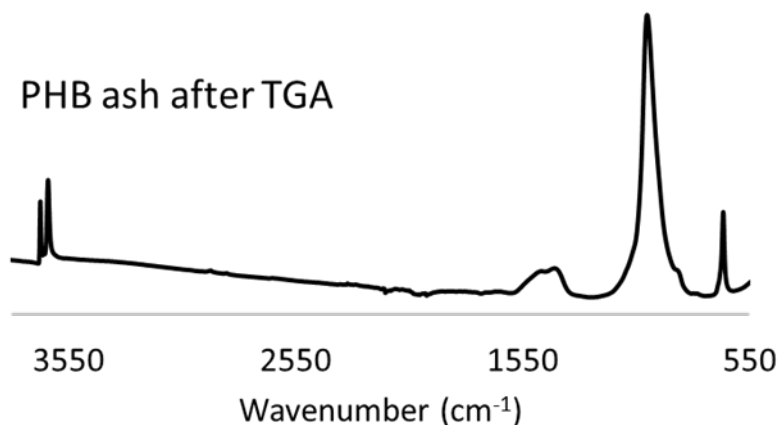


Figure 4.5 FTIR spectrum of PHB ash after TGA analysis.

Viscoelastic behavior of the resins was also studied using DMA analysis in 3-point bending mode at 1 Hz and at different temperatures. Figure 4.6 shows the storage and loss moduli as well as the $\tan \delta$ (loss factor) of the resins as a function of temperature. The overall trends in the moduli and $\tan \delta$ for both PLA and PA11 resins are similar. This is mainly due to their close glass transition temperatures (PLA at ~ 65 °C and PA11 at ~ 55 °C). The low

glass transition temperature for PHB (at $\sim 5^\circ\text{C}$) makes the response a plateau with no peak in damping behavior (i.e., $\tan \delta$). At low temperatures, PLA has a higher storage modulus compared to the other resins. All resins go through a similar softening as temperature increases. Around the glass transition temperature, the loss modulus and $\tan \delta$ exhibit peaks for the PLA and PA11 resins. This is where they dissipate and dampen energy the most. However, for the PHB resin, which has a much lower relative T_g value, the loss modulus shows a relative plateau and does not show a distinct peak.

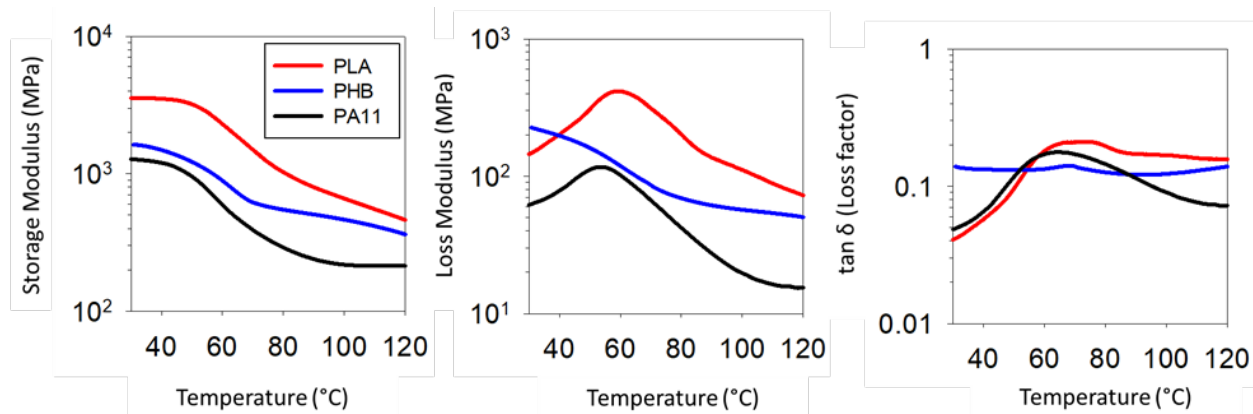


Figure 4.6 Linear viscoelastic properties of the hot-pressed PLA, PHB, and PA11 samples measured in 3-point bending at 1 Hz at different temperatures ($5^\circ\text{C}/\text{min}$ temperature sweep).

Figure 4.7 shows a spider plot including different material properties of the resins. It includes storage modulus value (E_1) and $\tan \delta$ at 30°C as the indicators for stiffness and damping properties, as well as melting and glass transition temperatures (T_m and T_g , respectively) as indicators of their thermal resistance. This spider plot is a good way to compare important performance properties of the resin in order to identify their potential aeronautic related applications.

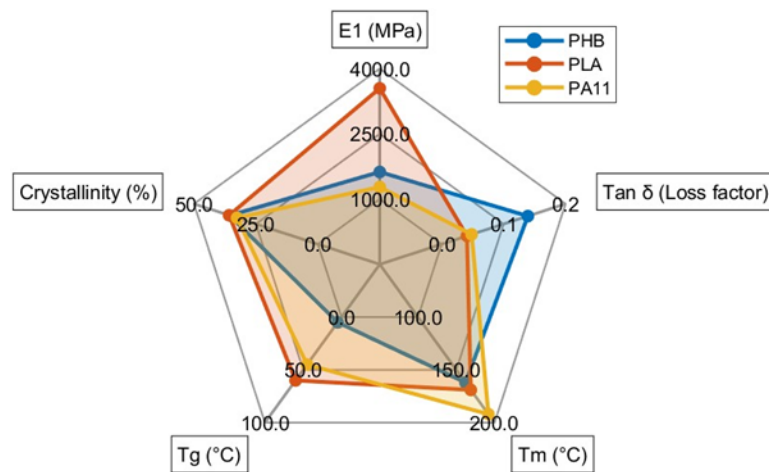


Figure 4.7 Spider plot to compare different properties of the resins. E1 and tan δ are storage modulus and loss factor values at 30 °C.

4.1.1.4 Summary and Conclusion

In this study, three different sustainably derived thermoplastic resins were studied as part of the Sustainable Manufacturing of Aircraft (SUMAC) project which looks to minimize environmental impacts on an aircraft full lifecycle. For this purpose, polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), and polyamide-11 (PA11) were characterized using techniques such as differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and dynamic mechanical analysis (DMA). Here, using Figure 4.7 as a baseline, the potential aircraft use cases for each resin was identified. For this purpose, we first highlight their strengths across key properties.

PHB offers high damping and high thermal resistance, making it suitable for vibration-damping panels and non-structural insulation. PLA shows high stiffness which is well-suited for interior parts like tray tables or 3D-printed brackets where mechanical strength is needed at minimal cost. PA11 provides the best thermal performance. Its flexibility and durability make it a strong candidate potentially for tubing, seals, and connectors in aircraft systems. Table 4.3 summarizes the key features of the resins.

This report provides guidance for the future development of manufacturing processes for sustainably derived polymer fiber composites. Overall, these materials show promising potentials to contribute to the advancement of lighter, more environmentally friendly, and cost-effective aircraft without sacrificing performance.

Table 4.3 Summary table to compare the resins' key features and their potential aircraft applications.

Material	Stiffness	Damping	Thermal resistance	Potential Aircraft Applications
PHB	Moderate	High	High	Cabin panels, Insulation
PLA	High	Low	High	Seat Shells, 3D-printed Parts
PA11	Low	Moderate	High	Tubes, Seals, Grommets

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4.1.1.5 References

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4.1.2 Environmental Effects on SUMAC Composites: Moisture Uptake Analysis

4.1.2.1 Introduction

Bio-sourced thermoplastics and natural fibers offer multifunctional benefits such as weight savings, vibration damping, acoustic abatement, and safe communication, along with the potential to reduce environmental impacts. Nevertheless, the intrinsic sensitivity of these materials to moisture remains a key barrier, as absorbed water may compromise thermal stability, induce chemical degradation, and reduce mechanical performance. In this study, the moisture absorption behavior of bio-sourced thermoplastic resins, natural fibers, and flax-PA11 composites was investigated under controlled humidity exposure.

4.1.2.2 Experimental Methods

Moisture conditioning experiments were conducted using a Thermotron environmental chamber maintained at 25 °C and 85% relative humidity. Prior to testing, all samples were vacuum-dried at 40 °C for 12–24 h to establish a consistent baseline mass. The test set included three bio-sourced thermoplastics (PLA, PHB, and PA11), hemp fibers, Bcomp woven flax fabric, braided flax fabric, commingled flax-PA11 fabrics, and braided flax-PA11 composites (six coupons) fabricated at NASA GRC, as shown in Figure 4.8. Resin films were cut to 4x4 cm², fabrics to 6x6 inch² (or 15.24x15.24 cm²), and six composite coupons to length of 10 in. Exposure durations ranged from 1-3 h for fibers, 120 h for resins, to over 836 h (34 days) for composites. Gravimetric measurements were performed using an analytical balance to monitor moisture uptake, while post-conditioning analyses employed Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC) to assess chemical and thermal changes.

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Figure 4.8 Moisture uptake samples: (top) natural fiber fabrics – flax-PA11 commingled fabric, hemp fabric, Bcomp woven flax fabric, braided flax fabric; (bottom) braided flax-PA11 composite coupons.

4.1.2.3 Results and Discussion

The extent of moisture absorption differed markedly between resins, fibers, and composites. Among the thermoplastic matrices, PHB absorbed the least water (0.13%), followed by PLA (0.29%), while PA11 exhibited the highest uptake (0.58%), as shown in Figure 4.9. Natural fibers absorbed substantially greater quantities, with hemp showing the most pronounced uptake at 7.77%, while braided flax and Bcomp woven flax absorbed 4.31% and 4.15%, respectively (see Figure 4.10). Commingled flax-PA11 fabrics absorbed 2.18%. Figure 4.11 shows that the braided flax-PA11 composite absorbed an average of 3.64% moisture during the 836 h exposure and had not reached saturation, suggesting continued diffusion.

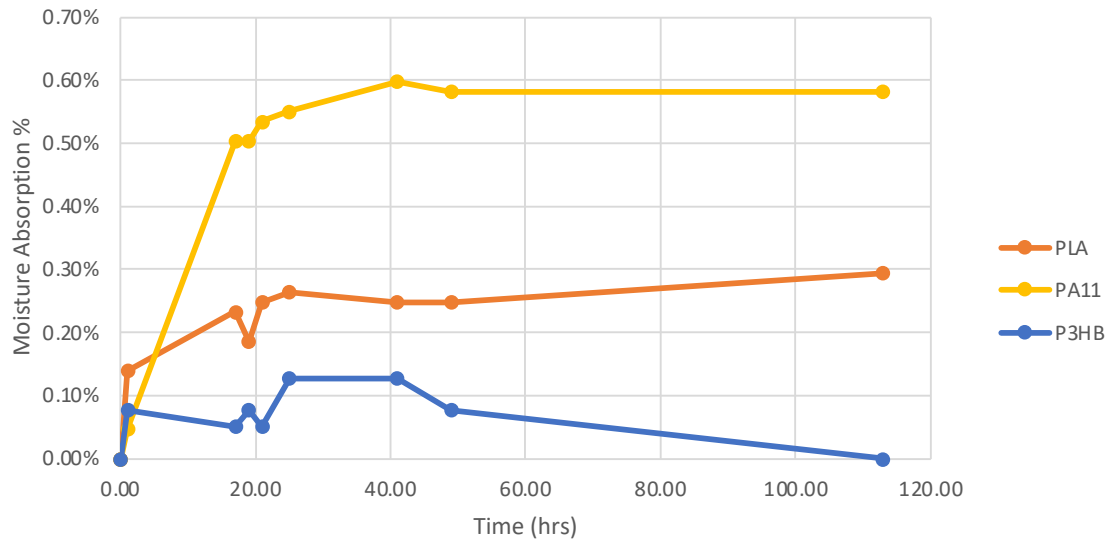


Figure 4.9 Moisture absorption of bio-sourced thermoplastic resins as a function of exposure time: PLA (orange), PA11 (yellow), and PHB (blue).

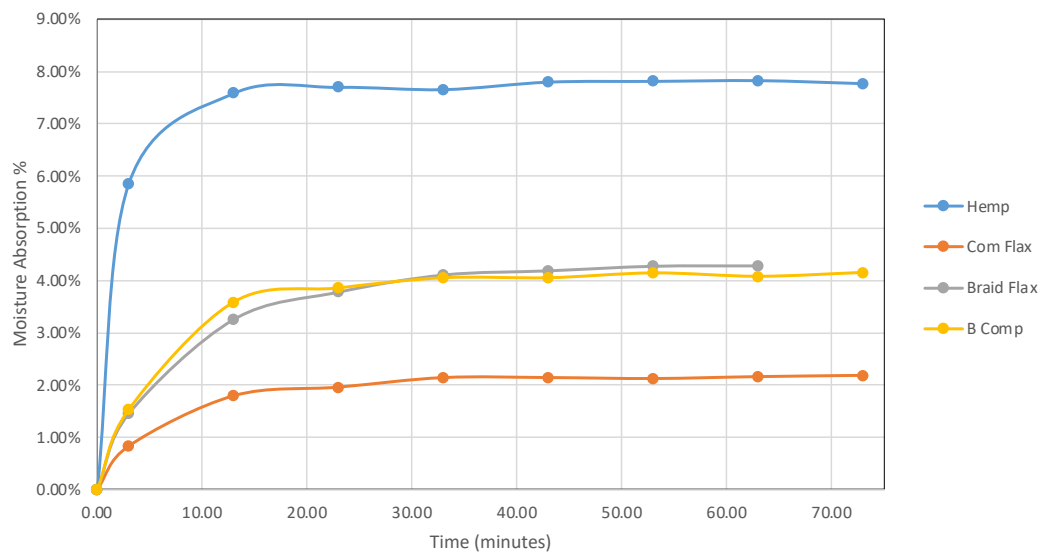


Figure 4.10 Moisture absorption of natruual fiber fabrics as a function of exposure time: hemp fabric (blue), flax-PA11 commingled fabric (orange), braided flax fabric (gray), and Bcomp woven flax fabric (yellow).

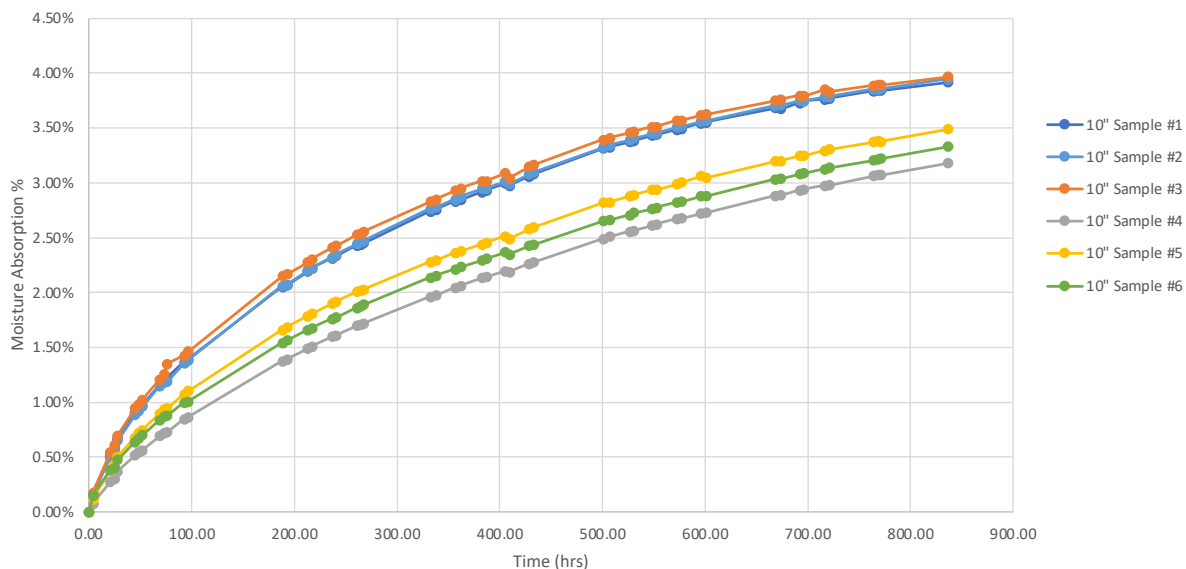


Figure 4.11 Moisture absorption of 10"-long flax-PA11 composite coupons as a function of exposure time.

The kinetics of absorption also differed across materials. Resin films and natural fiber fabrics approached saturation within approximately 30 min, while composite samples absorbed water much more slowly. This slower uptake was attributed to the encapsulation of fibers by the thermoplastic matrix, which slows down moisture diffusion. Nevertheless, moisture uptake in composite coupons was strongly influenced by the presence of unsealed cut sides, where exposed fiber bundles acted as capillary pathways for water ingress. This observation indicates the importance of side-sealing treatments to mitigate moisture sensitivity in natural fiber composites.

The DSC thermal analysis revealed measurable changes in polymer transitions following moisture conditioning. In PA11, the melting point (T_m) increased from 185 °C to 192 °C, while the glass transition temperature (T_g) decreased from 57 °C to 51 °C, indicating a change in polymer structure under humid conditions. PHB exhibited a slight reduction in melting point from 172 °C to 170 °C, with its glass transition remaining constant at 38 °C. PLA showed a modest increase in melting point from 168 °C to 171 °C, with no measurable change in T_g at 54 °C.

FTIR analysis confirmed that chemical structure changes accompanied these physical changes. PHB displayed an increase in O–H stretching absorbance, consistent with hydrogen bonding between absorbed water and polymer chains. PA11 exhibited modest increases in both O–H and N–H absorbance, suggesting intermediate sensitivity to water uptake. PLA displayed the strongest changes, with pronounced O–H absorbance indicative of hydrolytic breakage of ester linkages. This degradation mechanism raises concerns for the long-term durability of PLA-based composites in humid service environments.

These results show that PHB is the most resistant to water uptake but exhibits embrittlement after moisture conditioning, which limits its use for SUMAC applications. PLA, while absorbing modest amounts of water, undergoes hydrolysis that reduces stability

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and performance. PA11 shows a higher absorption capacity than PHB but maintains thermal and structural integrity under humid conditions, positioning it as the most balanced resin for SUMAC composite applications.

4.1.2.4 Conclusions and Key Takeaways

Moisture conditioning studies established that natural fibers absorb far more water than bio-sourced resins, with the hemp fabric demonstrating the greatest moisture uptake. Fabric architecture was also identified as an important factor influencing absorption behavior, indicating that weave style and fiber packing density should be carefully considered when evaluating environmental durability. The resin matrix provided a protective encapsulation that slowed water diffusion into composites. However, unsealed edges with exposed fibers remained dominant pathways for moisture ingress. Among the thermoplastic matrices studied, PA11 provided the most favorable combination of moisture tolerance, thermal stability, and mechanical property. PHB exhibited the lowest uptake but experienced embrittlement after moisture conditioning. PLA showed hydrolysis-induced degradation, raising concerns for long-term service reliability. These findings highlight the need for improved encapsulation and side-sealing strategies to enhance the environmental durability of natural fiber composites.

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4.1.3 Environmental Effects on SUMAC Composites: UV Weathering and Testing

4.1.3.1 Introduction

Bio-sourced thermoplastics and natural fibers offer multifunctional benefits such as weight savings, vibration damping, acoustic abatement, and safe communication, along with the potential to reduce environmental impacts. The main challenges in developing the use of bio-composites are the lack of knowledge about their durability and the limited studies on the evolution of their mechanical properties [1-2]. In this study, the durability of bio-sourced thermoplastic resins was investigated under an accelerated UV radiation exposure environmental condition. Colorimetry, Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Tensile testing were utilized to evaluate any changes in overall physical properties and mechanical performance.

4.1.3.2 Experimental Methods

The three bio-sourced thermoplastics included in the test set were poly (lactic acid) (PLA), Poly(3-hydroxybutyrate) (PHB), and Polyamide 11 (PA11). PLA, PHB, and PA11 were received from the NASA Glenn Research Center manufacturing team and used as received. The bio-based thermoplastics were cut to 2x2 cm².

UV-weathering was conducted in a QUV-Spray chamber with UVB-313 lighting (Figure 4.12). The exposure was conducted in accordance with ASTM G154: Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials using Cycle 5 Cycle E. For these studies, the total exposure time was 72 h that consisted of 24 h periods of light at 80°C (176°F). No cycle for condensing humidity at 50°C (122°F) was included. The UV lamp irradiance was 0.62 W/m². Bio-based resin samples were placed inside the QUV-spray chamber and removed after 72 h and were evaluated by Optical Microscopy, Colorimetry, Fourier Transform Infrared Spectroscopy (FTIR), tensile testing, and Differential Scanning Calorimetry (DSC) to assess changes in physical, thermal, mechanical, and chemical properties.

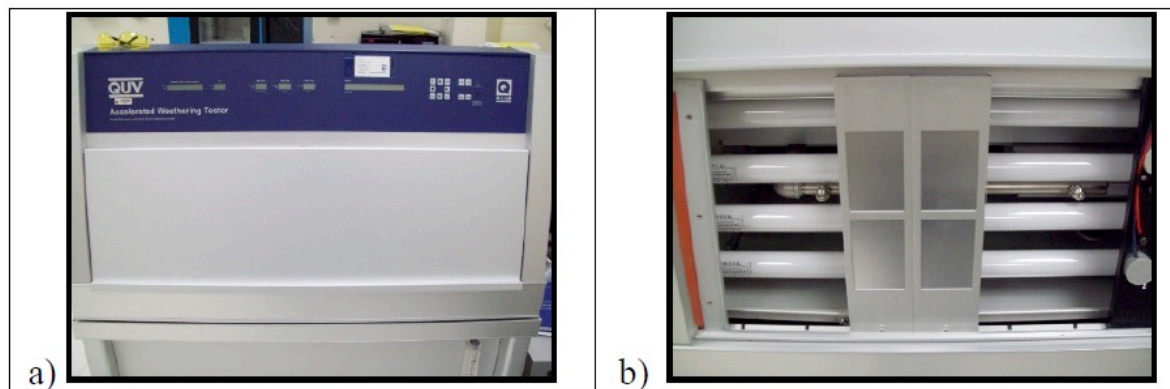


Figure 4.12 QUV test chamber: (a) QUV-Spray chamber with (b) UVB-313 lighting.

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4.1.3.2.1 Colorimetry

Colorimetry is a technique that measures or detects the effects of ultraviolet (UV) exposure on materials. UV-sensitive dyes or pigments change color when exposed to UV radiation, allowing for the detection of UV light presence, dosage, and potential material degradation such as color fading or yellowing in polymers. In this regard, a qualitative analysis of the effect of UV and thermal aging of bio-based thermoplastic resins was performed by colorimetry. In the context of thermoplastic resin degradation, analyzing changes in color due to exposure to different environmental conditions can correlate to changes in the physical and mechanical properties of the material [3-4]. Measurements were performed on bio-based resins using an FRU WR-10 Handheld Colorimeter. Color readings were performed on pristine specimens and on the UV exposed side of the test specimens. The CIELAB system was used, which considers the colorimetric coordinates L^* , a^* , and b^* ; where L^* is the luminosity, a^* and b^* represent, respectively, the spectrum between shades of red to green and yellow to blue [5-6]. The color difference can be quantified by the parameter ΔE^* , which summarizes the difference between all the coordinates of the CIELAB system [4-6]. i = initial; pristine, no UV exposure and f = final, after # hours of UV exposure:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (4.2)$$

$$\Delta L^* = L_f - L_i \quad \Delta a^* = a_f - a_i \quad \Delta b^* = b_f - b_i \quad (4.3)$$

The color difference in the bio-based materials was quantified by the parameter $\Delta C^*\%$, which denotes the color change efficiency based on chroma:

$$\Delta C_t^* = [(\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (4.4)$$

$$\Delta C_a^*\% = \Delta C_a^* / \Delta C_t^* \times 100\% \quad (4.5)$$

ΔC_t^* denotes a total color change based on chroma (a^* and b^*). ΔC_a^* and ΔC_b^* denote color (chroma) change after irradiation based on a^* and b^* coordinates, respectively. The CIELAB color parameters for Δa , Δb , and ΔL were recorded and used to calculate the color change efficiency parameters (ΔC_t^* , ΔC_a^* , and ΔC_b^*) for the pristine and UV exposed bio-based films.

4.1.3.2.2 FTIR Spectroscopy

Measurements were performed on coated Al panels on a Thermo Scientific Nicolet iS5-FTIR spectrometer equipped with the iD7 ATR accessory. A total of 8-32 scans were obtained for each of the resin films that were referenced against a background obtained for the same number of scans.

4.1.3.2.3 Differential Scanning Calorimeter

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Differential Scanning Calorimetry (DSC) was performed on a TA Differential Scanning Calorimeter to acquire thermal properties of bio-based resins at a heating rate of 10°C/min up to a maximum temperature of 325°C.

4.1.3.2.4 Tensile Testing of Bio-based Resin Thin Films

Individual tensile tests were performed on the pristine and QUV weathered bio-based resin films using an Instron 5944 Tensile tester equipped with a 2kN load cell. Each film was cut to a 5.08 mm width with variable thickness and a 50 mm gauge length. Tensile tests were conducted at a ramp rate of 5mm/min strain rate (10% of gauge length). At least 3 coupons per specimen were prepared and tested.

4.1.3.3 Results and Discussion

UV weathering of the three bio-based resins resulted in a degree of degradation in overall physical properties. Among the bio-based thermoplastic matrices (see Figure 4.13), PHB had the greatest loss of transparency, followed by PLA which lacked clear visual change, while PA11 increased turbidity and yellowing.

Table 4.4 shows the results of the colorimetric analysis of the bio-based resins before and after QUV weathering. The values of the variations in the color change efficiency parameters, (equations (4.4) and (4.5)), which defines whether the color change is noticeable or not, are listed in Table 4.5 [4-7].

From the ΔC^* results, the color change is noticeable to the naked eye for all bio-based resins. The color change efficiency chroma b values, $\Delta C^*_b\%$, for all the UV exposed bio-based samples gave values greater than 70%. Furthermore, since the difference in luminosity (ΔL^*) was positive for the PHB, this indicates that the sample became lighter than the pristine sample. However, for the PLA and the PA11 samples, the difference in luminosity was negative thus indicating instead that the sample became darker than the pristine sample. The variations of Δa^* and Δb^* indicate, respectively, that the samples are becoming greener and more yellowish [7]. An example of the color change is shown in Figure 4.13. Yellowing is characteristic of photo-oxidation processes caused by UV radiation [8,9]. Specifically, PA11, went through the process of photodegradation, creating the yellow color. Figure 4.14 demonstrates that PA11 exhibited the largest increase in the colorimetric parameter Δb^* , reflecting the most pronounced yellowing in comparison to PLA and PHB.



PRISTINE PHB



PRISTINE PLA



PRISTINE PA11

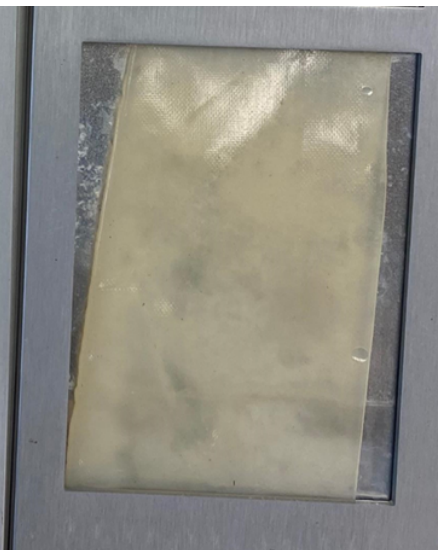
(a)



PHB



PLA



PA11

(b)

Figure 4.13 Bio-based thermoplastic resins after 72 hours of QUV weathering: (a) pristine and (b) QUV exposed.

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Table 4.4 Colorimetric analysis of the bio-based thermoplastic resins (PLA, PHB, and PA11) before and after QUV weathering for 24, 48, and 72 hours.

	Terms	Final	Initial	Δ
PLA 24hrs	L*	70.66	75.04	-4.38
	a*	0.03	-0.46	0.49
	b*	2.73	2.47	0.26
PLA 48hrs	L*	71.07	75.04	-3.97
	a*	-0.35	-0.46	0.11
	b*	2.39	2.47	-0.08
PLA 72hrs	L*	69.95	75.04	-5.09
	a*	-0.27	-0.46	0.19
	b*	2.66	2.47	0.19
PHB 24hrs	L*	79.64	76.13	3.51
	a*	-0.96	-1.04	0.08
	b*	2.01	2.06	-0.05
PHB 48hrs	L*	82.3	76.13	6.17
	a*	-0.83	-1.04	0.21
	b*	4.83	2.06	2.77
PHB 72hrs	L*	85.95	76.13	9.82
	a*	-0.54	-1.04	0.5
	b*	3.66	2.06	1.6
PA11 24hrs	L*	72.44	73.68	-1.24
	a*	-0.11	0.08	-0.19
	b*	3.62	3.32	0.3
PA11 48hrs	L*	71.5	73.68	-2.18
	a*	-0.28	0.08	-0.36
	b*	7.13	3.32	3.81
PA11 72hrs	L*	70.81	73.68	-2.87
	a*	-0.18	0.08	-0.26
	b*	7.43	3.32	4.11

Table 4.5 Variation of color change efficiency after 72 hours.

Resin	ΔC_t^*	$\Delta C_a^* \%$	$\Delta C_b^* \%$
PLA	0.26	70.7	70.7
PA11	4.11	6.3	99.8
PHB	1.67	29.8	95.4

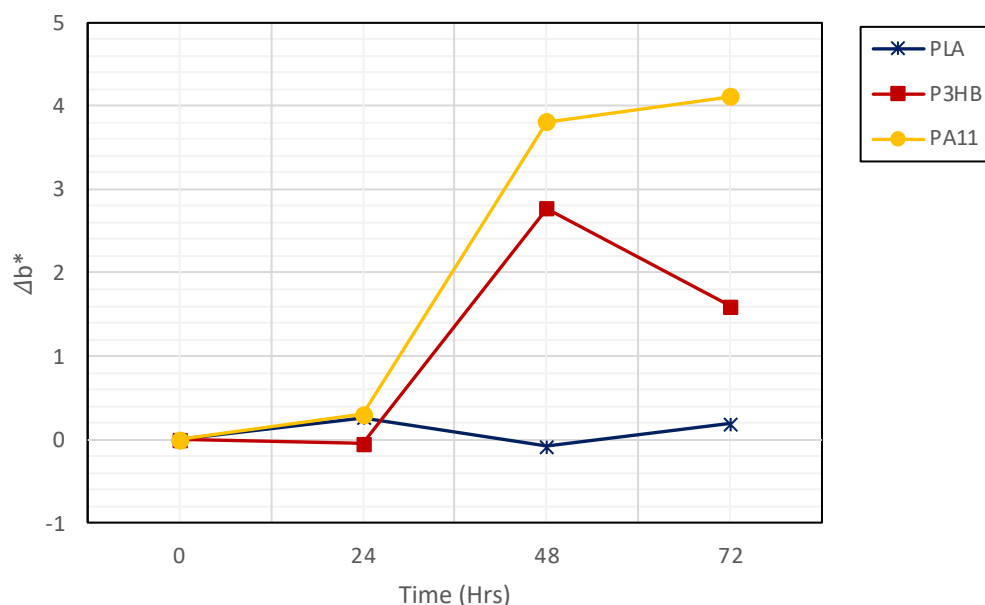


Figure 4.14 The change of colorimetric parameter b^* for each bio-sourced thermoplastic films, as a function of UV exposure times (pristine, 24hrs, 48hrs, and 72hrs).

Pristine and QUV weathered bio-based resins were also characterized for their chemical and thermal properties via FTIR and DSC. The FTIR spectra of the bio-based resins before and after 72 hours of QUV weathering are shown in Figure 4.15. The DSC graphs of bio-based resins are shown in Figure 4.16. FTIR and DSC analysis of the QUV weathered exposed bio-based resins (PLA, PA11, and PHB) did not indicate any change overall in chemical properties or thermal properties due to UV degradation.

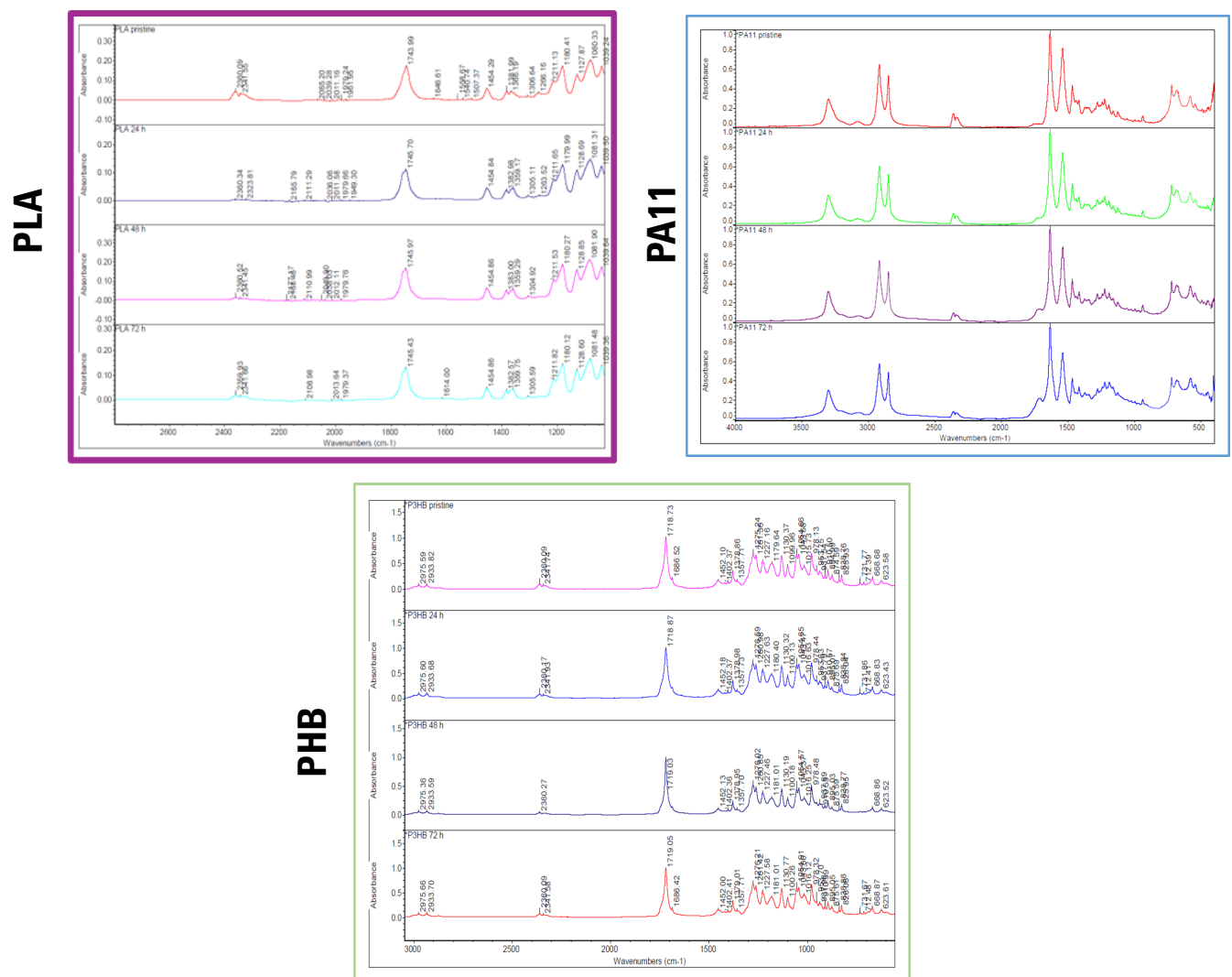
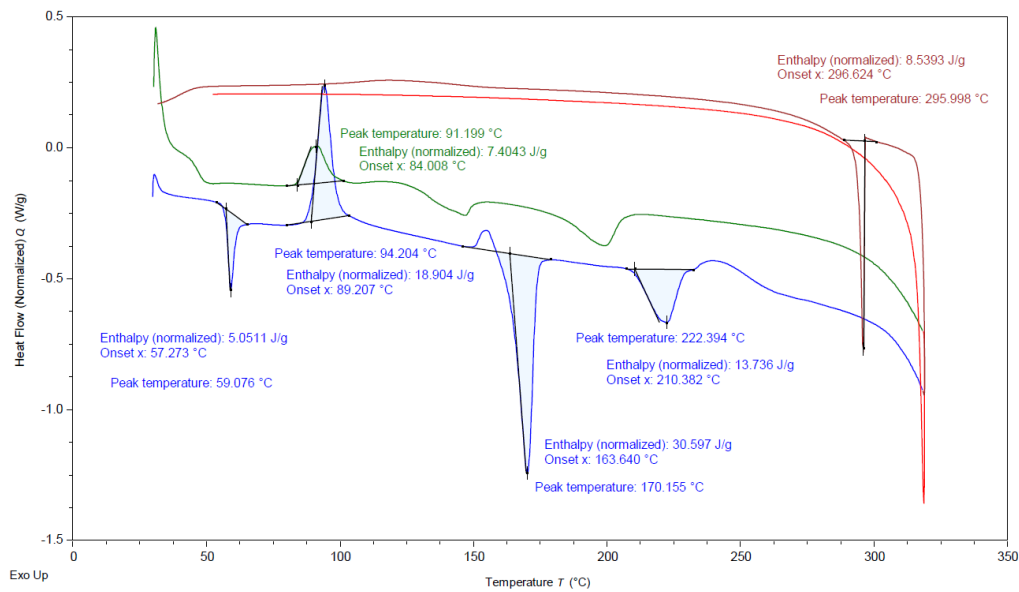
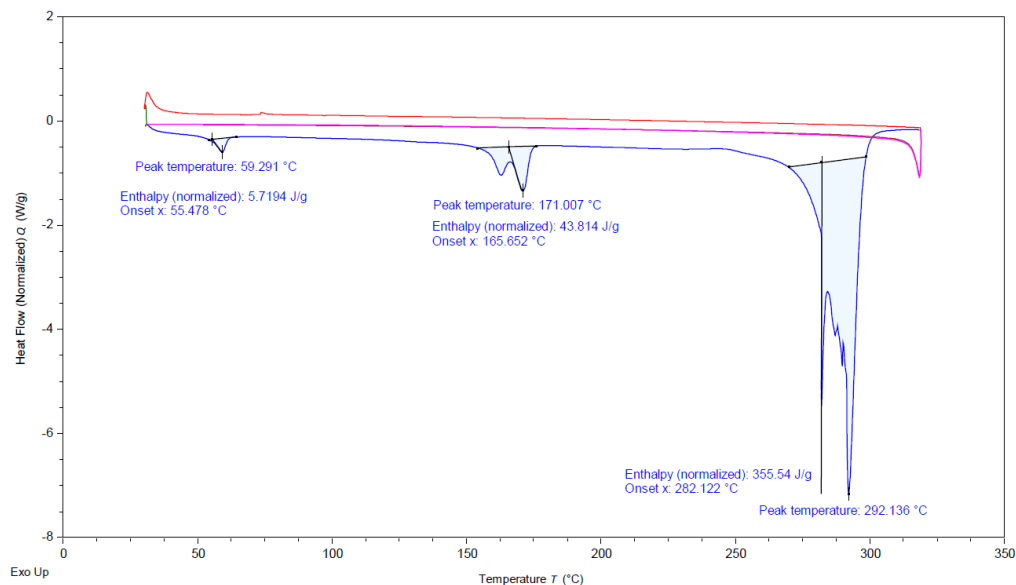


Figure 4.15 FTIR spectra for Bio-based Resins before and after 72 hours QUV exposure.

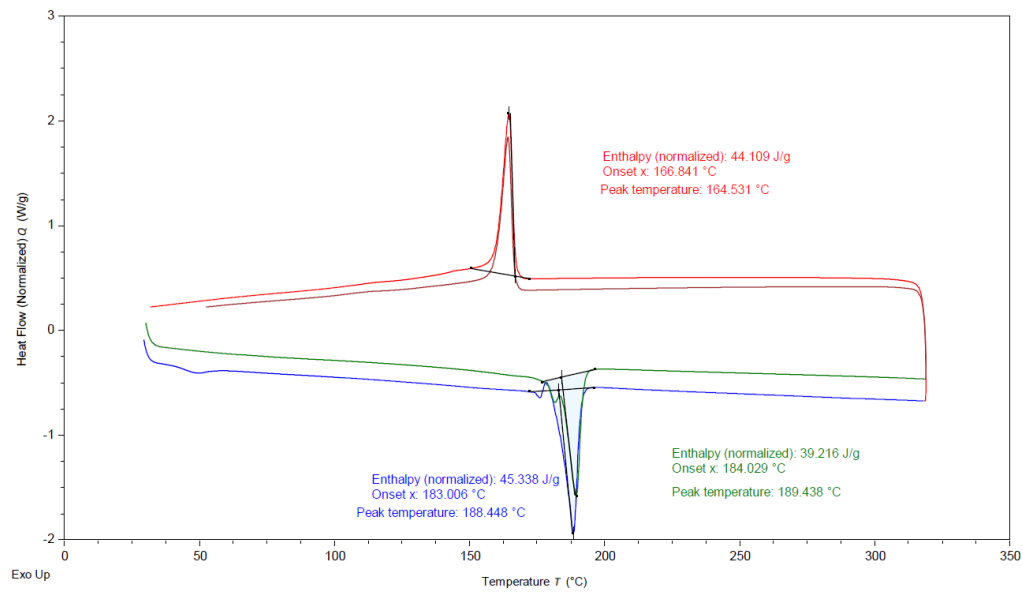


(a)

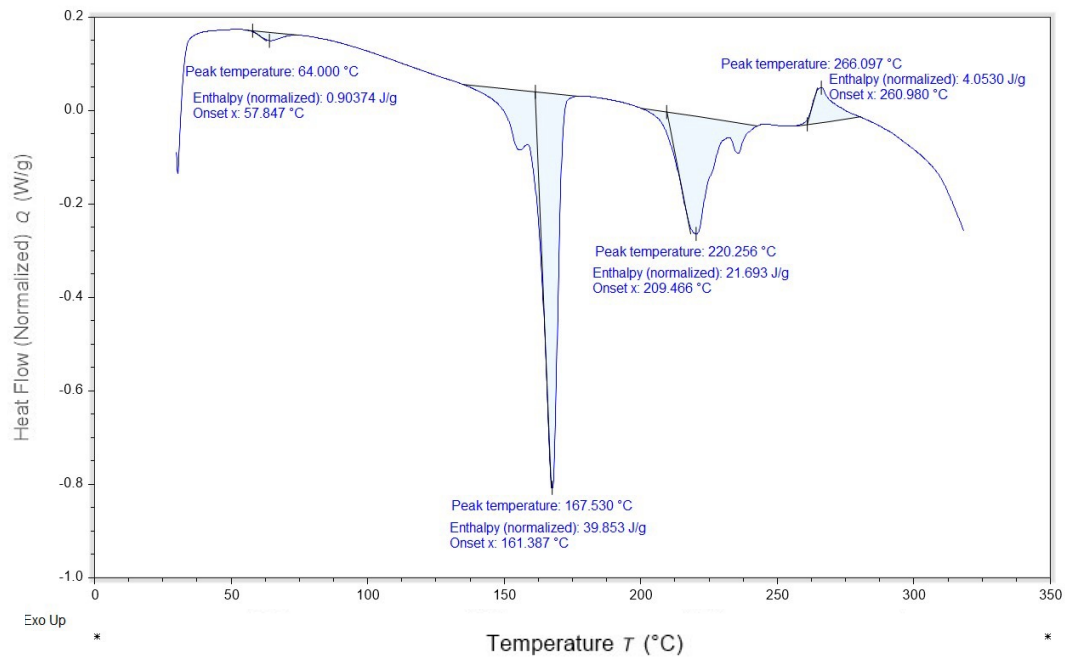


(b)

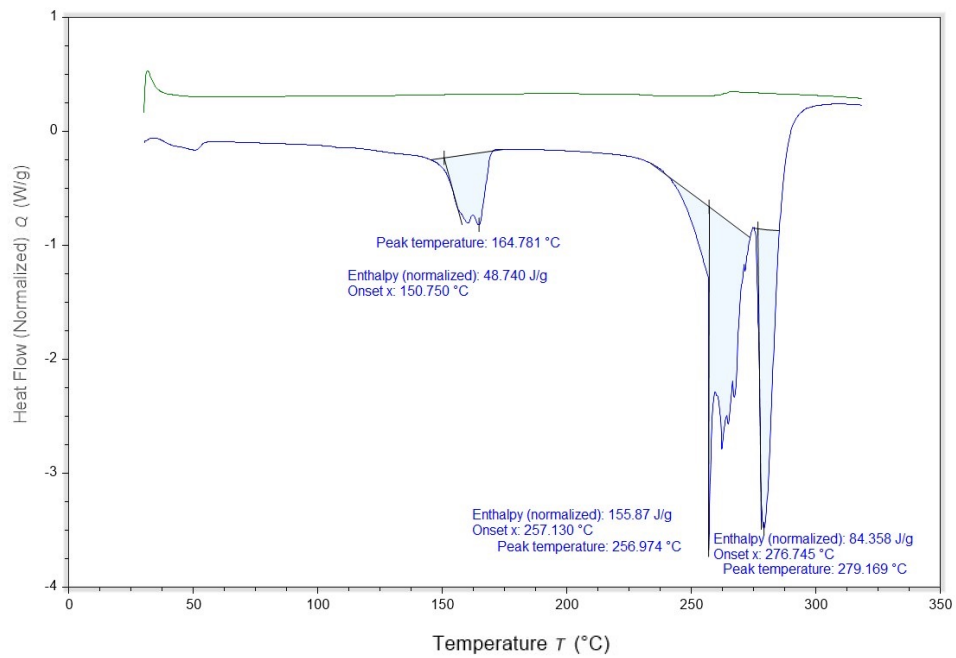
Figure 4.16 DSC analysis of Bio-Based Resins before and after 72 hours of QUV exposure: (a) PLA, pristine; (b) PHB, pristine; (c) PA11, pristine; (d) PLA, 72 hour UV exposure; (e) PHB, 72 hour UV exposure; (f) PA11, 72 hour UV exposure.



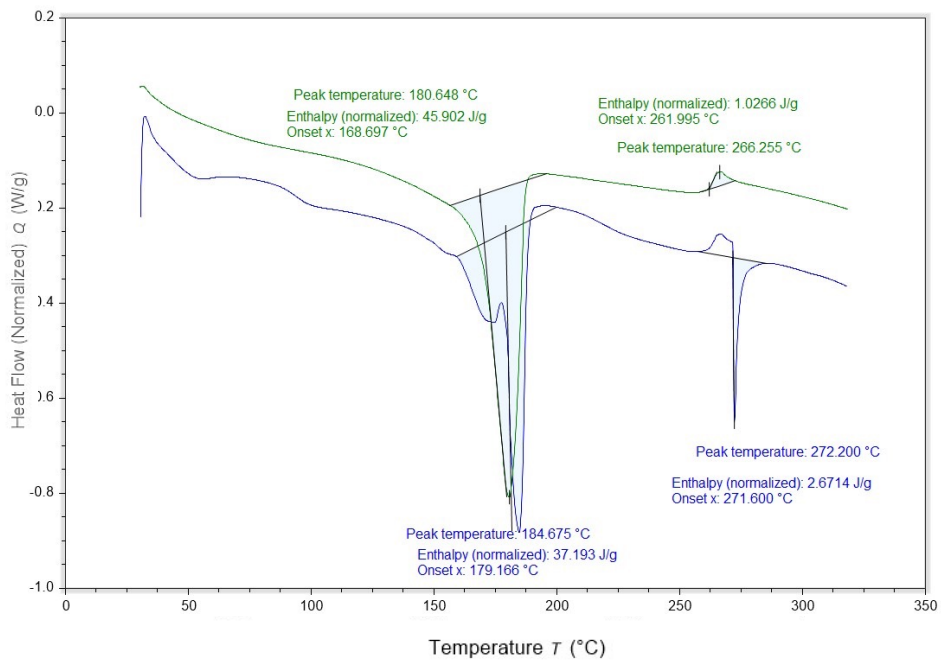
(c)



(d)



(e)



(f)

Figure 4.17 - Figure 4.19 include Tensile stress-strain plots for bio-based resins before and after 72 hours of QUV weathering along with tables summarizing mechanical testing data. Mechanical data for PLA are not included as it exhibited the greatest amount of degradation. As a result, PLA became very brittle and broke into pieces during handling. Pristine bio-based resins and the QUV weathered bio-based resins PA11 and PHB were tensile tested.

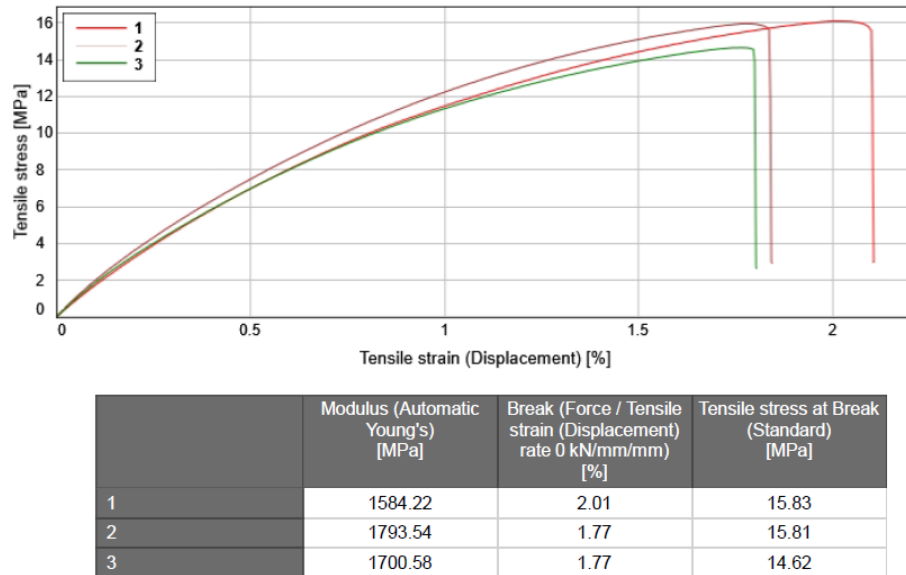


Figure 4.17 Tensile testing for pristine PHB.

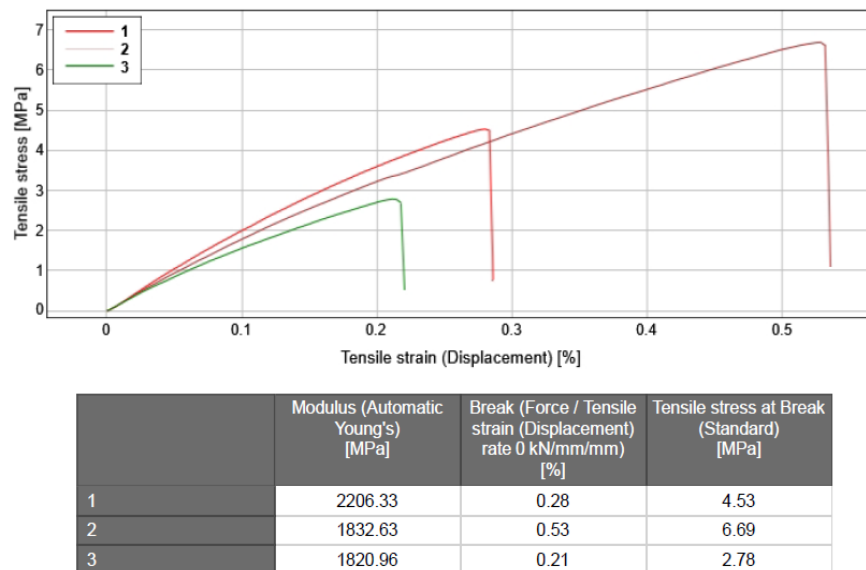


Figure 4.18 Tensile testing for PHB After 72 hours QUV weathering.

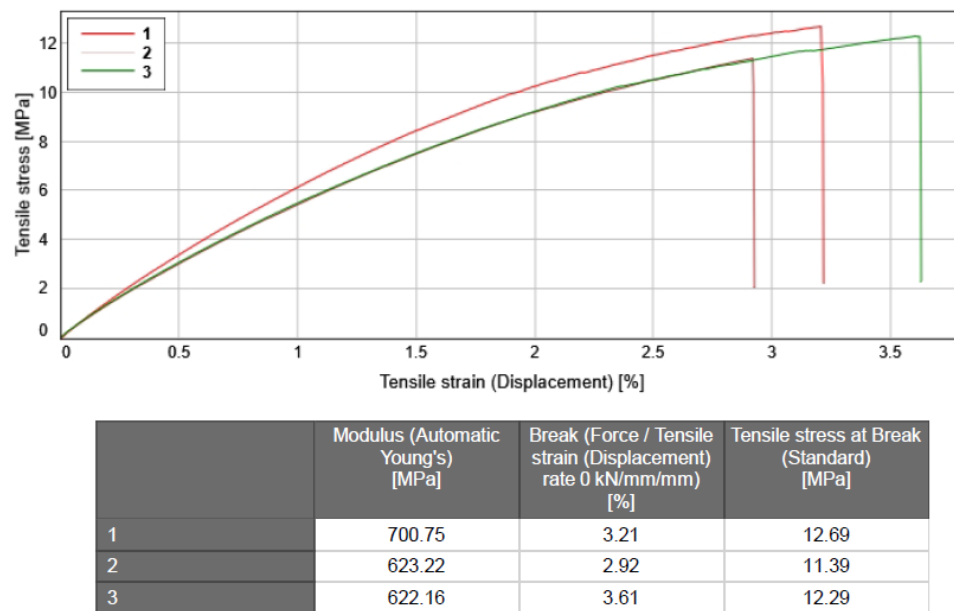


Figure 4.19 Tensile testing for PA11 After 72 hours QUV weathering.

Preliminary mechanical property assessments demonstrate the effects of QUV weathering on the durability and performance of the samples. PLA and PHB significantly decrease in mechanical strength properties, whereas PA11 retains its strength even after degradation.

4.1.3.4 Conclusions and Key Takeaways

In this study, the combined effects of UV radiation at elevated temperature on the chemical, thermal, and mechanical properties of bio-based resins PLA, PA11, and PHB were analyzed. The results analyzed showed that:

- All the bio-based resins exhibited degradation in overall physical properties from UV exposure at elevated temperature. Specifically, PA11 experienced the process of photodegradation, creating yellow color.
- PLA and PHB significantly decreased in mechanical properties, whereas PA11 retained its strength after QUV weathering.
- FTIR and DSC did not indicate any change in chemical or thermal properties for the bio-based resins.
- PA11 demonstrated to be the most durable of the bio-based resins at least with its mechanical properties, throughout all environmental and characterization tests.

Overall, from an operational point of view, the results obtained demonstrate that UV protection, either through the use of additives in the polymer matrix or through an external layer of UV-absorbing material, will be key in maintaining the structural integrity of a material for applications on aircraft that will be exposed to sunlight and the elements.

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4.1.3.5 References

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4.2 Natural Fibers for Reinforcement

4.2.1 Introduction

Why natural fibers?

Conventional carbon fiber–reinforced polymers, while offering excellent mechanical properties, are energy-intensive to produce, difficult to recycle, and pose challenges for end-of-life disposal. In contrast, natural fibers such as flax, hemp, and jute present a renewable and recyclable alternative with inherent multifunctional benefits that can be strategically leveraged for aerospace applications. The SUMAC project explores these opportunities, aiming to demonstrate how natural fiber-reinforced composites can advance sustainable composite technology, while meeting performance requirements for AAM and commercial aircraft.

One of the most direct advantages of natural fibers lies in their density. Carbon fibers typically have a density of approximately 1.8 g/cm³ and glass fibers have about 2.5 g/cm³, whereas natural fibers have average density closer to 1.5 g/cm³. As flax and hemp natural fibers can offer mechanical reinforcement equivalent to glass fibers, this density difference of nearly 20% translates directly into weight reduction in composite structures. For aerospace applications where mass efficiency is critical, even modest reductions in structural weight can lead to significant improvements in fuel efficiency, payload capacity, and overall vehicle performance. In the emerging field of AAM, where electric propulsion and distributed lift systems impose strict weight budgets, lightweight natural fiber composites offer a unique value proposition.

Beyond weight savings, natural fibers provide intrinsic vibration damping capabilities that surpass those of carbon fibers. This property is largely attributed to their hollow core structure and hierarchical microfibrillar architecture (see Figure 4.20), which dissipate vibrational energy through internal friction and structural compliance. For aircraft cabin interiors, rotorcraft fuselages, and AAM vehicles, enhanced low-frequency vibration damping improves passenger comfort, reduces structural fatigue, and mitigates high-frequency acoustic noise transmission. These benefits are particularly attractive in AAM platforms, where cabin

Use Case Highlight: Natural Fibers

Hemp and flax natural fibers offer multifunctional advantages that enhance performance, safety, and comfort for future aerospace systems:

- **Weight Reduction:** Natural fibers can achieve up to 20% weight savings compared with carbon fibers, improving energy efficiency and payload capacity.
- **Vibration Damping:** Their hollow core and microfibrillar structure dissipate vibrational energy up to 250% more effectively than carbon fibers, enhancing ride comfort and reducing structural fatigue.
- **Acoustic Noise Abatement:** Their hollow core and hierarchical morphology scatter and absorb sound, providing inherent cabin noise reduction without added insulation.
- **Safe Communication:** Unlike conductive carbon fibers, natural fibers are electrically insulating, enabling safe, interference-free communications critical for Advanced Air Mobility.

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quietness and comfort are critical for public acceptance especially during AAM operation in urban areas [1].

The same hollow core morphology that contributes to damping also provides natural fibers with excellent acoustic noise attenuation. Their hollow and hierarchical microstructure scatters and absorbs incident sound waves, making natural fiber composites effective in reducing cabin noise levels and external sound propagation. Incorporating natural fibers into panels, linings, or secondary structural components (ex. bulkheads inside AAM vehicles) could therefore yield dual benefits, structural performance coupled with improved acoustic environments, without the need for additional damping or insulation materials (ex. headsets for passengers).

A further advantage of natural fibers, particularly relevant to the AAM domain, is their radio-frequency (RF) transparency. Unlike carbon fibers, which are electrically conductive and shield electromagnetic signals, natural fibers are electrically insulating. This property allows composites reinforced with natural fibers to transmit RF signals with minimal interference, an essential capability for modern aerospace systems that rely heavily on high-bandwidth communications, navigation, and sensing technologies. In AAM vehicles, where robust communication links are required for safety, air traffic integration, and autonomous flight systems, materials that do not compromise communication signal transparency are of particular importance to vehicle safety. The use of natural fiber composites therefore not only contributes to sustainability and weight savings but also enables safe and reliable communication.

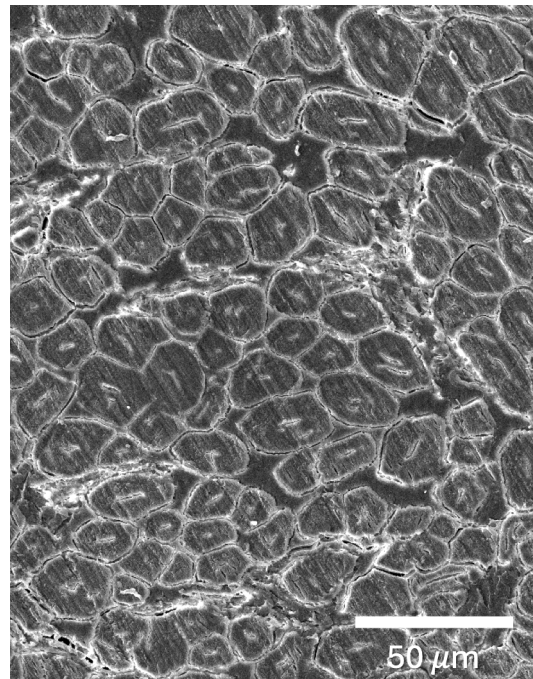


Figure 4.20 Electron microscope image of flax fibers, showing cross-sectional view of their hollow cores. The scale bar represents 50 μm .

In addition to these performance attributes, natural fibers offer a compelling sustainability. They are derived from rapidly renewable resources, sequester atmospheric carbon dioxide during cultivation, and can be processed with significantly lower energy inputs compared to synthetic carbon fibers. When combined with recyclable thermoplastic matrices, natural fiber composites align with circular economy principles, offering potential for reuse, reprocessing, or more benign disposal pathways at end of service life.

In this SUMAC project, natural fibers are explored in combination with bio-sourced thermoplastic matrices to deliver multifunctional, sustainable solutions tailored for interior and secondary structures in AAM vehicles and potentially commercial aircraft. By leveraging the inherent advantages of natural fibers, SUMAC aims not only to reduce environmental

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impacts but also to enhance safety, comfort, and performance in next-generation air transportation.

Fiber Down-Selection Considerations

While natural fibers offer promising advantages for aerospace composites, the SUMAC project focused its initial evaluation on flax and hemp, two of the most viable candidates for structural applications. A definitive down-selection between these fiber systems requires a comprehensive assessment of their mechanical properties, processability, and long-term durability under aerospace service conditions. Additional experimental insights from composite manufacturing trials and computational modeling will be necessary to identify the optimal reinforcement system for SUMAC composites.

From a processing and availability standpoint, flax currently holds an advantage. It has a long history of industrial use, particularly in Europe, where mature supply chains and well-established fiber processing infrastructure support its use in sustainable composite applications. Hemp, although gaining traction as an alternative reinforcement, still faces challenges related to regulations and processing technologies. In particular, U.S. hemp processing infrastructure requires further development to consistently produce high-quality, textile-grade fibers suitable for aerospace applications.

Sustainability considerations, however, reveal the potential of hemp as emerging natural fiber for composite. Hemp is among the highest-yielding natural fibers on Earth, producing 250–300% more fiber per acre than cotton and over 600% more than flax, while requiring only one-half to one-third of the water resource. It grows rapidly, requires fewer herbicides and pesticides, and produces higher biomass yields per unit area than flax, giving it a distinct environmental advantage. From this perspective, hemp represents one of the most resource-efficient fiber systems available for sustainable composites [2].

Furthermore, flax cultivation and applications are largely dominated by European countries, where industrial processing infrastructure is already established. By contrast, hemp cultivation is expanding rapidly in the United States, creating an opportunity to accelerate domestic fiber processing technologies. Developing a U.S.-based hemp supply chain could reduce reliance on imported flax, strengthen domestic agriculture and advanced manufacturing, and position the United States as a leader in sustainable composites for aerospace and future aviation.

Given these trade-offs, flax currently offers greater near-term readiness due to its processing maturity and commercial availability, while hemp presents a longer-term opportunity for higher sustainability and U.S. domestic economic impact. The final fiber system selection will depend on further evaluation of processing efficiency, mechanical performance, durability, and integration into thermoplastic composite systems. Insights from material characterization, composite fabrication, and modeling studies will guide this decision to ensure an optimal balance of performance, manufacturability, and sustainability for SUMAC composites.

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4.2.2 Experimental

4.2.2.1 Materials

Natural fibers were evaluated for their mechanical properties. Especially, specific procedures were developed to reliably characterize their morphological characteristics and mechanical properties of individual fibers and yarns. This is critical to understanding the behavior of natural fiber reinforcement for SUMAC composites. In this work, a variety of natural fibers were tested, including hemp fibers from EnviroTextiles, LLC., CO, flax fibers from Bcomp Inc., Switzerland, braided flax fibers from A&P Technology, Inc., OH, and commingled flax-PA11 fibers from Concordia Fibers, RI. Table 4.6 summarizes the natural fiber samples evaluated for mechanical property testing in this work. Key characteristics such as processing method, weave structure, fiber composition, and origin are provided as well.

4.2.2.2 Variability

The size and geometry of natural fibers vary considerably due to their inherent heterogeneity. This variability complicates characterization and necessitates carefully designed, reliable experiment procedures. The large standard deviations observed in the mechanical data indicate not only the irregular cross-sectional shapes of the fibers but also their intrinsic anisotropy and variability in material properties. Figure 4.21 shows cross sections of multiple fibers, highlighting key features such as collapsed hollow cores, irregular shape, and variations in diameter. In addition, when performing mechanical testing on yarns, which consist of multiple fibers twisted together, accurately determining the yarn diameter is challenging. As shown in Figure 4.22, the diameter can vary considerably along even a short (~ 1 mm) segment of yarn. This variability introduces undesirable subjectivity in diameter measurements and can lead to significant errors in calculated tensile strength. To address this, industry standards define yarn properties using linear density, expressed in tex, defined as grams per 1000 meters of yarn (g/km) [3]. This eliminates reliance on a perceived diameter. Normalizing the breaking force by the linear density produces a pseudo strength value, which serves as an indirect estimate of the intrinsic strength of the constituent fibers, as illustrated in Figure 4.23. Expressed in N/tex, this normalization enables meaningful comparisons between yarns with different diameters and structures, making it particularly useful for evaluating multiple fiber candidates. While this approach provides an effective estimate of fiber strength at the yarn level, direct measurement of individual fiber mechanical properties remains essential to fully characterize intrinsic material behavior.

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Table 4.6 Natural fiber samples evaluated for mechanical property testing.

Fiber Type	Company	Sample Name	Notes
Hemp	EnviroTextiles	B601	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; plain weave.
	EnviroTextiles	B602	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; plain weave.
	EnviroTextiles	B605	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; prepared for dyeing; plain weave.
	EnviroTextiles	B607	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; prepared for dyeing; plain weave.
	EnviroTextiles	B608	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; prepared for dyeing; plain weave.
	EnviroTextiles	B610	Semi-bleached with peroxide, preshrunk; degummed; “greige” with potato starch sizing on warp; prepared for dyeing; plain weave.
	EnviroTextiles	100% Twill	“Greige” with potato starch sizing on warp; 2×2 twill fabric pattern.
	EnviroTextiles	Colorado Winter Retted Bast 100% Hemp	Grown in Colorado.
	EnviroTextiles	Colorado 100% Hemp Roving	Made from bast sample; processed in Colorado.
Flax	Bcomp	Bcomp Flax	2 × 2 twill fabric pattern; yarns unidirectional.
	A&P Technology	Braided Flax	Biaxial fabric pattern; unidirectional flax yarns surrounded by small spiral cellulose yarns.
	Concordia Fibers	Flax-PA11 Commingled Fiber	Composition: flax fiber, 62.7 wt% (54.6 vol%) and PA11 fiber, 37.3 wt% (45.4 vol%).
Others	EnviroTextiles	Fiber C, washed	Leaf fiber & process; non-hemp fiber.
	EnviroTextiles	Fiber C, yarn	Standard fiber quality; multiple yarn sizes & weave structures; non-hemp fiber.
	EnviroTextiles	Fiber P#2	–
	EnviroTextiles	Fiber X	Agave-based byproduct fibers.

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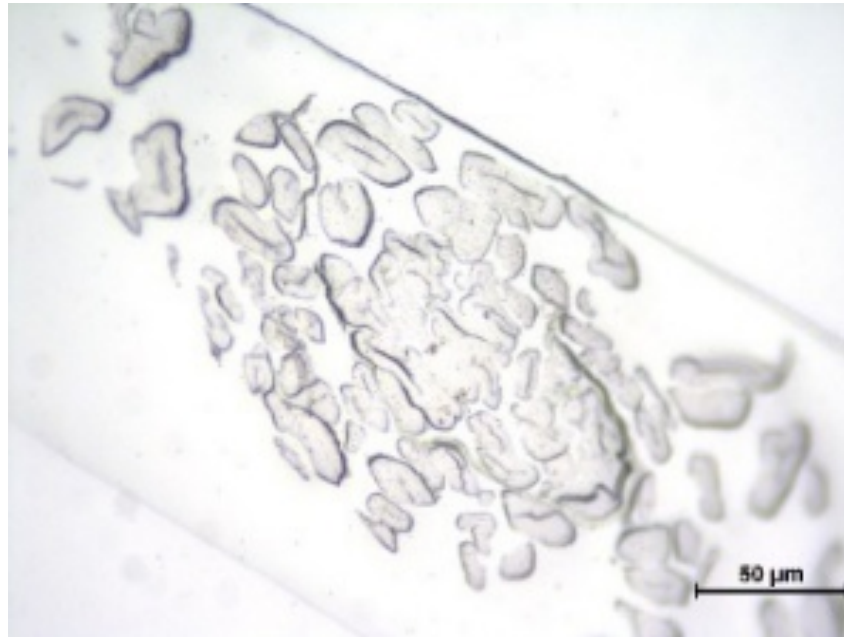


Figure 4.21 EnviroTextiles Hemp B608 Cross Section, Optical Microscope 50X.



Figure 4.22 EnviroTextiles Hemp B608 Yarn, Optical Microscope 10X.

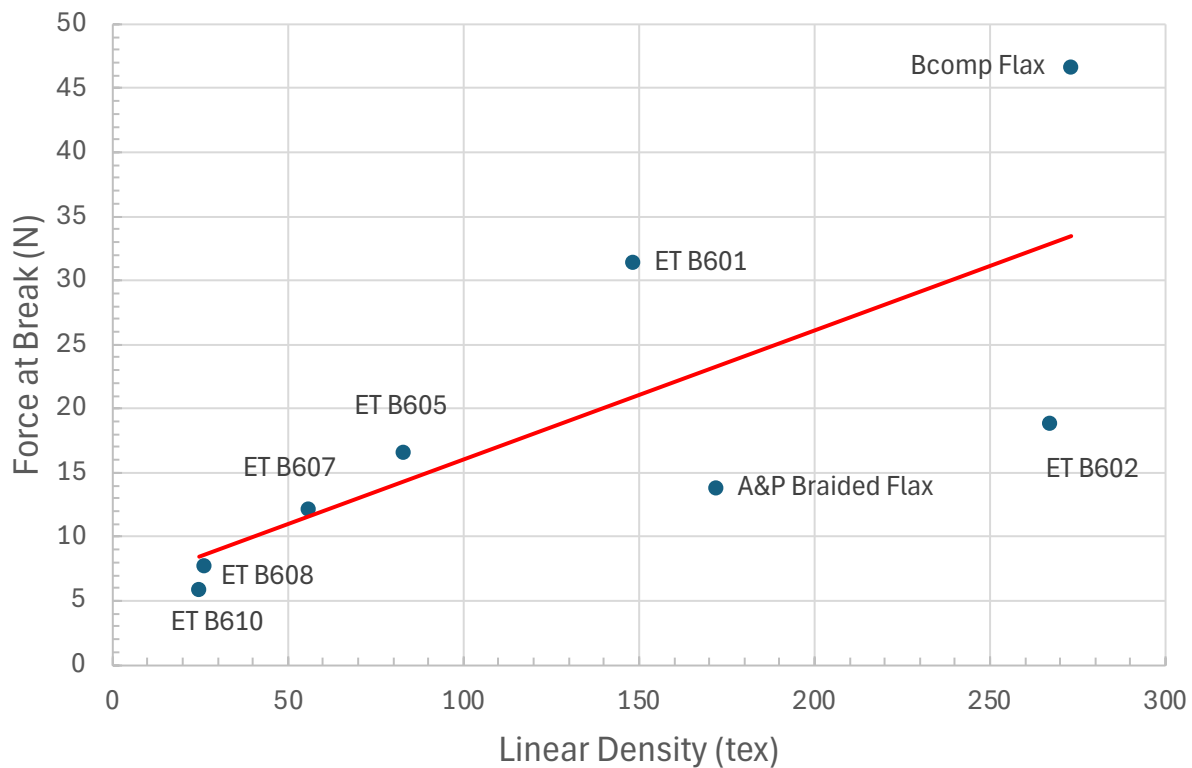


Figure 4.23 Correlation of force at break and linear density (tex) of various natural fiber samples.

4.2.2.3 Tensile Testing of Individual Fibers and Yarns

Individual fiber tensile tests were conducted using an Instron 5848 Microtester equipped with a 5 N load cell (see Figure 4.24), chosen for its sensitivity to the low breaking forces (<1.0 N) typical of natural fibers. Fibers were mounted on 3 cm × 3 cm paper coupons with a 1 cm square cutout defining a ~10 mm gauge length, determined optimal after preliminary testing. A guideline was drawn on each coupon to ensure fibers were centered and perpendicular to the clamps, providing uniform load distribution during testing, as illustrated in Figure 4.25. Various adhesion methods were evaluated; superglue was selected for its rapid curing and minimal mess, while double-sided tape and epoxy proved unsuitable due to fiber slippage or handling complexity. A small slack was introduced during mounting to prevent premature fracture, and fibers were sandwiched between a secondary paper grid for stability. After securely installing the test sample coupon, the top and bottom sides of the paper coupon are cut prior to testing so that the load is applied only to the fiber sample. At least five coupons per specimen were prepared and tested in a horizontal configuration with extension arms attached to the right side of the crosshead to accommodate the gauge length beyond the Instron's travel limit and mitigate bending momentum applied to the 5N-load cell equipped at the left side (see Figure 4.26). Samples were prestressed to around 15–

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20 MPa to remove slack, and the gauge length was measured again. Tensile tests were conducted at a ramp rate of 10% of the gauge length per minute (e.g., 1 mm/min for a 10 mm fiber). Following fracture, fiber diameters were measured again at the break location to ensure accurate cross-sectional area calculations, reducing variability due to the irregular geometry of natural fibers.

Yarn tensile testing was performed on the Instron 5944 with a 2 kN-load cell. Each yarn was cut to 3 cm and weighed to determine linear density (tex). Tensile force was normalized by linear density to estimate pseudo-strength, enabling meaningful comparisons across yarns of differing diameters and constructions while reflecting the intrinsic mechanical properties of the constituent fibers.

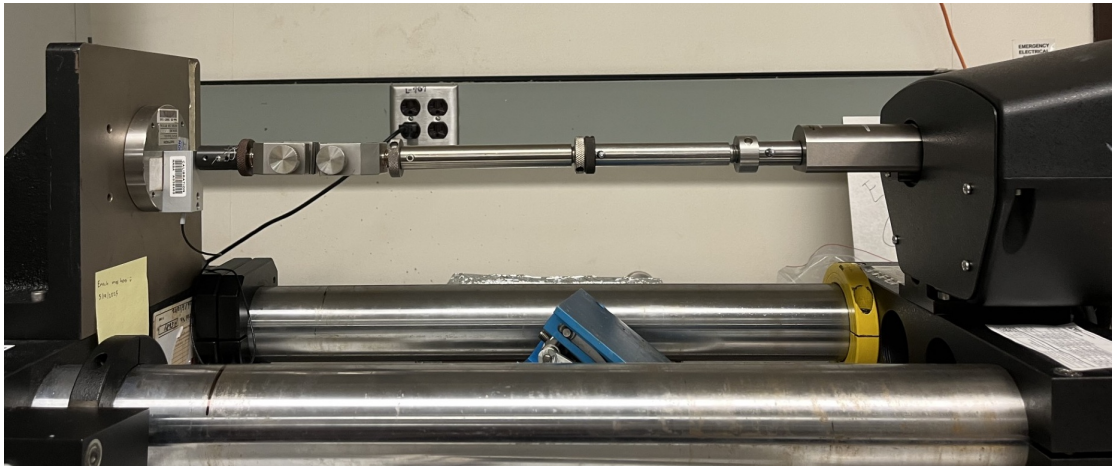


Figure 4.24 Instron 5848 microtester in horizontal configuration with 5-N load cell and extension arms, used for individual fiber tensile testing

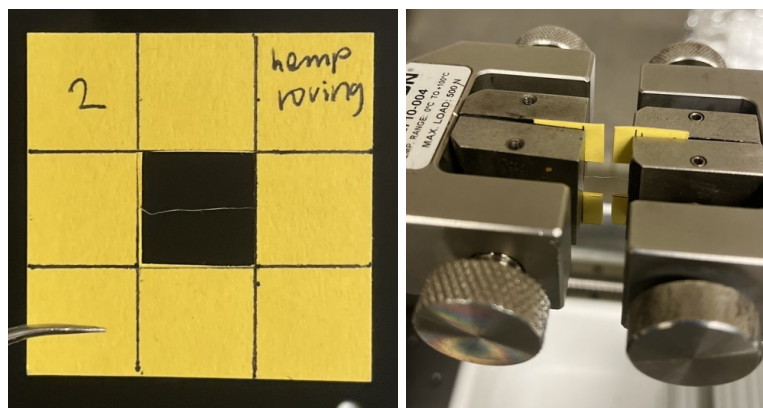


Figure 4.25 Individual fiber preparation for tensile testing. Fibers are placed on paper coupons with a 1-cm² cutout and aligned perpendicular to the clamps, with slight slack introduced to prevent preloading.

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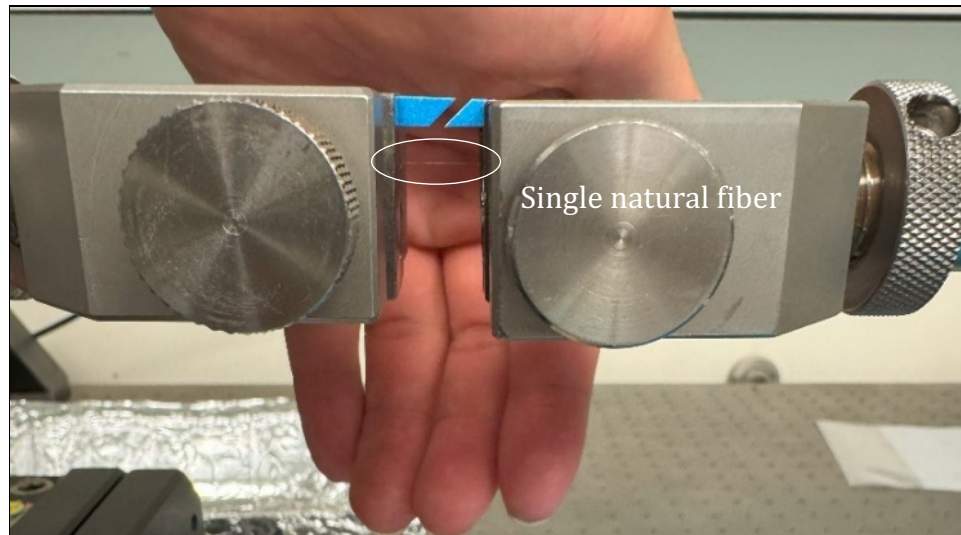


Figure 4.26 Individual fibers loaded into the Instron 5848 microtester. The top side of the paper coupon has been cut, leaving only the fiber gauge length between the grips.

4.2.3 Results and Discussion

Table 4.7 summarizes literature values of mechanical properties of natural fibers and PA11 fiber [4-8]. Flax fibers exhibit tensile strengths of approximately 600–2000 MPa, % elongation at break of 1–4%, and Young's modulus of 12–85 GPa. Hemp fibers show tensile strengths of 550–1110 MPa, elongation around 1.6%, and modulus of 58–70 GPa. PA11 thermoplastic fibers are significantly more ductile, with tensile strengths of 25–55 MPa, elongation at break of 160–260%, and modulus of 0.90–1.60 GPa. These ranges provide baselines for evaluating SUMAC candidate fibers.

Mechanical testing of individual fibers is summarized in Table 4.8. Flax fibers, particularly A&P Technology Braided Flax, as shown in Figure 4.27, demonstrate higher tensile strength (906 ± 768.5 MPa) and modulus (52.9 ± 27.2 GPa) than other flax fibers, reflecting their commercial processing optimization, better fiber alignment, and controlled manufacturing conditions for composite applications. Bcomp Flax show slightly lower strength (880.2 ± 596.3 MPa) and modulus (42.1 ± 21.7 GPa) than A&P Flax (see Figure 4.28). Hemp fibers exhibit greater variability in their tensile properties compared to flax. Among the hemp samples, EnviroTextiles (ET) 100% Hemp Twill demonstrates the highest individual fiber tensile strength (1238.5 ± 719.1 MPa, Figure 4.29), surpassing even flax fibers. ET Hemp B607 and B608 show tensile strengths ranging from 492 to 800 MPa (see Figure 4.30 and Figure 4.31), with corresponding moduli of 16–35 GPa and elongation at break values of 3–4%. ET Colorado Winter Retted Bast 100% Hemp also exhibits high tensile strength (1059.6 ± 235.9 MPa) and a modulus of ~ 53 GPa, indicating the influence

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of winter cultivation and retting conditions. The large standard deviations observed across hemp fibers reflect both intrinsic heterogeneity and experimental uncertainty. Factors such as fiber diameter variation, irregular cross-sectional morphology, and compositional differences in cellulose, hemicellulose, lignin, and pectin are key contributors to the scatter in mechanical properties.

Furthermore, the flax-PA11 commingled fibers from Concordia Fibers exhibit promising behavior between pure natural fibers and bio-sourced PA11 fibers. As shown in Figure 4.32, flax fibers isolated from the flax-PA11 commingled ones show the highest tensile strength (1432.5 ± 803.0 MPa) among all individual fibers tested, along with high modulus (40 ± 14 GPa) and reasonable elongation-at-break value ($\sim 3.7\%$). The PA11 fibers from the commingled fibers are highly ductile, with low tensile strength (112.7 ± 21.5 MPa) and modulus (1.4 ± 0.1 GPa) but elongation exceeding 100%. The tensile strength was significantly greater than the literature value (see Table 4.7). Therefore, the combination in commingled flax-PA11 fibers enables a tailored balance of stiffness and ductility, which would be advantageous for SUMAC composite reinforcement, providing structural strength and improved toughness.

Yarn-level properties are summarized in Table 4.9. Linear density-normalized tensile strength (N/tex) allows comparison across fibers with varying diameters and structures. Bcomp Flax Yarn exhibited the highest pseudo-strength, reflecting optimized fiber alignment, tight processing control, and commercial manufacturing. Hemp yarns displayed lower pseudo-strength but similar trends as their constituent fibers. Fiber bundles, such as ET Colorado 100% Hemp Roving, showed reduced strength (333.3 ± 186.8 MPa) but increased elongation ($\sim 5.8\%$) due to load redistribution among misaligned fibers. Other bundles, including ET Fiber P#2, demonstrate improved strength and modulus (598.3 ± 75.0 MPa, 17.2 ± 2.9 GPa), showing the impact of fiber quality, processing, and alignment. Unfortunately, detailed specifications and material composition data for the “other” fiber samples were not made available by EnviroTextiles.

Table 4.7 Literature values of mechanical properties of flax, hemp, and PA11 fibers.

Type	Tensile Strength (MPa)	% Elongation at Break	Young’s Modulus (GPa)
Flax	$\sim 600 - 2000$	$\sim 1 - 4$	$\sim 12 - 85$
Hemp	$\sim 550 - 1110$	~ 1.6	$\sim 58 - 70$
PA11	$\sim 25 - 55$	$\sim 160 - 260$	$\sim 0.90 - 1.60$

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Table 4.8 Mechanical properties of individual natural fibers (ET: EnviroTextiles).

Type	Individual Fiber Sample	Tensile Strength (MPa)	% Elongation at Break	Young's Modulus (GPa)
Hemp	ET 100% Hemp twill	1238.5 ± 719.1	3.2 ± 0.8	47.5 ± 22.1
	ET Colorado Winter Retted Bast 100% Hemp	1059.6 ± 235.9	2.7 ± 0.7	53.0 ± 11.6
	ET Hemp B607	492.6 ± 233.6	4.4 ± 1.5	15.8 ± 4.3
	ET Hemp B608	800.4 ± 366.4	3.0 ± 0.4	35.1 ± 1.7
	Hemp 1(Bleached)	518.1 ± 318.3	3.0 ± 0.4	20.7 ± 11.3
Flax	Bcomp Flax	880.2 ± 596.3	2.4 ± 0.8	42.1 ± 21.7
	A&P Technology Braided Flax	906 ± 768.5	2.0 ± 1.0	52.9 ± 27.2
	Concordia Commingled Fiber – Flax	1432.5 ± 803.0	3.7 ± 0.4	40.0 ± 14.0
PA11	Concordia Commingled Fiber – PA11	112.7 ± 21.5	100.1 ± 9.9	1.4 ± 0.1

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Table 4.9 Mechanical properties of natural fiber yarns (ET: EnviroTextiles).

Type	Yarn Sample	Force/Linear Density (N/tex), [N/(kg/m)]	% Elongation at Break	Young's Modulus (GPa)	Linear Density(tex) 1 tex = 1 gram/km	Tensile Strength (MPa) with Measured Diameter
Hemp	ET Hemp B601 Yarn	0.215 ± 0.021 [214686 ± 20611]	6.1 ± 0.7	7.1 ± 1.3	148.0 ± 23.4	329.0 ± 54.5
	ET Hemp B602 Yarn	0.071 ± 0.012 [70668 ± 11918]	10.1 ± 1.6	1.0 ± 0.2	267.0 ± 13.5	73.1 ± 15.8
	ET Hemp B605 Yarn	0.207 ± 0.050 [207062 ± 49517]	7.5 ± 1.2	3.6 ± 1.0	82.8 ± 46.3	198.9 ± 33.1
	ET Hemp B607 Yarn	0.222 ± 0.023 [222045 ± 23066]	9.25 ± 1.4	5.3 ± 0.9	55.6 ± 11.4	381.5 ± 67.2
	ET Hemp B608 Yarn	0.284 ± 0.028 [284286 ± 28314]	6.7 ± 1.2	6.1 ± 1.0	26.0 ± 4.3	343.7 ± 38.3
	ET Hemp B610 Yarn	0.230 ± 0.051 [230273 ± 51278]	5.7 ± 1.3	8.7 ± 3.6	24.5 ± 7.3	310.7 ± 103.7
	ET 100% Hemp Yarn	0.295 ± 0.34 [295023 ± 33508]	4.1 ± 0.8	10.3 ± 2.1	32.4 ± 13.2	378.0 ± 101.4
	ET Colorado 100% Hemp Roving (bundle)		5.8 ± 1.0	14.1 ± 6.6		333.3 ± 186.8
Flax	Bcomp Flax Yarn	0.172 ± 0.012 [172238 ± 19657]	1.5 ± 0.1	12.0 ± 1.7	273.0 ± 77.4	143.2 ± 23.0
	A&P "Braided/Woven" Flax Yarn	0.082 ± 0.031 [82342 ± 30739]	1.4 ± 0.4	4.3 ± 1.4	171.8 ± 91.6	45.5 ± 19.5
Others	ET Fiber C (Leaf) (bundle)		8.4 ± 2.8	8.8 ± 1.4		436.0 ± 87.5
	ET Fiber P#2 (bundle)		5.0 ± 0.3	17.2 ± 2.9		598.3 ± 75.0

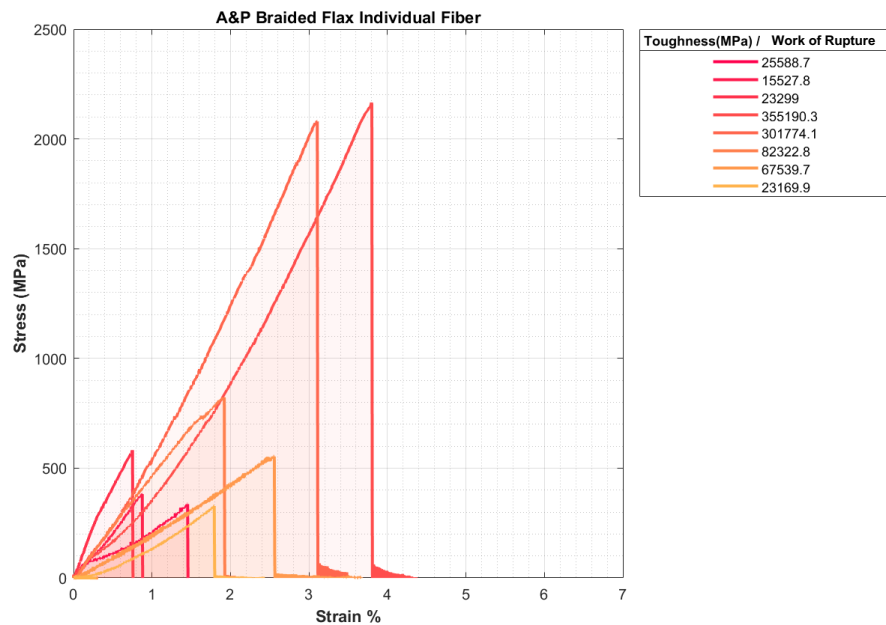


Figure 4.27 Tensile stress-strain plots of A&P Technology Braided Flax individual fibers. The work of rupture, the area under the stress-strain curve, of each measurement is also displayed in the legend.

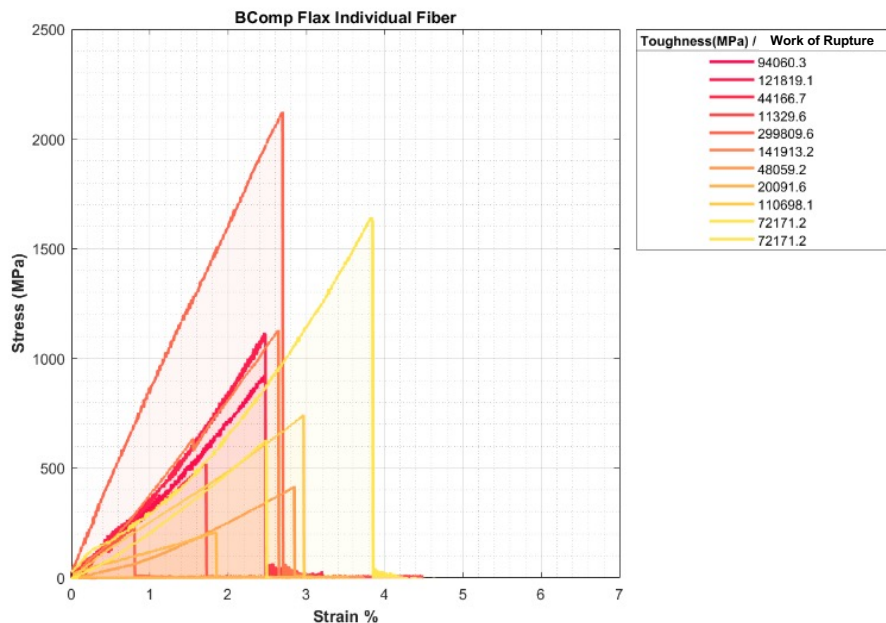


Figure 4.28 Tensile stress-strain plots of Bcomp Flax individual fibers. The work of rupture, the area under the stress-strain curve, of each measurement is also displayed in the legend.

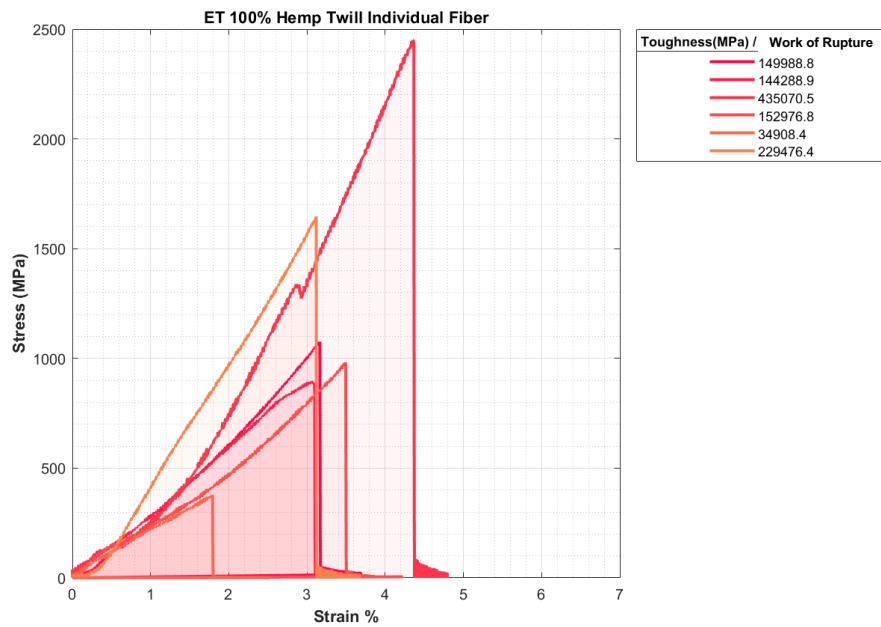


Figure 4.29 Tensile stress-strain plots of ET 100% Hemp Twill individual fibers. The work of rupture, the area under the stress-strain curve, of each measurement is also displayed in the legend.

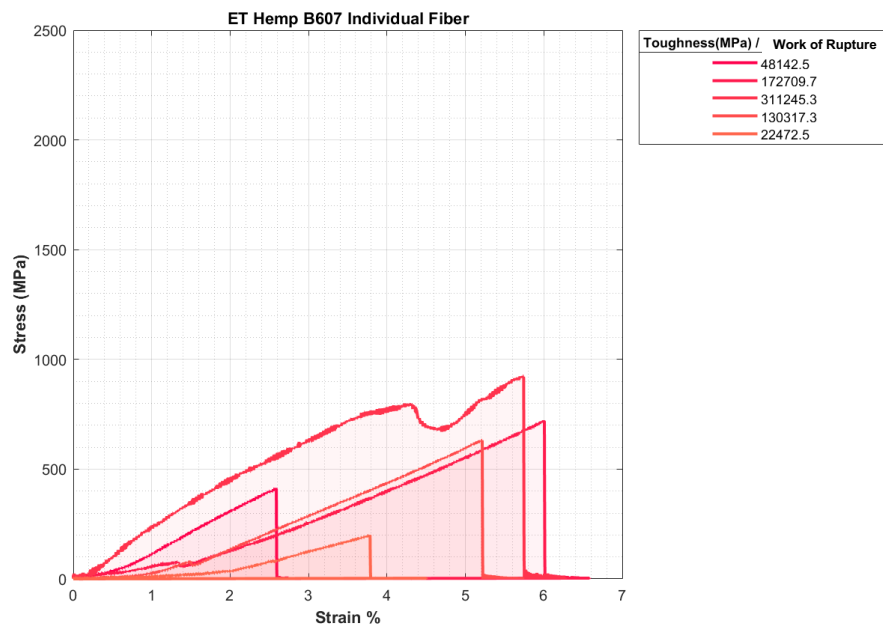


Figure 4.30 Tensile stress-strain plots of ET Hemp B607 individual fibers. The work of rupture, the area under the stress-strain curve, of each measurement is also displayed in the legend.

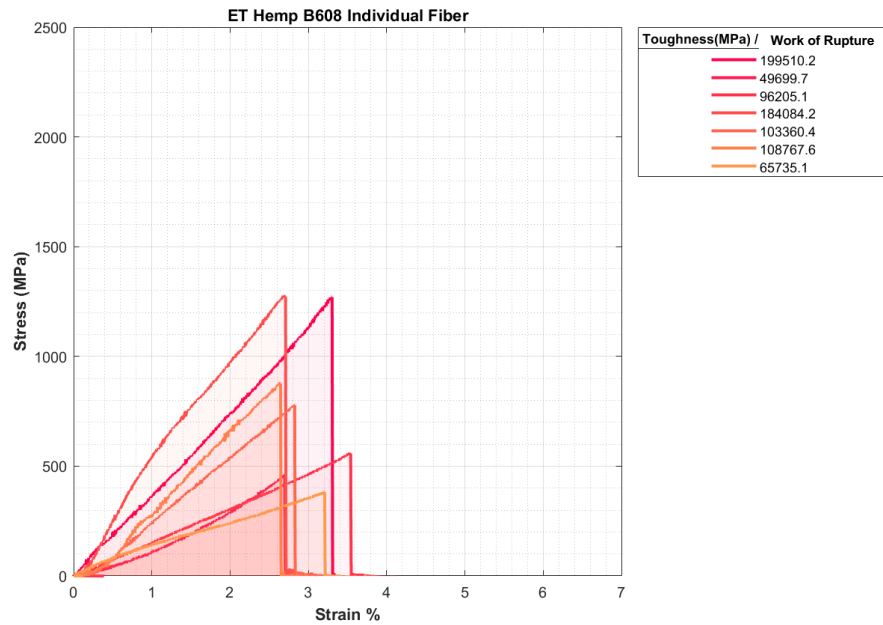


Figure 4.31 Tensile stress-strain plots of ET Hemp B608 individual fibers. The work of rupture, the area under the stress-strain curve, of each measurement is also displayed in the legend.

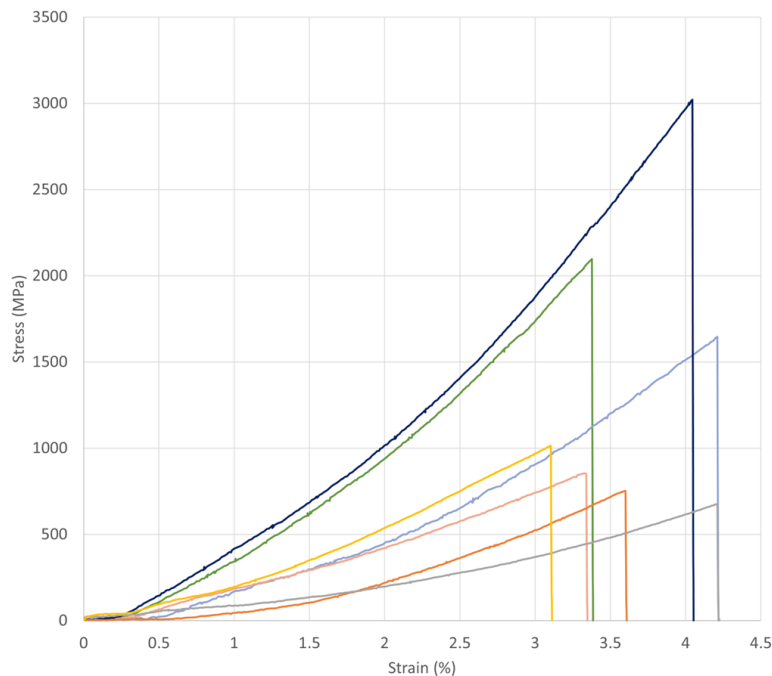


Figure 4.32 Tensile stress-strain plots of individual flax fibers isolated from Concordia flax-PA11 commingled fibers.

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4.2.4 Summary and Future Work

Natural fibers, including flax and hemp, offer a compelling combination of lightweight, multifunctional, and sustainable properties, making them promising candidates for SUMAC composite applications. Compared to conventional carbon fiber composites, natural fibers provide significant weight savings, intrinsic vibration damping, acoustic attenuation, and radio-frequency transparency. These attributes are particularly valuable for AAM and urban aviation platforms. In this investigation, mechanical characterization of natural fibers confirms that flax and hemp fibers achieve performance within expected ranges, with A&P Technology Braided Flax exhibiting the highest strength and stiffness among flax fibers, and ET 100% Hemp Twill showing the best performance among hemp fibers. Commingled flax-PA11 fibers further demonstrate the ability to combine high stiffness with ductility, offering design flexibility for tailored composite solutions. Yarn-level screening using linear density-normalized strength enables efficient down-selection of fiber candidates, while multi-scale characterization from fibers to yarns and bundles ensures reliable performance evaluation. These findings provide a foundation for designing SUMAC composites that balance mechanical performance, multifunctionality, and sustainability. In addition, the obtained mechanical properties of natural fibers can be used as input parameters for the SUMAC computational team to improve their computational models for composite design optimization.

Future work will focus on comprehensive fiber down-selection through mechanical, thermal, and long-term durability testing under representative AAM operational conditions. Prototype composite panels, such as bulkhead panels, will be fabricated to assess processability, fiber-matrix interactions, and structural and damping performance. Multi-scale modeling will integrate experimental data to support design optimization, and commingled fiber systems will be further refined to achieve the optimal balance of stiffness and ductility. Expansion of domestic hemp processing infrastructure is anticipated to strengthen the U.S. hemp fiber supply chain and manufacturing capabilities, positioning the United States as a leader in the natural fiber composite market. Finally, multifunctional performance—including vibration damping, acoustic attenuation, and interference-free communication—will be evaluated to ensure that SUMAC composites meet the operational requirements of next-generation AAM vehicles.

4.2.5 References

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4.3 Sustainable Manufacturing

4.3.1 Introduction

An abundance of naturally derived constituent materials are available to composite engineers, with material selection driven by the structural requirements of an intended application. Flax fiber is among the more mature options for plant-based reinforcement materials, having been well characterized in the literature, and is currently used as a composite reinforcement for automotive, marine, and sporting good applications. As a composite reinforcement, flax demonstrates mechanical properties competitive with E-glass [1]. In addition, the flax morphology provides inherent vibration damping and resistance to damage from fatigue [2]. These properties are particularly attractive for advanced air mobility vehicles where vibrational loads are experienced throughout the aircraft.

An alternative to flax fiber is hemp, which has also been well characterized in the literature and has a long history in composite materials. In 1941, hemp fibers were used in resin matrix composites to create the body of a Henry Ford automobile, capable of withstanding impacts 10 times stronger than comparable metal panels. Hemp is also currently used in composite applications within the automotive, marine, and sporting goods industries. Three bio-based resins were selected for evaluation within the SUMAC project including polylactic acid (PLA), polyhydroxybutyrate (PHB), and polyamide-11 (PA11). While considerable work has been individually reported for these candidate resins and fibers, the publicly available literature is lacking in basic material and mechanical properties of interest to the SUMAC project, where the intended application is composite structures for aviation. The purpose of the manufacturing and mechanical test task was to gain experience in the processability of natural fiber and bio-based thermoplastic composites and test the strength of the resulting materials.

4.3.2 Experimental

4.3.2.1 Fiber Architecture

Flax Braid: The flax fiber selected for this effort was sourced from Terre de Lin in Saint-Pierre-le-Viger, France. The flax was then braided by A&P Technologies in Summerside, OH to yield a preform with a quasi-isotropic [0/+60/-60] architecture and an areal weight of 405 g/m² (gsm). The flax tows were bound with cellulose fibers for handling. Flax was selected for this study in part due to its availability in a variety of forms including uni-directional fibers, weaves, and braids. The braided form of a fiber reinforcement has been demonstrated in the aerospace industry on structures including wing flaps for Bombardier, jet engine stator vanes, and the fan case of GE's GenX engines [3]. The braiding process offers numerous options for fiber angle and braid architecture, ultimately offering improved impact and fatigue properties relative to uni-directional or woven material forms. Unfortunately, unidirectional fiber variants were not delivered prior to project closeout.

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Commingled Flax/PA11 Braid: A commingled variant of the braided flax was evaluated where PA11 filaments were co-mingled with flax fiber, then braided to the same [0/+60/-60] preform, with an areal weight of 512 gsm, due to the resin filaments, and a 55% fiber volume fraction. This material allowed an assessment of the manufacturability of a prepreg as compared to film infusion.

2x2 Twill Flax Weave: Woven flax was procured from RBT Biocomposites in Alberta, Canada, which is a distributor of Bcomp materials from Fribourg, Switzerland. The specific weave selected was Bcomp ampliTex 5040, a 0°/90° 2x2 twill with an areal weight of 300 gsm, which is a common architecture used in composites for aerospace and marine applications. The weave pattern also simplifies computational material models.

Hemp Weave: A 100% hemp plain weave was procured from EnviroTextiles in Glenwood Springs, CO. Based on the results of individual fiber and bundle testing, the B607 medium weight Summer Cloth was chosen for panel manufacturing due to having superior tensile strength. As received, the fabric was pre-shrunk and pre-bleached and contained a starch-based sizing agent to aid in weaving.

The combinations of fiber, fiber architecture, and resin evaluated are described in Table 4.10. In general, the fiber to resin weight ratio was 50%, unless otherwise stated. The fiber volume fraction of the commingled material was 55%.

Table 4.10 Natural fiber and bio-based resin combinations evaluated by manufacturing trials and mechanical testing.

Fiber/Architecture	Resin
Braided Flax	PLA
	PHB
	PA-11
Co-Mingled Braided Flax	PA-11
2x2 Twill	PLA
	PHB
	PA-11
Hemp	PLA
	PHB
	PA-11

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4.3.2.2 Process Development and Panel Processing

Processing cycles were based on material property data generated in the fiber and resin task then adjusted based on fiber wet-out, void content, and in the case of PLA, microcracking.

The general process flow for panel fabrication is depicted in Figure 4.33 and proceeded as follows: manufacture thermoplastic film, dry fiber, alternately stack resin and fiber (targeting 50% by weight), place in picture frame tooling, and hold in press at low temperature and low pressure. When the composite temperature reached the target processing temperature, the pressure was increased and held to allow resin interdiffusion across the ply interface. The laminate was then cooled under pressure. Details of this process for each material are provided in the next sections. Panels for process development ranged from 6" x 6" to 12" x 12". Later, panels used for mechanical testing were manufactured as 12" x 12" panels.

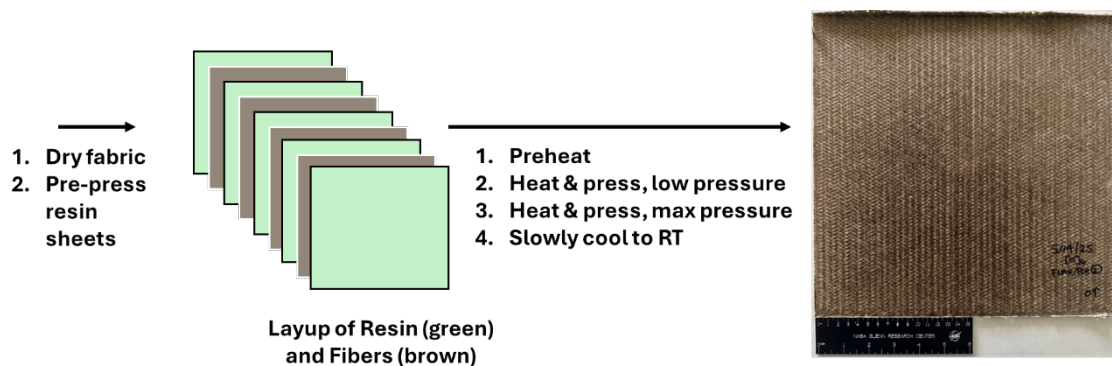


Figure 4.33 General fabrication process for natural fiber/thermoplastic composite panels.

4.3.2.2.1 Film processing (PLA, PHB, and PA11)

Resin thermal and rheological data presented in the resin section was used to inform resin film and composite process development. Additional details are presented in this section.

The IMF 101 HT 5D5 grade of PLA resin contains higher melting polymer chains that are designed to increase material performance. While the composite manufacturing process requires melting of only the lower melting point constituent, producing sufficiently thin films required melting the granules past the higher melting peak centered at 223°C, shown in Figure 4.34. Therefore, PLA films were prepared by placing ~60g of PLA resin pellets

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between two sheets of Teflon and placing directly onto the platens of the press. When processing PLA, Teflon is used instead of Frekote-coated Kapton due to a possible side reaction that might occur with the PLA resin. The pellets were pressed at 232°C for 30 sec at 275 psi and quenched by immediately removing from the press to create amorphous films that could easily be handled. After quenching, 12"x12" squares were cut for processing.

PHB films were produced by placing ~60g of PHB granules between Loctite Frekote coated Kapton at 410°F (210°C) and pressing at 210 psi for 2 min. The films were immediately removed from the press and allowed to cool to room temperature before being cut into 12"x12" squares.

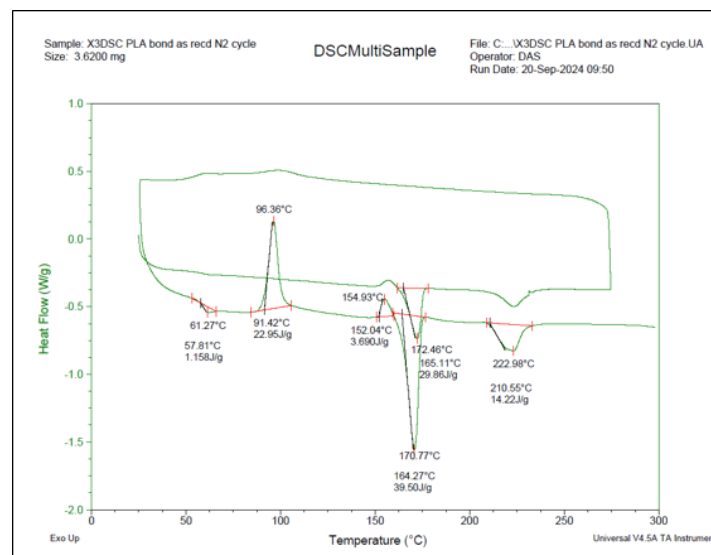


Figure 4.34 DSC curve of Pond IMF 101 HT 5D5 PLA

4.3.2.2.2 Fiber Drying

The time and temperature required to dry flax fiber was selected based on thermogravimetric analysis (TGA) data, Figure 4.35. TGA data was collected for a braided flax fiber sample held at 121°C (250°F) in air for 120 minutes. Data shows an initial weight loss due to water at 121°C with weight loss, leveling off by 60 minutes at this temperature. A drying time of 120 minutes was selected in practice to ensure moisture removal. The drying process proceeded by precutting the fiber to dimensions required for panel processing. Those plies were stacked and placed in an air circulating oven and dried at 121°C for 2 hours.

A temperature sweep TGA experiment was also run from 45°C to 395°C on a braided flax fiber sample, in addition to the other fiber weaves used for this study (Figure 4.36). The

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goal of this experiment was to identify any significant weight changes that may be attributed to decomposition around processing temperatures. The TGA curves for all the fibers were similar, with significant thermal degradation occurring well beyond 210°C, which is the highest processing temperature of the composites. The similar thermal behavior of the fibers also confirmed that the same pre-drying procedure could be used for all the variations.

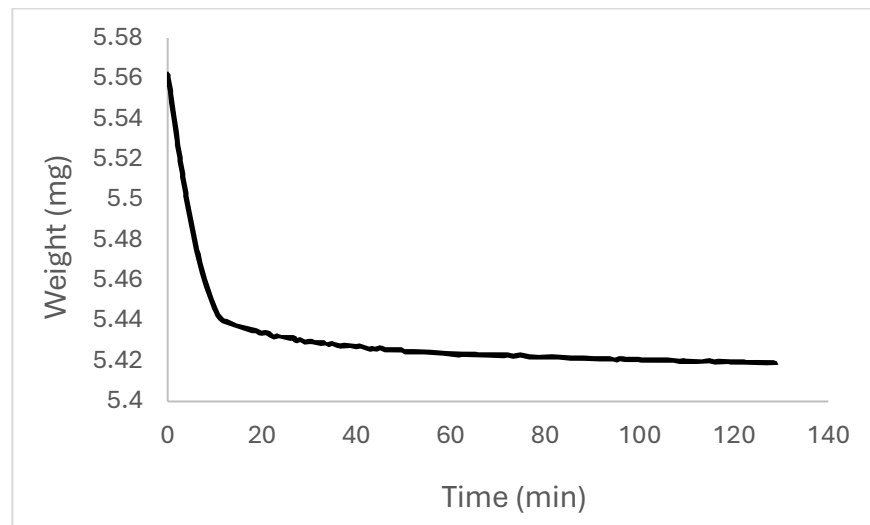


Figure 4.35 Isothermal TGA test data showing weight loss as a function of time.

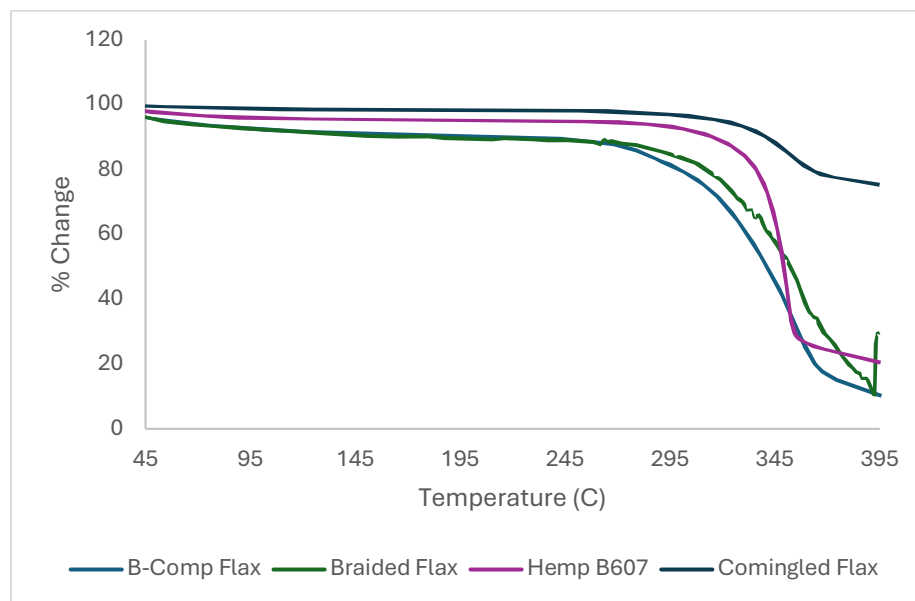


Figure 4.36 TGA temperature sweep data of natural fiber fabrics.

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4.3.2.2.3 Effects of Time, Temp, and Pressure (PA11, PLA, PHB):

Flax/PA11: Composites were compression molded by alternate stacking of six plies of braided flax and PA11 film where the target resin content was 50% by weight and a 0.32 cm (1/8 inch) laminate thickness. Due to the low density of the fiber, this equates to 43% fiber volume, which is quite low relative to traditional carbon fiber or glass composites. This higher resin content was initially used to evaluate wet-out and manufacturability, later work following process development focused on reducing the resin content of the laminate.

The initial pressure and temperature profile followed for process development of flax/PA11 included a short duration (5 minute) hold at 210°C, and 70-psi pressure, in an effort to mitigate resin flow out of the tool. This led to poor resin infiltration throughout the braided fiber and high void content, as shown in Figure 4.37.

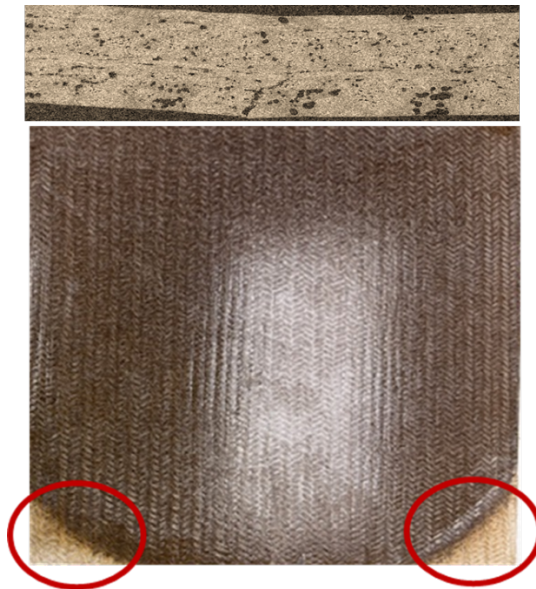


Figure 4.37 Considerable void content was observed following preliminary consolidation trials for flax/PA11, as well as poor fiber wet-out across the panel.

Ultimately an optimized processing cycle shown in Figure 4.38, with increased hold time and pressure, was adopted. This process was used for all flax/PA11 composites, including braided flax, commingled, and Bcomp. This process reduced void content and improved resin flow across the panel. It should be noted that panels manufactured with the Bcomp 2x2 twill used 8 plies, as opposed to 6 plies used for braided parts due to a greater ply thickness of the braided material.

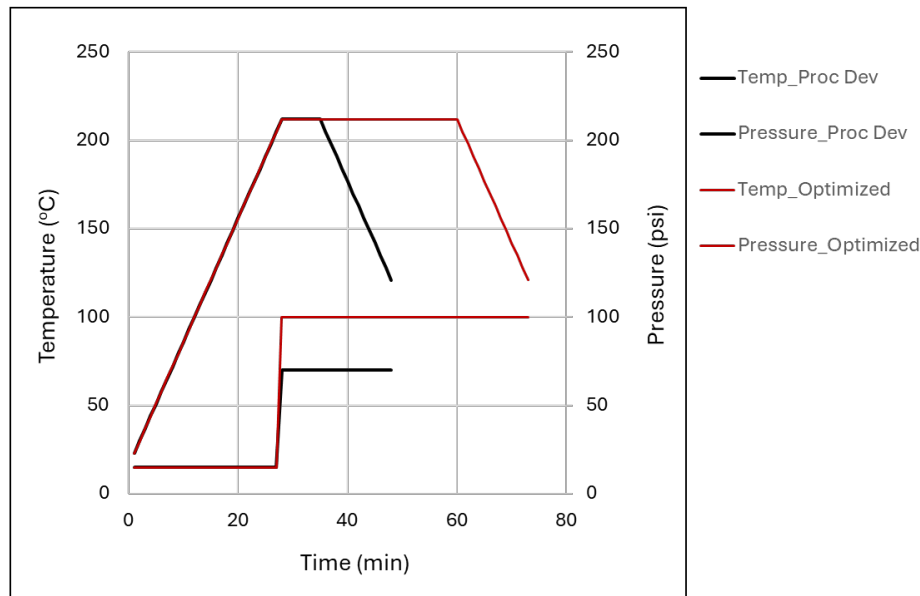


Figure 4.38 Temperature and pressure profile for compression molding flax/PA11 panels.

Optical microscopy is a valuable tool for characterizing the consolidation and void content of the natural fiber/thermoplastic composites. Additional features were observed such as the fiber weave pattern, resin pooling, fiber-resin interfacial characteristics and variation in fiber type. Figure 4.39 and Figure 4.40 call out examples of such features for the braided flax/PA11 laminates manufactured following the optimized processing profile. The nature of the braided architecture results in more resin pooling relative to a woven fiber form. The cross-section of a braided flax/PA11 coupon illustrates representative resin pooling between fiber tows, with voids evident within these resin rich regions. In addition, cellulose fibers, used to bind flax bundles, are visible and defects attributed to poor fiber-resin interfacial adhesion is noted.

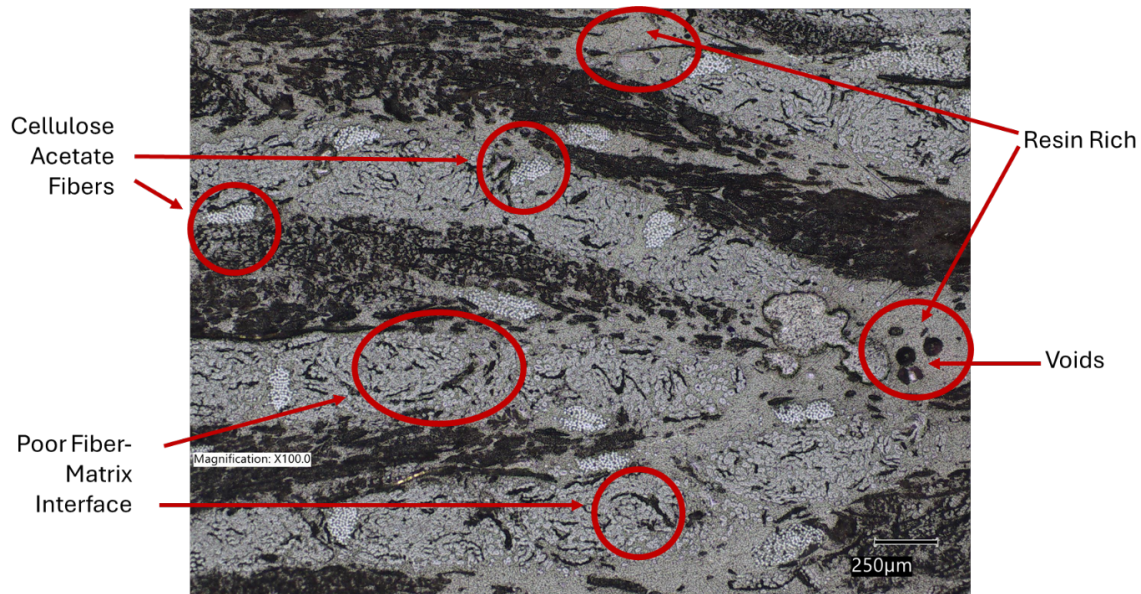


Figure 4.39 Photomicrograph of Braided Flax/PA11 cross-section illustrating fiber details and common defects.

SEM was also utilized in conjunction with optical microscopy to better visualize the fiber-matrix interface. The flax fiber used in these studies was not modified and the poor fiber-matrix interfacial adhesion can be seen in the SEM image, as illustrated in Figure 4.40. In addition, the lumen, or hollow core, of the flax fiber is clearly seen by SEM.

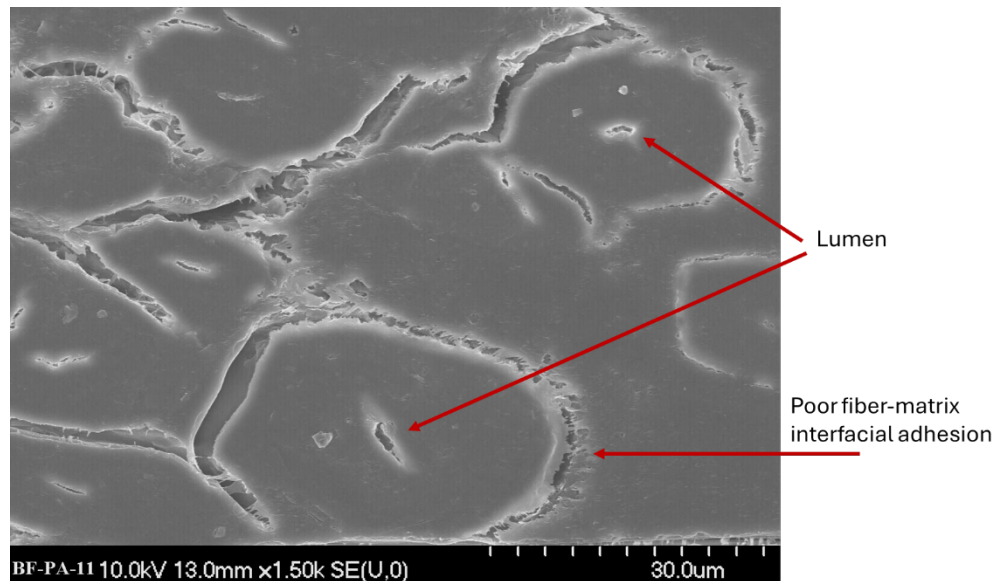


Figure 4.40 SEM image from a braided flax/PA11 coupon indicating low interfacial adhesion.

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Braided Flax/PLA: Due to the hydrophilicity of the flax fibers, the potential degradation of the PLA matrix due to a hydrolysis reaction at elevated temperatures must be considered in process development [4]. An initial study was done to identify an optimal processing time of the composite that avoids significant matrix degradation due to hydrolytic degradation.

Panels were made by stacking four 4" x 4" pre-dried flax sheets with alternating PLA sheets to achieve a target resin content of 50%. As discussed previously, Teflon sheets were used as release liners. All samples were preheated and held at 182°C for 15 min before applying a pressure of 100 psi for a dwell time of 10, 20, 40, 60, 80, or 100 min. The panel was then slowly cooled under pressure to room temperature before being removed from the mold.

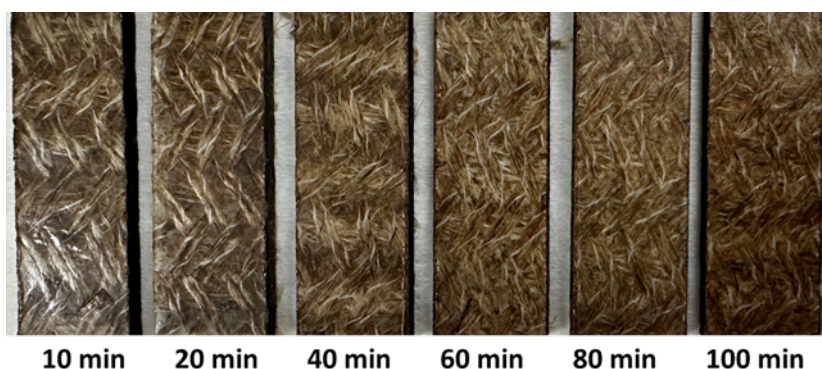


Figure 4.41 Braided flax/PLA coupon samples from panels manufactured at 10, 20, 40, 60, 80, and 100-min dwell times.

Visible discoloration of the composites was observed in the samples held at dwell times longer than 40 min (Figure 4.41). Fourier-Transform Infrared (FTIR) spectroscopy was used to evaluate the extent of potential degradation by characterizing functional groups present in a material by detecting signature molecular motion at certain frequencies, shown in Figure 4.42. A broad peak around 3300 cm^{-1} and a slight peak centered around 3480 cm^{-1} corresponds to the OH stretching of lactic acid, which is a degradation product of PLA due to hydrolytic scission. Because the FTIR spectrum of the neat flax fiber also contained a broad peak centered around 3300 cm^{-1} , the smaller peak centered around 3480 cm^{-1} was used to track the evolution of lactic acid. In the 10 min dwell time samples, no visible peak was detected. As dwell time increased, so did the intensity of the peak. This is consistent with an increase in hydrolytic degradation of the PLA matrix as dwell time at elevated temperatures increases.

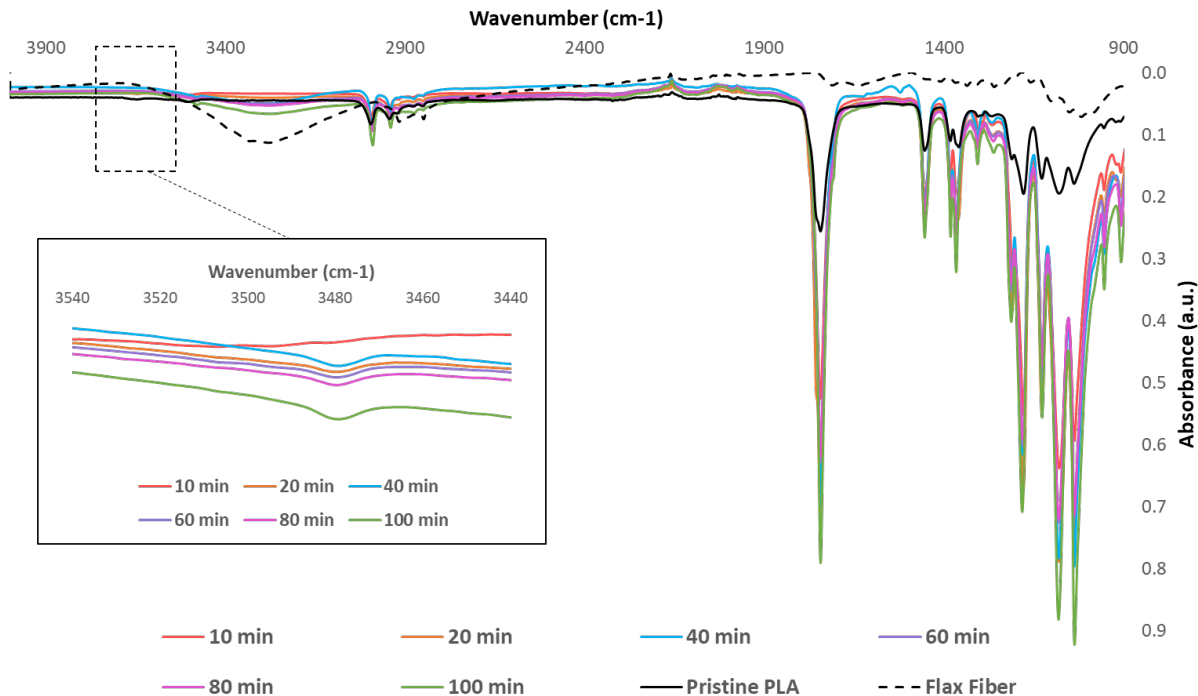


Figure 4.42 FTIR spectra of braided flax/PLA composite samples, pristine PLA and flax fiber. A slight peak centered around 3480 cm^{-1} was observed in the 10 min sample, and increased in intensity with increasing dwell time, which is consistent with progression of hydrolysis.

Dynamic Mechanical Analysis (DMA) in 3-point bend mode was also used to evaluate the effects of degradation due to hydrolysis. DMA evaluates the viscoelasticity of a material and can be used to detect changes in stiffness or thermal behavior. The same trend in the FTIR data was further supported by the DMA data (Figure 4.43), which showed a decrease in the melting point (T_m) and a shift in the glass transition temperature (T_g) of the PLA matrix as dwell time increased. The most significant shift was observed in samples held for 40 min or longer. From this data, 20 min was chosen as the optimal dwell time, as it produced sufficiently consolidated panels with minimal negative effects from hydrolytic degradation.

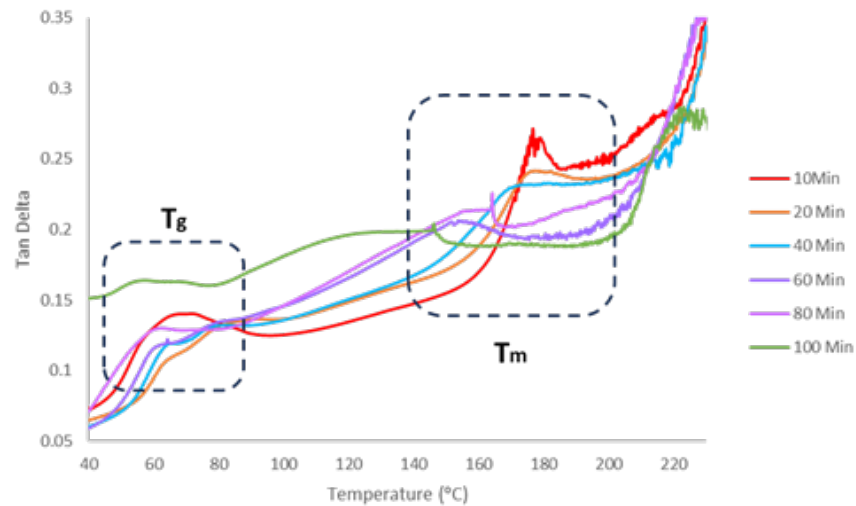


Figure 4.43 DMA Tan Delta vs. temperature data for the braided flax/PLA composite samples, showing a shift in both the glass transition temperature (T_g) and melting temperature (T_m) of the resins that were held at dwell times 40 min and longer.

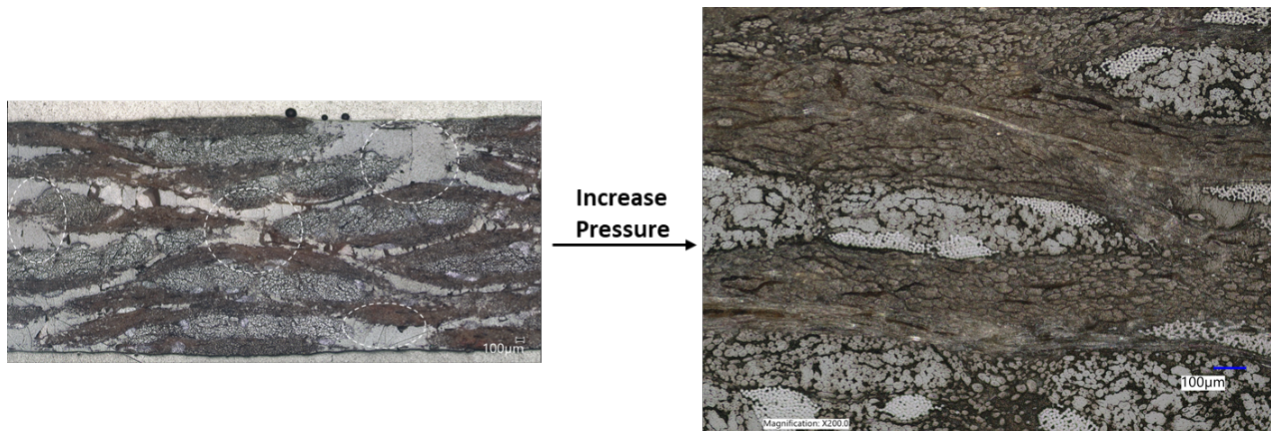


Figure 4.44 Microscopy images of braided flax/PLA composite. Significant cracking was observed in the composite cross sections before process optimization (left). Increased pressure and layup modification significantly reduced the presence of cracks (right).

The PLA resin exhibited significant cracking in PLA-rich regions where the resin was allowed to pool, as observed both visually on the surface and internally through photomicroscopy. To mitigate this, the layup pattern was adjusted so that PLA sheets were stacked only inside of the flax fibers, and not on the top and bottom like in other panel manufacturing iterations. The pressure was also increased to 140 psi to aid in resin infusion. This successfully eliminated the cracking that had been previously observed in the panels, shown in Figure 4.44. When taking all these process parameters into consideration, the optimized processing profile of the braided flax/PLA composites is shown in Figure 4.45.

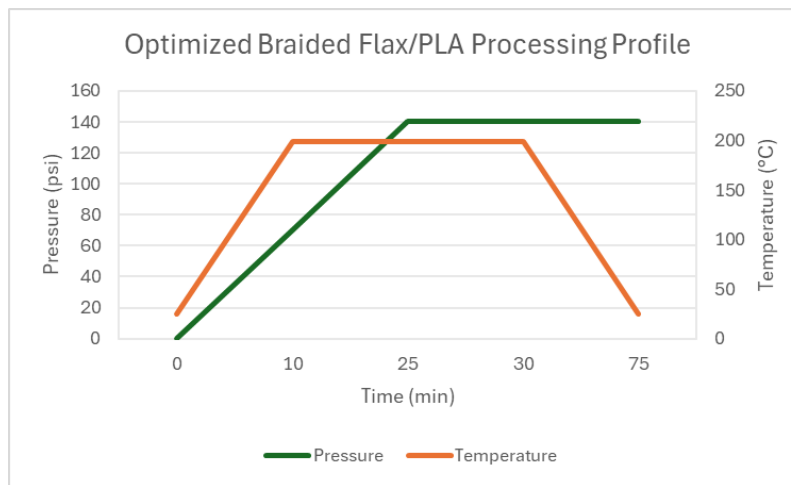


Figure 4.45 Optimized processing profile for braided flax/PLA composites

Braided Flax/PHB: A similar processing profile to the optimized PLA method was used to manufacture the braided flax/PHB panels, with a few notable exceptions. A standard layup was used, including PHB sheets on the top and bottom of the flax. The processing temperature was held at 180°C because the processing window of PHB is relatively narrow, with the degradation temperature close to its melt temperature [5]. Finally, the pressure of manufacturing was increased to 250 psi to promote full wetting of the fibers at the lower processing temperature. The optimized processing profile is shown in Figure 4.46.

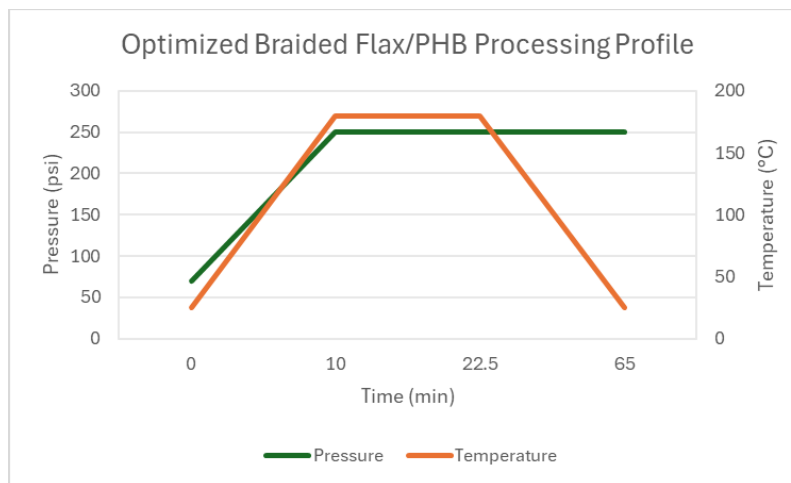


Figure 4.46 Optimized processing profile for braided flax/PHB composites.

Photomicroscopy images of the composite cross sections, in Figure 4.47, confirmed that the panels produced using this optimized process were well consolidated with good resin wetting of the fibers.

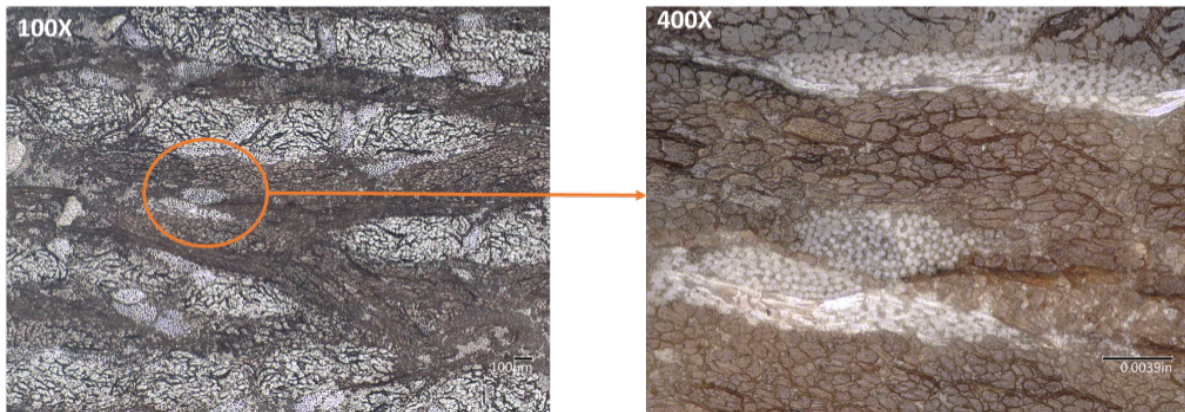


Figure 4.47 Microscopy images of the cross section of braided flax/PHB composites at 100X (left) and 400X (right).

2x2 Twill Flax/PLA: The tighter woven architecture of the Bcomp 2x2 Twill Flax required modifications to the process developed for the braided flax/PLA composites. The twill panels also benefitted from the modified layup pattern, shown in Figure 4.48, although significant cracking was still observed in the cross section of the composite, shown in Figure 4.49.

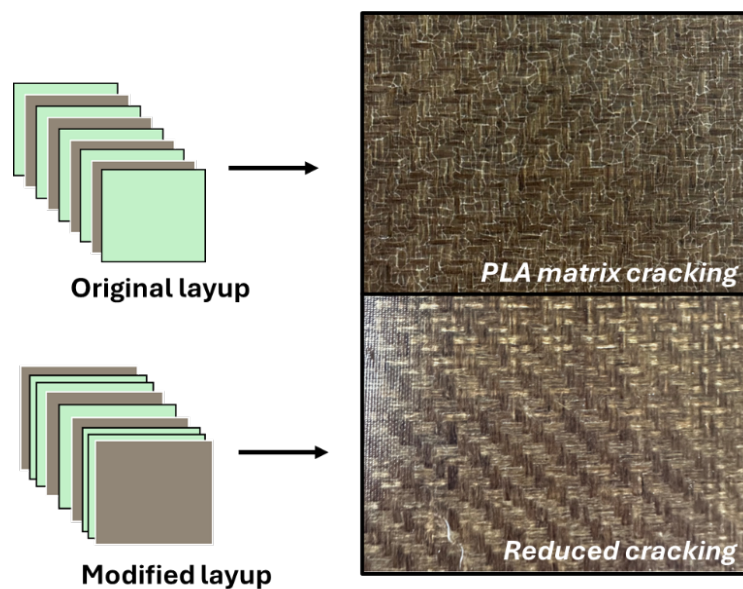


Figure 4.48 Matrix cracking on the surface of the twill/flax composite due to original layup (top) and the elimination of cracking due to a modified layup (bottom).

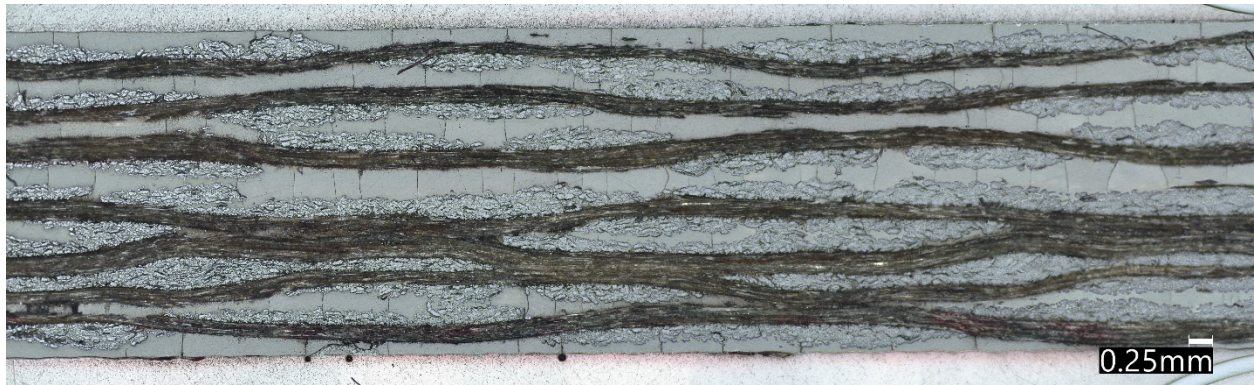


Figure 4.49 Cross section microscope image of significant internal cracking in twill flax/PLA composites that occurred prior to process optimization.

It was hypothesized that increased pressure was needed to completely infuse the twill fibers with the PLA resin. A 20-min hold at an intermediate pressure step of 104 psi was introduced in addition to a 10 min hold at a maximum pressure of 208 psi, which successfully produced well consolidated panels. The optimized processing profile is shown in Figure 4.50.

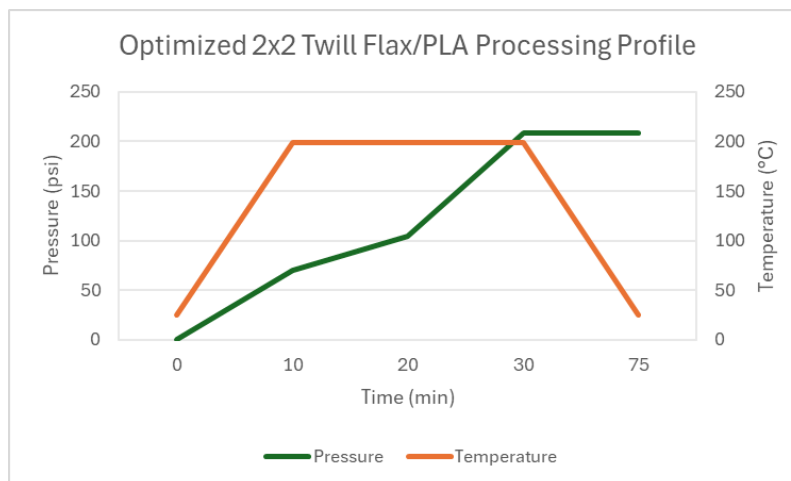


Figure 4.50 Optimized processing profile for twill flax/PLA composites.

2x2 Twill Flax/PHB: Based on the results of the 2x2 twill/PLA manufacturing optimization, an intermediate pressure step was also introduced when processing 2x2 twill/PHB panels. This process resulted in a well consolidated, consistent composite cross section, shown in Figure 4.51. The optimized processing profile is shown in Figure 4.52.

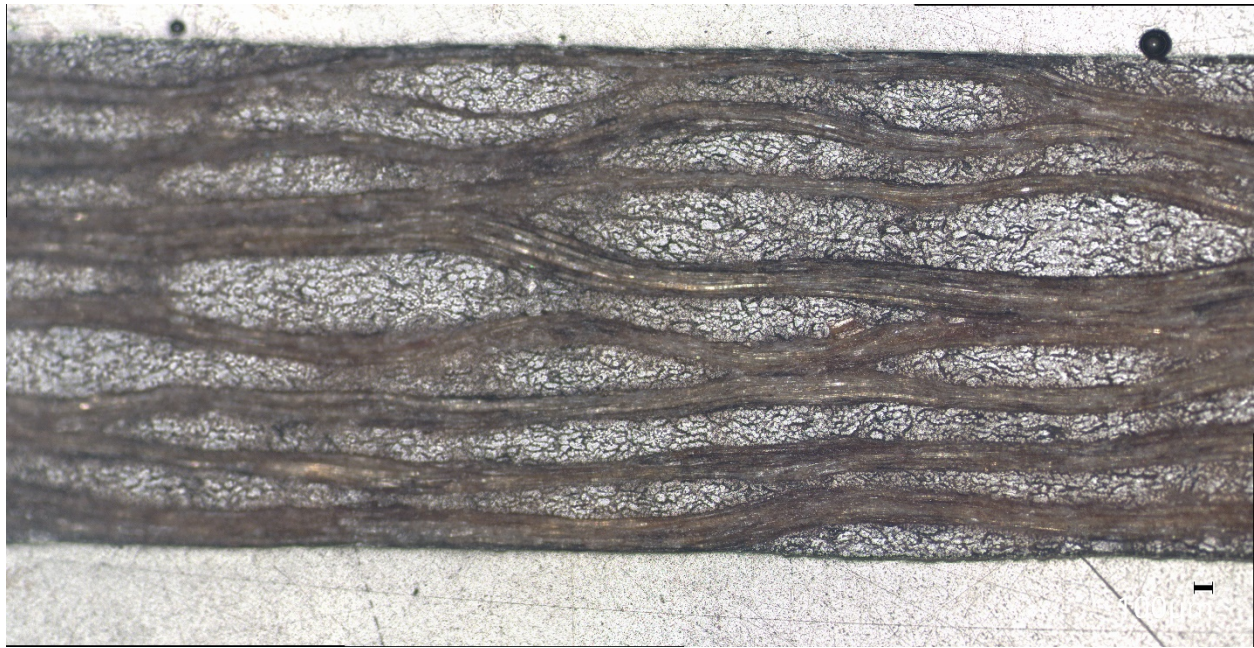


Figure 4.51 Cross section microscope image of twill flax/PHB composite showing well consolidated, fully wetted fibers.

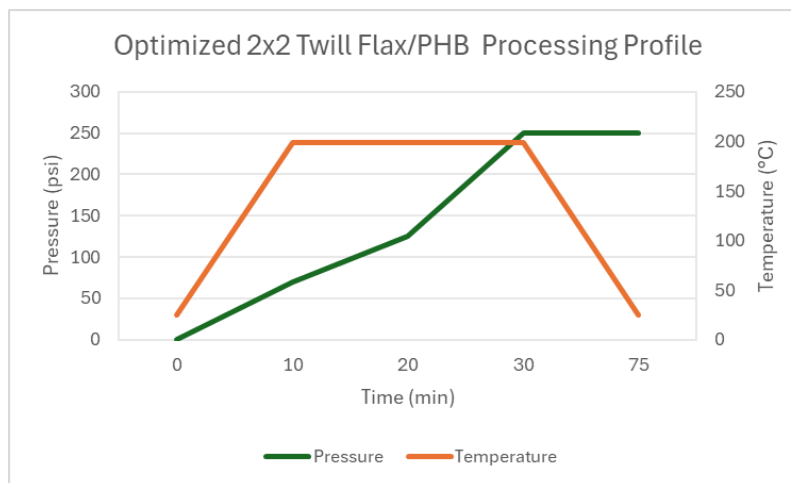


Figure 4.52 Optimized processing profile for twill flax/PHB composites.

Hemp B607/PLA and Hemp B607/PHB: An increase in pressure from the twill/PLA processing profile was required to completely wet the Hemp B607 fibers. Based on this processing adjustment, both the Hemp B607/PLA and Hemp B607/PHB had the same optimized processing profile. Cross-sectional images are shown in Figure 4.53, and the optimized processing profile is shown in Figure 4.54.



Figure 4.53 Optical microscope images at 100X of hemp/PLA cross section (top) and hemp/PHB (bottom) cross sections. Both iterations had some voids and regions of resin pooling, but generally were well consolidated.

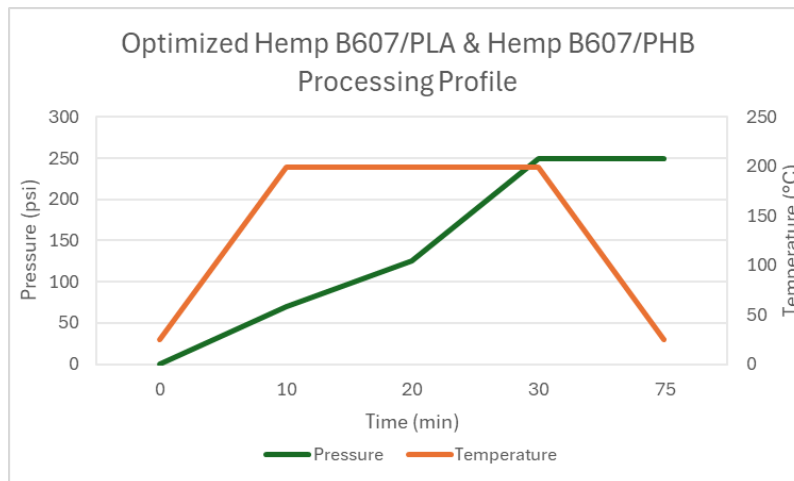


Figure 4.54 Optimized manufacturing processing profile for both hemp/PLA and hemp/PHB composites.

4.3.2.2.4 Material and Process Variations

Commingled Flax/PA11: The commingled material variant of flax braid was procured to evaluate the processability of a material form similar to a traditional prepreg, as compared to the film infusion process detailed in the previous sections. Commingling is a process that intimately blends the flax fibers with PA11 filaments to produce a hybrid yarn. This commingled yarn was then braided, resulting in a braided fiber/resin preform that could be stacked and consolidated. SEM images of the braided flax and commingled flax preforms

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are shown in Figure 4.55. A few differences can be seen between the two forms of the material. The flax ‘tows’ of the baseline braided material appear flat and spread compared to the more tightly bundled, yarn-like flax seen in the commingled material. The commingled preform also lacks the cellulose fibers required to secure flax tows, as seen in the baseline braid. Finally, the presence of the commingled PA11 filament leads to a smoother finish of the braided preform.

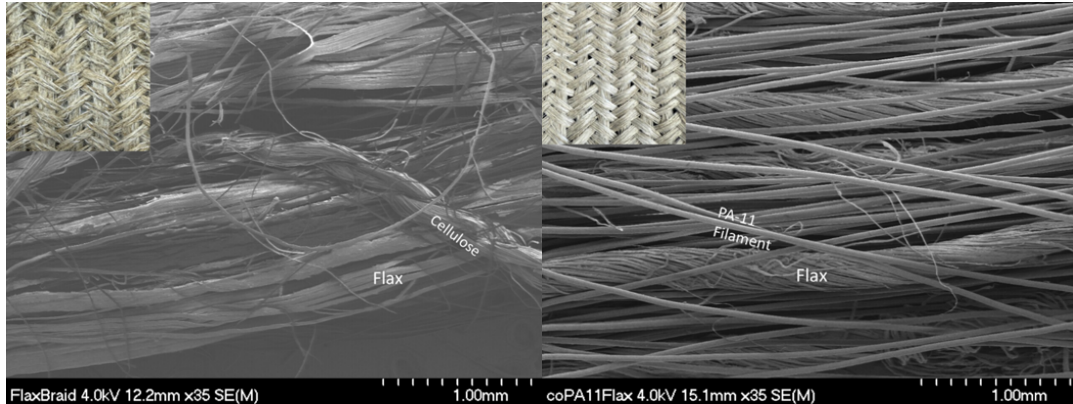


Figure 4.55 SEM images of braided flax (left) and co-mingled braided flax/PA11 (right)

Overall, the commingled preform simplified handling throughout the manufacturing process, but mechanical properties, void content, and composite appearance were comparable, regardless of the comingling or film infusion process.

Fiber volume fraction (V_f): The influence of fiber volume fraction on processability and mechanical strength was evaluated for Bcomp flax weave and PLA, PHB, and PA11 resins. For composites used in the aerospace industry, a 55% - 60% V_f is used to optimize strength and stiffness. Baseline panels for the SUMAC project used a 50% fiber content by weight for initial manufacturing trials. Based on the relative densities of the fiber and resin, this equates to a 43% V_f . The resin heavy ratio was selected for process development to tune process parameters. Once issues such as microcracking and resin degradation were worked through, the fiber volume was systematically varied.

Table 4.11 lists the fiber to resin weight ratios evaluated for PA11, and the corresponding fiber volume fractions. Similar calculations were made for the PHB and PLA composites.

Table 4.11 Fiber volume fraction of panels manufactured with increasing fiber content

Panel Label	Fiber wt%	Resin wt%	Fiber Volume %
Bcomp-PA11 50_50	0.5	0.5	43%
Bcomp-PA11-60_40	0.6	0.4	53%
Bcomp-PA11-65_35	0.65	0.35	59%
Bcomp-PA11-70_30	0.7	0.3	64%

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These calculations were based on the following material densities:

$$\rho_{\text{Flax}} = 1.35 \text{ g/cm}^3$$

$$\rho_{\text{PA11}} = 1.03 \text{ g/cm}^3$$

The laminate quality was inspected by optical microscopy. Figure 4.56 shows the 200X magnification of the baseline, 43 % Vf flax/PA11 panel. There are very few voids present in the figure indicating the composite was well consolidated. The panel thickness measured 2.95 mm and the photomicrograph shows the resin well infiltrated throughout the fibers.

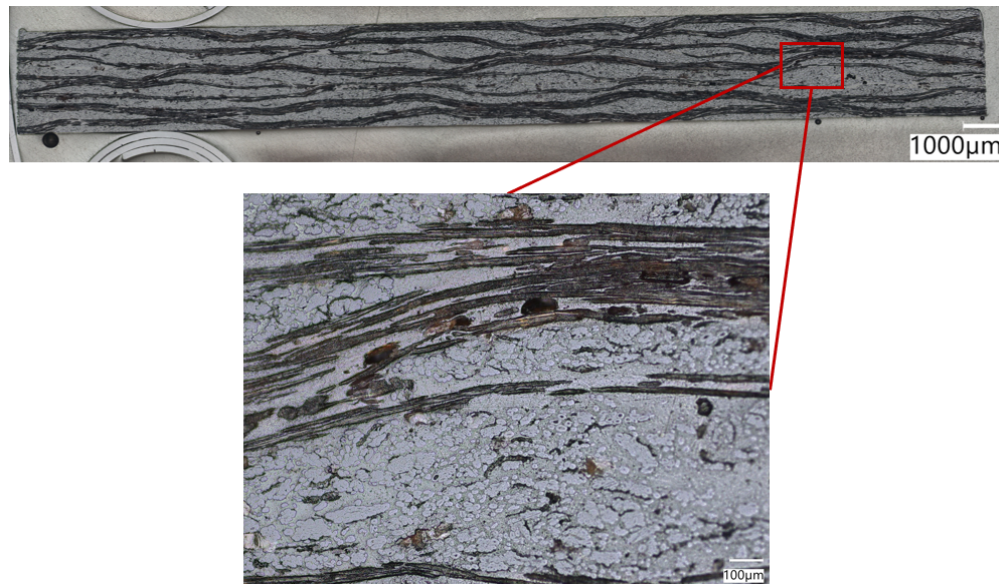


Figure 4.56 Microscopy Image at 200X for the 43% Fiber Volume Fraction Panel.

Figure 4.57 shows the 200X magnification of a 53 % fiber volume fraction. Unlike the 43% Vf panel, voids are apparent in the 53% panel. These voids specifically lay along the center of the composite thickness suggesting entrapped air between. The image showed fiber wet-out, despite the lower resin content. The thickness of the 53% Vf panel was 2.78 mm and may be higher than expected due to the presence of voids.

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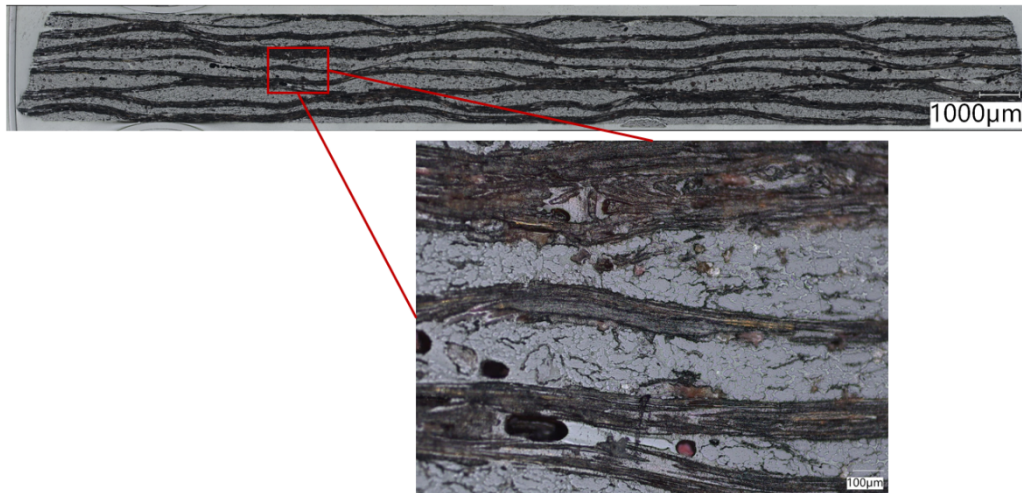


Figure 4.57 Microscopy Image at 200X for the 53% Fiber Volume Fraction.

Figure 4.58 shows the 200X magnification of the 59 % Vf panel and shows the highest void content of all panels evaluated. These voids were also concentrated near the mid-line of the composites but were also evident throughout the thickness. This could be due to a change in the weight of the caul plates used for this panel. The higher void content of this panel also affected the thickness, which was measured at 2.91 mm. This thickness was greater than the 53% fiber volume fraction which has more resin and is the opposite of what was expected. While there are voids, the microscopy image also showed that the fibers are fully wetted.

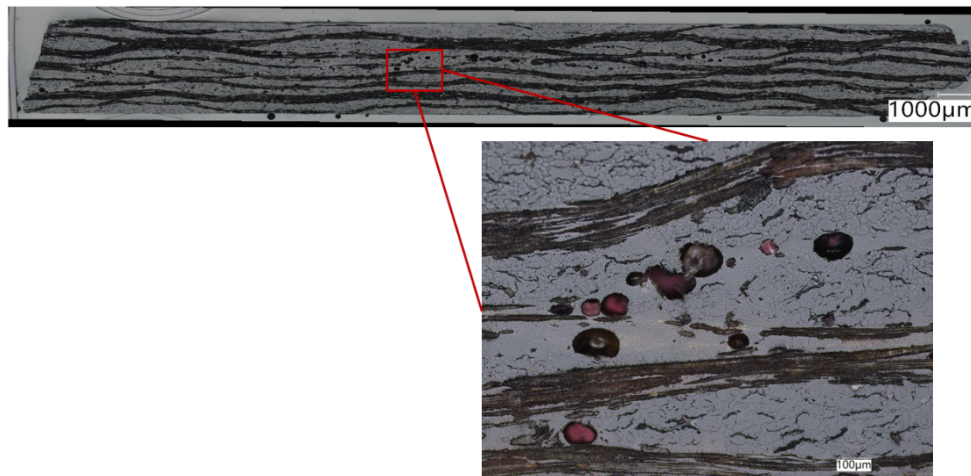


Figure 4.58 Microscopy Image at 200X for the 59% Fiber Volume Fraction.

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Figure 4.59 shows the 200X magnification of the 64% Vf panel. There are very few voids present in the figure indicating the composite was well consolidated. The panel thickness of 2.63 mm is reasonable due to the low resin content. Again, despite the low resin content the image also showed resin infiltration throughout the fibers.

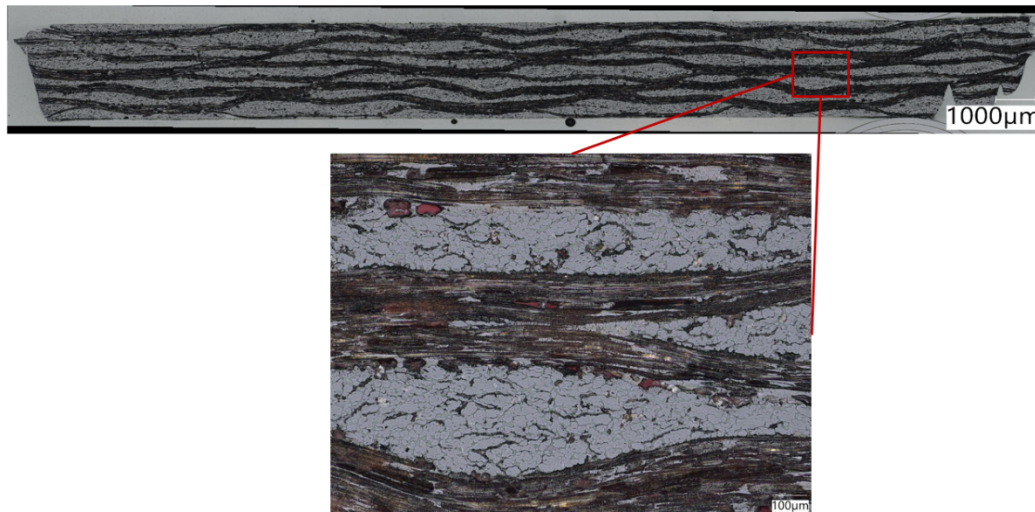


Figure 4.59 Microscopy Image at 200X for the 64% Fiber Volume Fraction

The same study was also performed with PA11 and the Hemp B607 to evaluate potential variations between flax and hemp-based fabrics. The calculated values used for the hemp fibers are shown in Table 4.12.

Table 4.12 Fiber volume fraction of panels manufactured with increasing fiber content.

Panel Label	Fiber wt%	Resin wt%	Fiber Volume %
B607-PA11 50_50	50	50	43%
B607-PA11-60_40	60	40	53%
B607-PA11-65_35	65	35	59%
B607-PA11-70_30	70	30	64%

These calculations were based on the following material densities, with the density of hemp fibers coming from Suardana et al. [6]:

$$\rho_{\text{Hemp}} = 1.25 \text{ g/cm}^3$$

$$\rho_{\text{PA11}} = 1.03 \text{ g/cm}^3$$

Optical microscopy was once again used to evaluate the composite consolidation quality. Similar to the trend observed in the flax/PA11 composites, as the fiber volume increased, the quality of the hemp/PA11 composite decreased. Figure 4.60 shows the side-by-side comparisons of the composite cross sections at 200X. Minimal voids were observed in the 43% Vf sample, indicating a well consolidated panel. As the Vf increased, so, too, did the

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occurrence of voids and inconsistent distribution of resin. This indicates a poorer composite quality in comparison to the 43% Vf sample and suggests that higher Vf does not correspond to a higher quality panel.

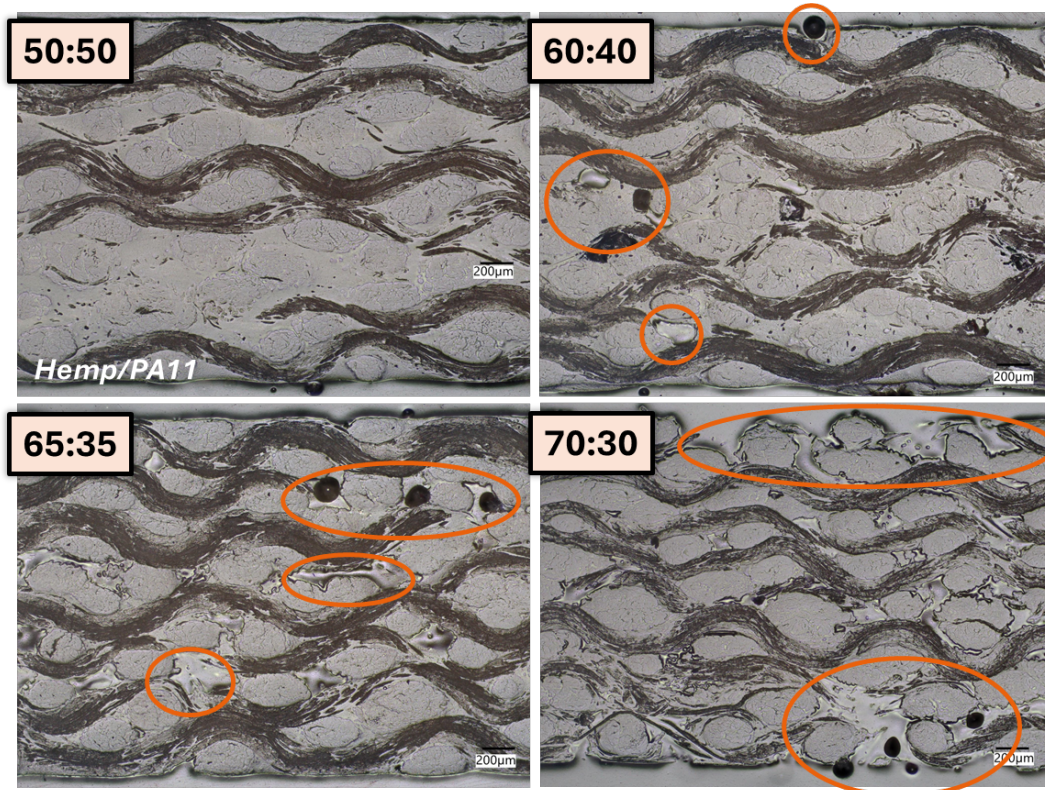


Figure 4.60 Cross section microscope images of hemp/PA11 composite samples at 200X of representative fiber volume fraction values.

4.3.3 Post Processing

Machining: Due to the hydrophilicity of the natural fibers, conventional composite manufacturing techniques such as water jet cutting or water-cooled diamond saw cutting resulted in fraying and damage of the samples edges. A CO₂ laser cutter was used to fabricate samples instead, which resulted in samples with precise dimensions. Figure 4.61 shows the difference between wet diamond saw fabrication (left) and laser fabrication (right). Optimized laser cut settings were ran at 100% power and 5% speed, which resulted in minimum charring of the edges. In denser samples, particularly the 8-ply Bcomp samples, multiple runs of the laser were required to fully cut through the panel.

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Figure 4.61 Braided flax/PLA samples after being cut on a wet diamond saw (left) and using a CO₂ laser (right).

4.3.4 Mechanical Testing

Mechanical testing is essential to characterize the performance of natural fiber composites and understand the interplay between processing, structure, and properties. As part of an iterative design loop, mechanical property data inform composite optimization strategies by identifying both strengths and limitations. This section summarizes a comprehensive testing regime used to evaluate the mechanical response of the developed natural fiber composites, including short beam shear (SBS), compression, tensile, and vibration damping tests. In addition, environmental conditioning was performed to assess material behavior under application-relevant conditions.

4.3.4.1 Coupon Conditioning

Both natural fibers used in this study are inherently hydrophilic, raising concerns about moisture uptake and its impact on mechanical performance. To simulate realistic service environments, selected composite coupons were moisture conditioned and tested in compression and shear. The braided flax/PA11 coupons were initially dried under vacuum for up to 24 hours. The coupons were then weighed and placed in a humidity chamber set to 29.4°C and 85% humidity. Typically, moisture conditioning would continue until the weight gain of the coupon was less than 0.5% - 1% over several days. However, the natural fiber composites continued to gain a small amount of weight following 30 days of exposure, therefore the coupons were pulled from the chamber at this time. Weight gain associated with moisture saturation is shown in Figure 4.62.

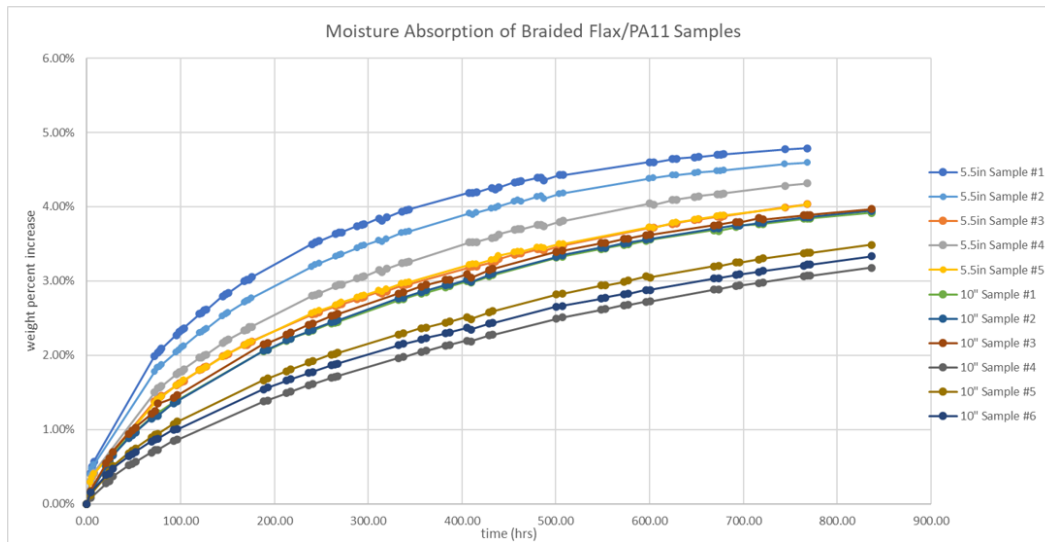


Figure 4.62 Percent weight increase due to moisture absorption in tension and compression coupons.

The plot shows a correlation between coupon size and moisture uptake. Tensile test coupons which were 10" x 1" absorbed overall less moisture than the 5.5" x 1" coupons for compression tests. The primary path for moisture uptake was along the machined edge of the coupon with the smaller compression coupons having a greater edge to surface ratio.

4.3.4.2 Short-Beam Shear Tests

Short-beam shear testing was performed in accordance with ASTM D2344 to evaluate the interlaminar shear strength of the natural fiber composite laminates. Figure 4.63 shows a typical test set-up [7]. Tests were conducted on an Instron Universal Testing Machine (UTM) equipped with a 2kN load cell, three-point bend fixture, and a National Instruments data acquisition (DAQ) system. The loading nose and support beams have a 6 mm and 3 mm diameter, respectively.

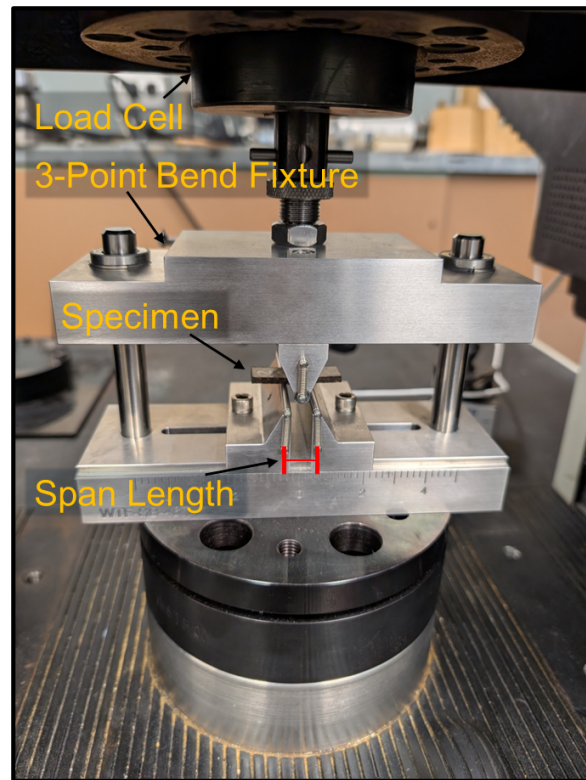


Figure 4.63 Three-point bend fixture for ASTM D2344 short-beam strength testing. Load cell, specimen, and span length of fixture beams are denoted.

Specimens were laser-cut from 12 x 12 in. consolidated panels, see panel preparation in Section 3.1.2.2, to dimensions of 38.1 mm. in length and 12.7 mm in width, with thickness in the range of 2.1 mm – 3.6 mm varying slightly depending on processing. To ensure accuracy, specimen dimensions were measured three times and averaged, with the mean thickness used to calculate the span-to-thickness ratio. After preliminary trials, a ratio of 6:1 was selected to define the support span length. For each test condition, 5 – 6 specimens were tested at room temperature. During testing, each specimen was placed on the support beams, and load was applied at the midpoint at a rate of 1.0 mm/min. until specimen failure or a 30% load drop was achieved. Apparent interlaminar shear strength, F^{sbs} , was then calculated through Equation (4.6):

$$F^{sbs} = 0.75 \frac{P_m}{bh} \quad (4.6)$$

where P_m is maximum load, b is width, and h is thickness.

Due to material variation and testing sensitivity, preliminary tests were conducted to determine the optimal span length for short-beam strength testing of these natural fiber composites. The span-to-thickness ratio can influence failure mode, and an optimal

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distance should promote shear failure of the specimen as shown in Figure 4.64. Here, shear failure occurs between the support beams and the loading nose.

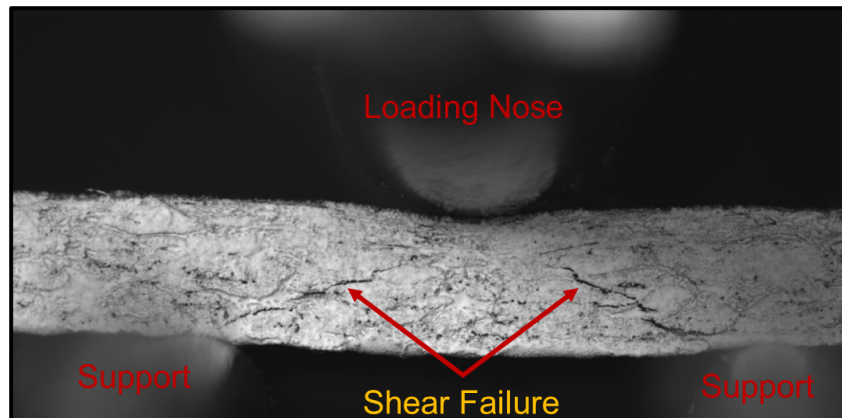


Figure 4.64 Shear failure occurs between loading nose and support beams during short-beam strength test.

Results from flax-PLA short-beam shear trials are presented in Figure 4.65. Variations in slope and peak load were observed, with further analysis revealing that specimens tested at lower span-to-thickness ratios (4:1 – 5:1) exhibited a progressive load increase without a distinct peak. This behavior is attributed to specimen deformation, where material was displaced between the bottom supports and the test transitioned from capturing shear failure to recording the force required to push the supports apart. This was confirmed by post-test measurements, which showed increased support spacing compared to the initial span. In contrast, specimens tested at larger ratios (e.g., 6:1) did not exhibit this issue, allowing for clearer determination of short-beam strength. Comparable ratios have been applied by Maples et al., while Feraboli et al. investigated a modified ASTM D2344 approach where higher span-to-thickness ratios facilitated easier and accurate interlaminar shear strength measurement [8, 9].

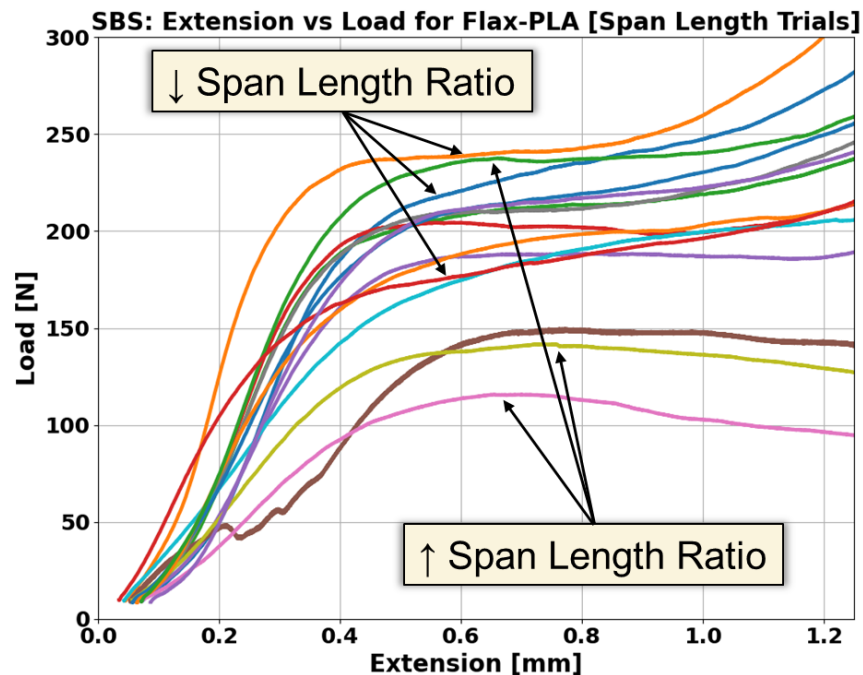


Figure 4.65 Short-beam strength (SBS) investigation of span-to-thickness ratios for Flax – PLA specimens. The applied load [N] and extension (displacement) [mm] are captured. Increased ratios result in curves with an apparent max load, whereas smaller ratios tend to perpetually increase.

With the span-to-thickness ratio established, a series of flax-PLA specimens were tested to evaluate the effect of dwell time during hot press processing. Figure 4.66 shows the average short-beam strength with 95% confidence intervals for each dwell time condition. As dwell time increased from 10 minutes to 20 minutes, the maximum load and corresponding short-beam strength improved. However, extending the dwell beyond 20 minutes led to a sharp decline, with values ranging from 2.86 MPa to 3.14 MPa between 40- and 100-minutes minimum strength at the longest cycle. This reduction is attributed to material degradation occurring during extended thermal exposure. Together with resin chemistry characterization, these results provide valuable insight into the bio-composite processing-performance relationship and inform optimization of the composite manufacturing cycle.

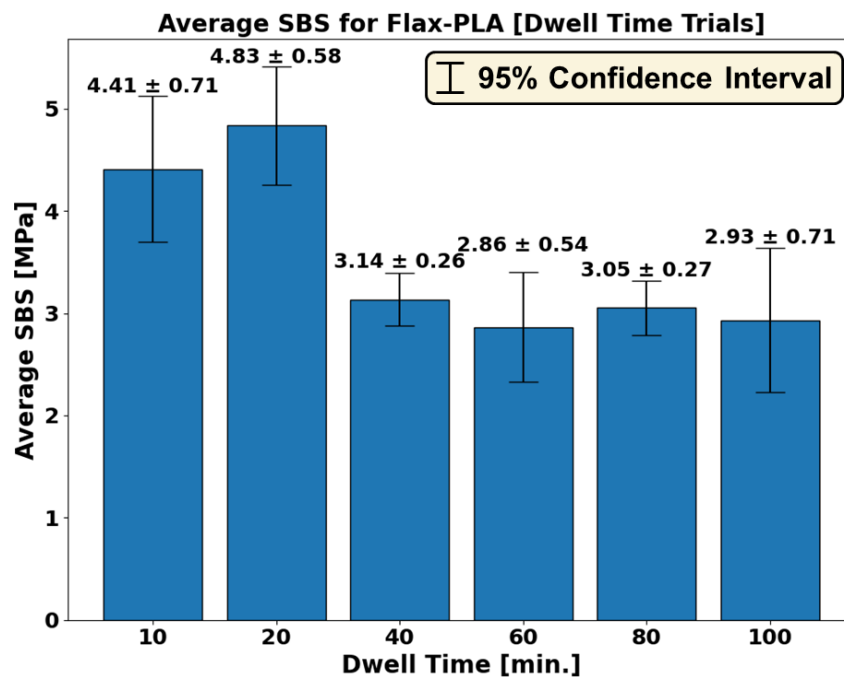


Figure 4.66 Short-beam strength (SBS) investigation of dwell time in the hot press cycle for Flax – PLA specimens. Increased dwell time results in reduced SBS due to material degradation.

Additional variations in the processing cycle were investigated, as shown in Figure 4.67. The effect of drying fiber and resin on short-beam strength revealed that drying only the braided flax produced the highest value (4.83 MPa) compared to no drying (2.98 MPa), drying only PLA (3.37 MPa), and drying both PLA and flax (3.30 MPa). In the latter case, the benefit of drying the flax appears to be offset by flaws or degradation introduced during PLA drying, limiting overall performance.

Quenched and quenched–annealed specimens performed similarly, both underperforming compared to the dried and non-dried variations. Braided flax PHB composites exposed to a 10-minute dwell outperformed the corresponding braided flax PLA specimens, likely due to inherent differences in resin properties. Several braided flax PA11 composites were also tested. Specimens subjected to a 30-minute dwell, with and without annealing, exhibited nearly identical strengths, confirming that annealing has negligible influence on mechanical performance for these bio-composites. As such, annealing will not be considered in future testing. Notably, the PA11 composites demonstrated the highest strengths among the materials examined (9.85 MPa and 9.87 MPa), outperforming other fiber–matrix combinations and processing variations.

The effect of environmental exposure was also assessed. Wetted braided flax PA11 specimens exhibited reduced strength relative to their dry counterparts, consistent with the hydrophilic nature of natural fibers and underscoring the importance of moisture resistance for real-world applications.

Preliminary tests were conducted on flax weave PLA and PHB composites fabricated with an eight-ply unidirectional layup $[0]_8$. The PLA composite achieved 4.64 MPa, slightly below the dried braided flax (4.83 MPa), while the PHB composite reached 5.61 MPa, underperforming the 10-minute dwell braided flax (6.16 MPa). Unless otherwise specified, a 20-minute dwell time was used for this test series.

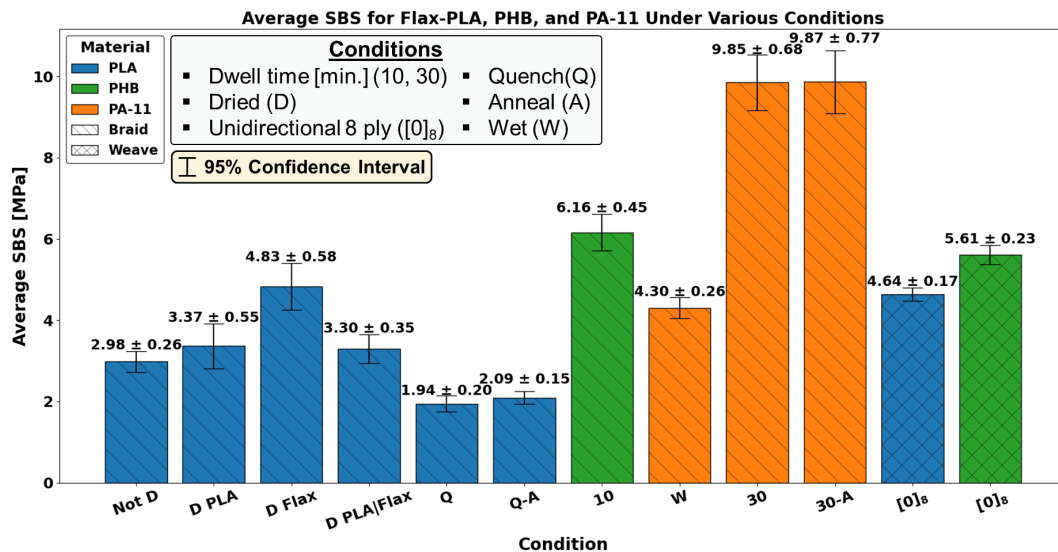


Figure 4.67 Short-beam strength (SBS) investigation of flax-based composites under various conditions: Dwell time is [10, 30] min. or 20 min if not specified; PLA and flax material can be pre-dried (D); the layup for weave architecture is unidirectional 8 ply $[0]_8$; Several specimens were quenched (Q), annealed (A), or wetted (W); Resins are PLA – Blue, PHB – Green, and PA11 – Orange; Fiber architecture is either a braid or weave represented by a diagonal or hatch pattern, respectively.

Figure 4.68 reports the average short-beam shear strength of flax braid, flax weave, and hemp weave composites manufactured with PLA, PHB, PA11, and a commingled PA11 variant. When comparing fiber architectures within the same resin system, the flax weave generally exhibited the highest strength, followed by the hemp weave and then the flax braid. An exception occurred with the commingled flax braid PA11, which achieved a strength of 8.06 MPa, comparable to that of the flax weave PA11 (7.96 MPa). This improvement is likely due to enhanced fiber–matrix interaction and consolidation in the commingled braid, which are less effective in the alternating fiber–resin ply configuration. Across resin systems for the same fiber architecture, PA11 consistently provided the highest strength, followed by PHB and then PLA.

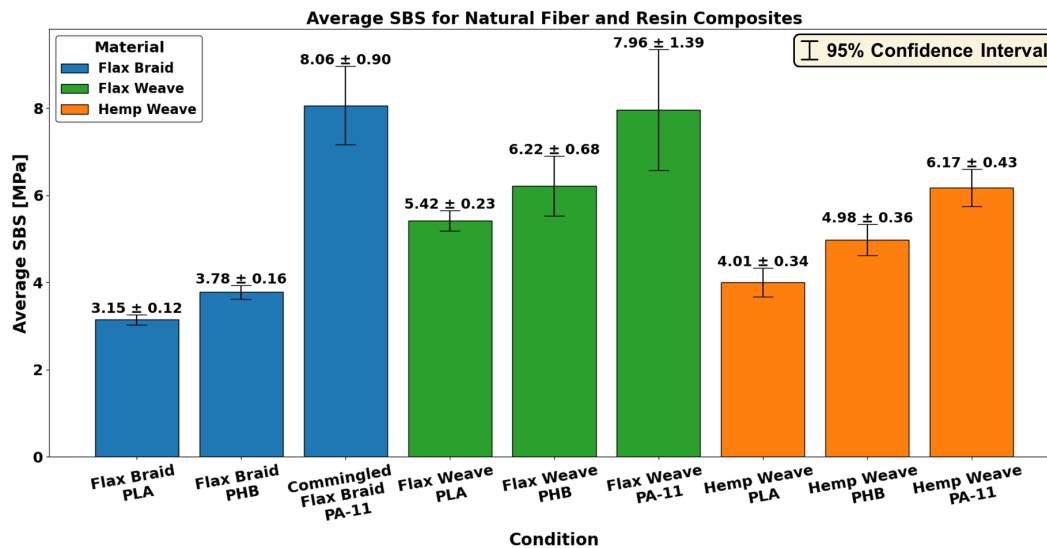


Figure 4.68 Average short-beam strength (SBS) for natural fiber and resin composite variations: Blue - flax braid; Green - flax weave; Orange - hemp weave; Resins include PLA, PHB, PA11, and a commingled flax braid PA11.

The effect of fiber volume fraction on the short-beam shear response of flax weave PA11 and hemp weave PA11 composites is shown in Figure 4.69A and Figure 4.69B, respectively. For the flax weave composite, shear strength increased with fiber content up to 59% fiber volume (10.77 MPa), after which a slight decrease was observed at 64% (10.10 MPa). This suggests a threshold beyond which additional fiber content no longer improves performance, likely due to insufficient resin infiltration during processing, leading to voids or incomplete consolidation. In contrast, the hemp weave composite did not exhibit the same trend. The highest shear strength occurred at the lowest fiber fraction (43%, 7.94 MPa), followed by a gradual reduction at 53% (7.51 MPa) and 59% (7.58 MPa), with a more pronounced drop at 64% (5.37 MPa). These results indicate that hemp weave composites display relatively consistent shear performance across intermediate fiber contents, with a sharp decline only once the fiber volume exceeds a critical threshold. Further investigation into fiber-matrix interactions, void content, and batch-to-batch variability is recommended to better understand the mechanisms driving these trends.

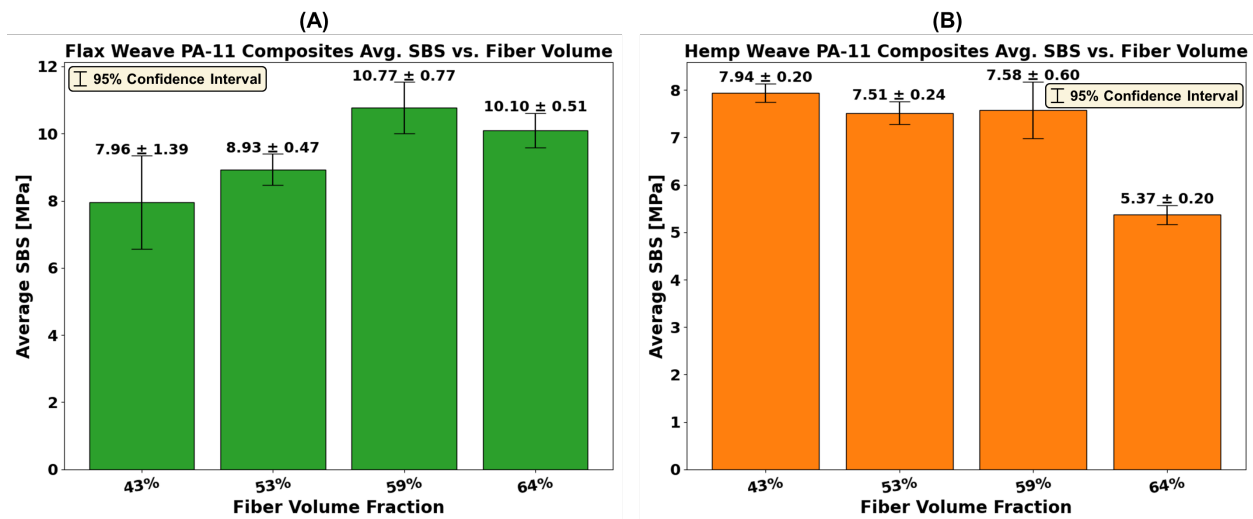


Figure 4.69 Average short-beam strength (SBS) for PA11 based natural fiber composites with varied fiber volume fraction: (A) Flax weave and (B) Hemp weave.

4.3.4.3 Compression Tests

Compression testing was performed in accordance with ASTM D6641 to determine the compressive strength and modulus of the natural fiber composite laminates, see Figure 4.70 for a typical test set-up [10]. Tests were conducted on an Instron Universal Testing Machine (UTM) equipped with a 50 kN load cell, a combined loading/compression (CLC) fixture, and a digital image correlation (DIC) system (Correlated Solutions). The DIC utilized a FLIR Grasshopper 3 camera with dedicated lighting and an image acquisition rate of 5 Hz. The recorded images were processed with VicSnap and Vic2D software (Correlated Solutions).

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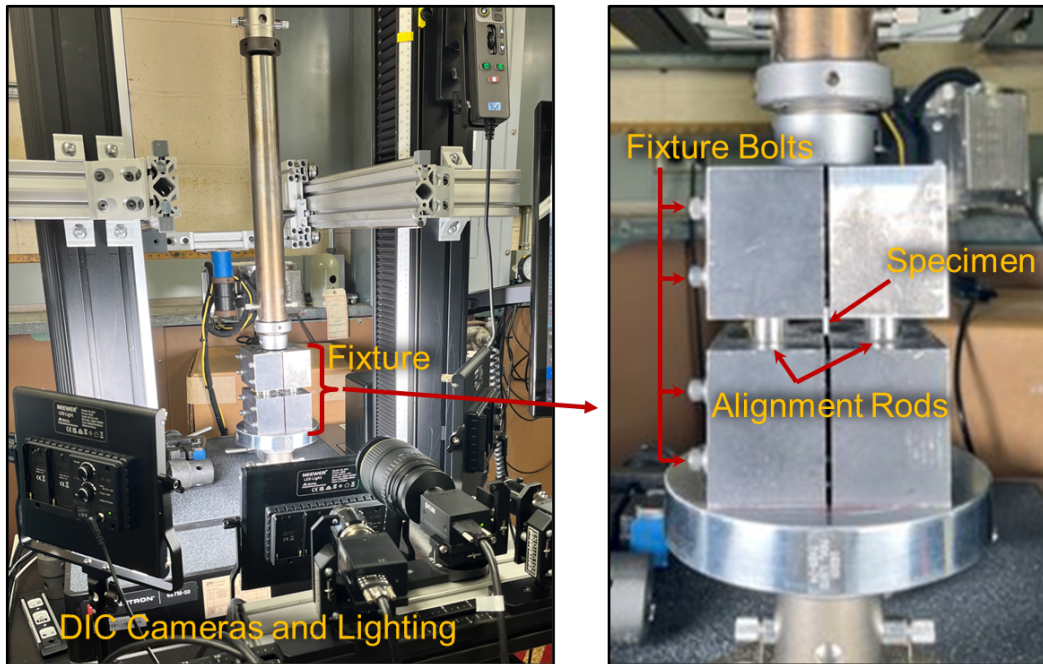


Figure 4.70 ASTM 6641 compression test setup. Cameras and lighting are positioned for digital image correlation. Alignment rods and fixture bolts help facilitate specimen failure in the gage section.

A typical specimen, DIC speckling pattern, and an example of through-thickness failure in the gauge section are provided in Figure 4.71. Specimens were laser-cut to 139.7 mm length and 25.4 mm width, as specified in the standard, with slight thickness variations depending on processing. To minimize the risk of buckling and ensure uniform load transfer, the specimens were oriented with a shim and secured within the CLC fixture during testing with fixture bolts tightened to 2.82 N-m. A gauge section of 12.7 mm was left exposed to induce failure, such as the through-thickness failure shown in Figure 4.71. Load was applied axially at a constant crosshead displacement rate of 1.3 mm/min until failure. The DIC system was used to capture strain data at corresponding loads and verify the bend percentage of specimens to ensure they remained within limits of the standard. This required the application of a white coat followed by a speckling of black paint to produce a speckle pattern for the DIC system to reference during testing. For each test condition, 5 – 6 specimens were tested at room temperature. Stress, σ , was then calculated by equation (4.7):

$$\sigma = \frac{F}{A} \quad (4.7)$$

where F is the applied load and A is the specimen cross-sectional area. The compressive stress for each specimen was determined from the peak load divided by cross-sectional area. Additionally, after several successful tests with failure in the gauge section, it was deemed that tabbing the specimens was unnecessary.

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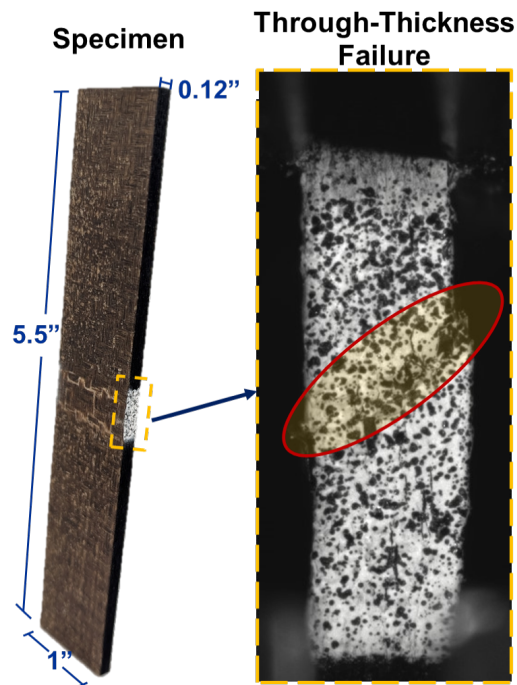


Figure 4.71 Compression specimen sized according to ASTM 6641. Example of through-thickness failure occurring in the gauge section due to compressive loading. The speckle pattern was applied for digital image correlation.

Figure 4.72 presents the average compressive strength of the different bio-composite systems evaluated. Composites with a PA11 matrix consistently outperformed those made with PLA or PHB. Among the PA11 variants, the flax weave composite exhibited the highest compressive strength (178.8 MPa), followed by the hemp weave PA11 (56.3 MPa) and the commingled braided flax PA11 (55.3 MPa). The PLA-based composites followed a similar trend but with reduced values of 49.1 MPa, 39.3 MPa, and 20.3 MPa, respectively. The only PHB-based composite tested was the hemp weave PHB, which yielded a compressive strength of 23.5 MPa, lower than both its PLA and PA11 counterparts. Based on this trend, PHB composites reinforced with flax weave or braided flax are also expected to exhibit comparatively low compressive strengths.

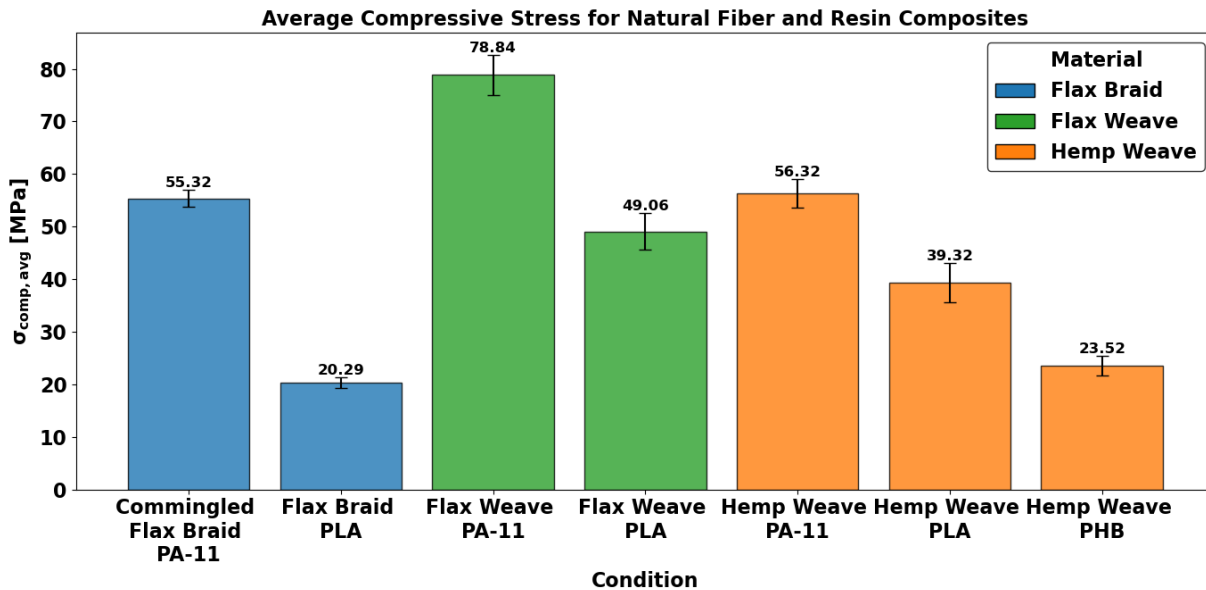


Figure 4.72 Average compressive strength, denoted by σ , for various bio-composites: Blue - flax braid; Green - flax weave; Orange - hemp weave; Resins include PLA, PHB, PA11, and a commingled flax braid PA11. One standard deviation is marked.

Figure 4.73 presents the average compressive strength of hemp weave PA11 composites at varying fiber volume fractions. As the fiber volume fraction increased from 43% (50/50 fiber-resin weight ratio) to 64% (70/30 weight ratio), the average compressive strength decreased from 56.3 MPa to 29.7 MPa. This reduction in strength was consistent across each incremental increase in fiber content. Similar to the trend observed in short-beam shear testing, hemp weave PA11 composites show a clear negative correlation between fiber volume fraction and mechanical performance.

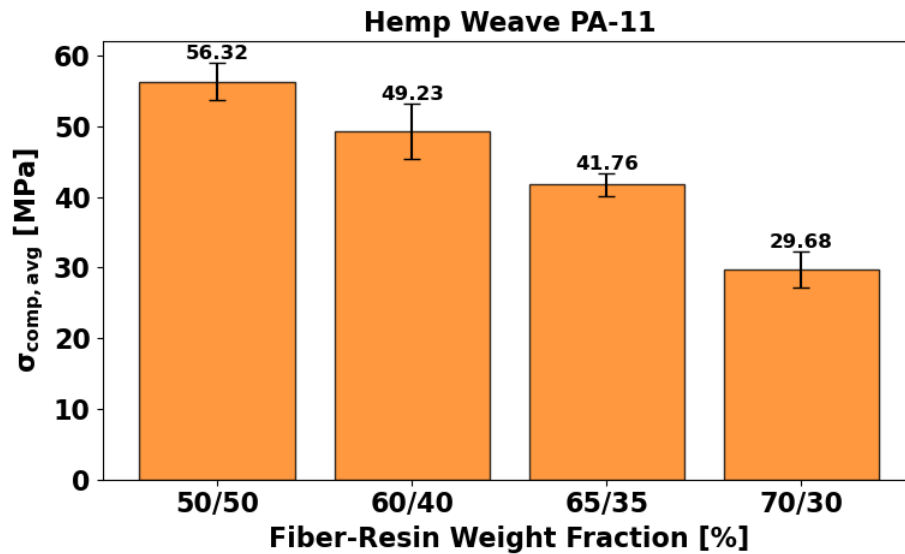


Figure 4.73 Impact of fiber-resin weight fraction (%) on average compressive strength, denoted by σ , for hemp weave PA11 composites: Weight fraction to fiber volume fraction conversion: 50/50 – 43%, 60/40 – 53%, 65/35 – 59%, and 70/30 – 64%. One standard deviation is marked.

Figure 4.74 shows the average compressive strength of flax weave PA11 composites at different fiber volume fractions. A clear dependence of maximum compressive stress on fiber volume fraction is observed. Specifically, compressive strength decreases with increasing fiber content, dropping from 78.8 MPa at 43% fiber volume to 58.2 MPa at 64%. An exception to this trend occurs at 59% fiber volume, where the average compressive strength (65.3 MPa) is slightly higher than that of the 53% fiber volume composite (64.9 MPa). This deviation is likely related to processing variations: the 59% panel exhibited a higher void content and greater thickness than the 53% panel, effectively causing it to behave more like a composite with a lower effective fiber volume fraction.

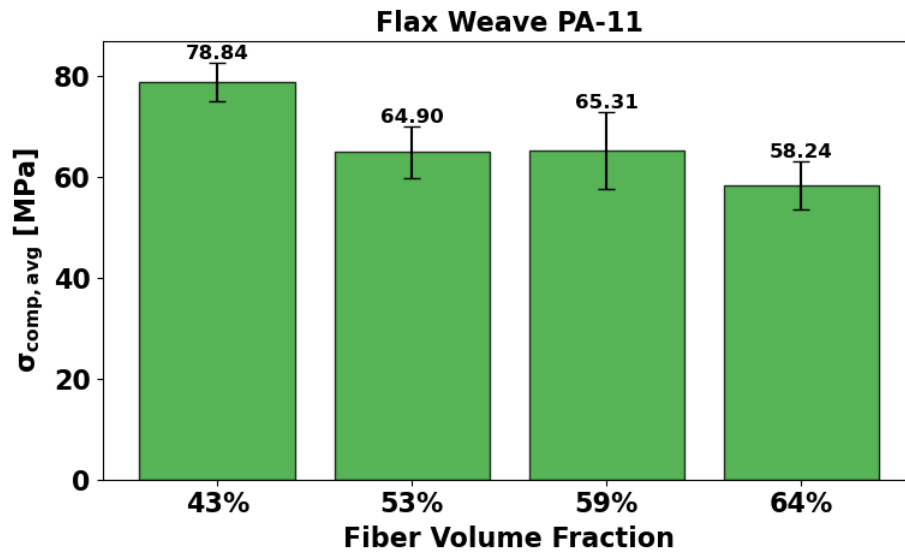


Figure 4.74 Impact of fiber volume fraction (%) on average compressive strength, denoted by σ , for flax weave PA11 composites. One standard deviation is marked.

4.3.4.4 Tension Tests

Tensile testing was performed in accordance with ASTM D3039 to evaluate the ultimate tensile strength and Young's modulus of the natural fiber composite laminates, see Figure 4.75 for a typical test set-up [11]. Tests were carried out on an Instron Universal Testing Machine (UTM) equipped with a tension fixture, a 50 kN load cell, an Epsilon Technology axial extensometer, and a National Instruments data acquisition (DAQ) system.

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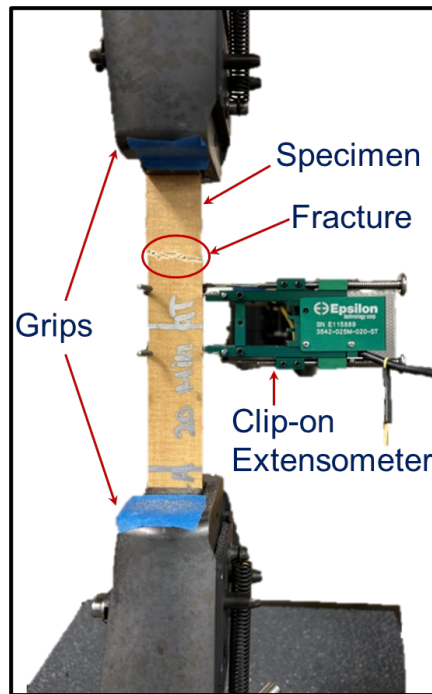


Figure 4.75 Tensile test setup with clip-on extensometer and specimen.

Specimens were laser-cut from consolidated panels to nominal dimensions of 250 mm in length and 25.4 mm in width, with thickness varying slightly based on processing conditions. This width was chosen to capture two unit cells across the specimen cross-section, which helped reduce variability in the measured results. To ensure measurement accuracy, specimen length, width, and thickness were each recorded three times with calipers and averaged, with the mean thickness used to calculate cross-sectional area. Specimens were also gripped at locations approximately 63.5 mm from each end. A centerline mark was applied to guide placement of the extensometer, which was mounted across the 25.4 mm gauge length at the specimen midpoint. Testing occurred at a load rate of 2 mm/min and continued until failure. During testing, the extensometer recorded strain response while the UTM simultaneously measured load and displacement. Stress was calculated using equation (3.3), see compression testing in Section 3.3.4.3, and Young's modulus was calculated by equation (4.8):

$$\sigma = E\varepsilon \quad (4.8)$$

where E is Young's modulus, and ε is strain. The ultimate tensile stress for each specimen was determined from the peak load divided by cross-sectional area. Young's modulus was determined from the linear elastic region of the stress-strain response using strain data acquired from the extensometer.

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The tensile response of PA11 matrix composites was consistent across fiber types, with average ultimate tensile strengths (UTS) ranging from 64.4 to 70 MPa. The commingled braided flax - PA11 variant had a slightly lower strength at 54.2 MPa. Although hemp-based composites exhibited slightly lower values than flax-based composites, overall performance remained comparable within this resin system. In contrast, PHB matrix composites demonstrated greater variability, with tensile strengths spanning 26 to 96.7 MPa. Hemp weave - PHB exhibited the lowest value (26 MPa), while braided flax - PHB and Bcomp (weave) flax - PHB achieved higher strengths of 59.4 MPa and 96.7 MPa, respectively. Among these, the Bcomp flax - PHB composite provided the highest performance. PLA matrix composites exhibited lower tensile strengths overall, ranging from 27.8 to 55.6 MPa across fiber types. Although hemp weave - PHB performed worse than hemp weave - PLA, the difference between the two systems was only 1.9 MPa, suggesting broadly comparable performance. Figure 4.76B shows the Young's modulus data, where resin seems to have a negligible impact compared to fiber architecture. The flax braid ranged from 7.7 to 10.3 GPa, the Bcomp flax ranged from 15.9 to 16.6 GPa, and the hemp weave ranged from 6.2 to 6.8 GPa. An additional difference in these trends compared to those of UTS in Figure 4.76A was observed for flax weave - PA11, which exhibited the highest modulus (16.6 GPa), a significantly larger than the other fiber-resin systems. Flax weave - PHB, which yielded the highest stress (96.7 MPa), followed suit with a Young's modulus of 15 GPa.

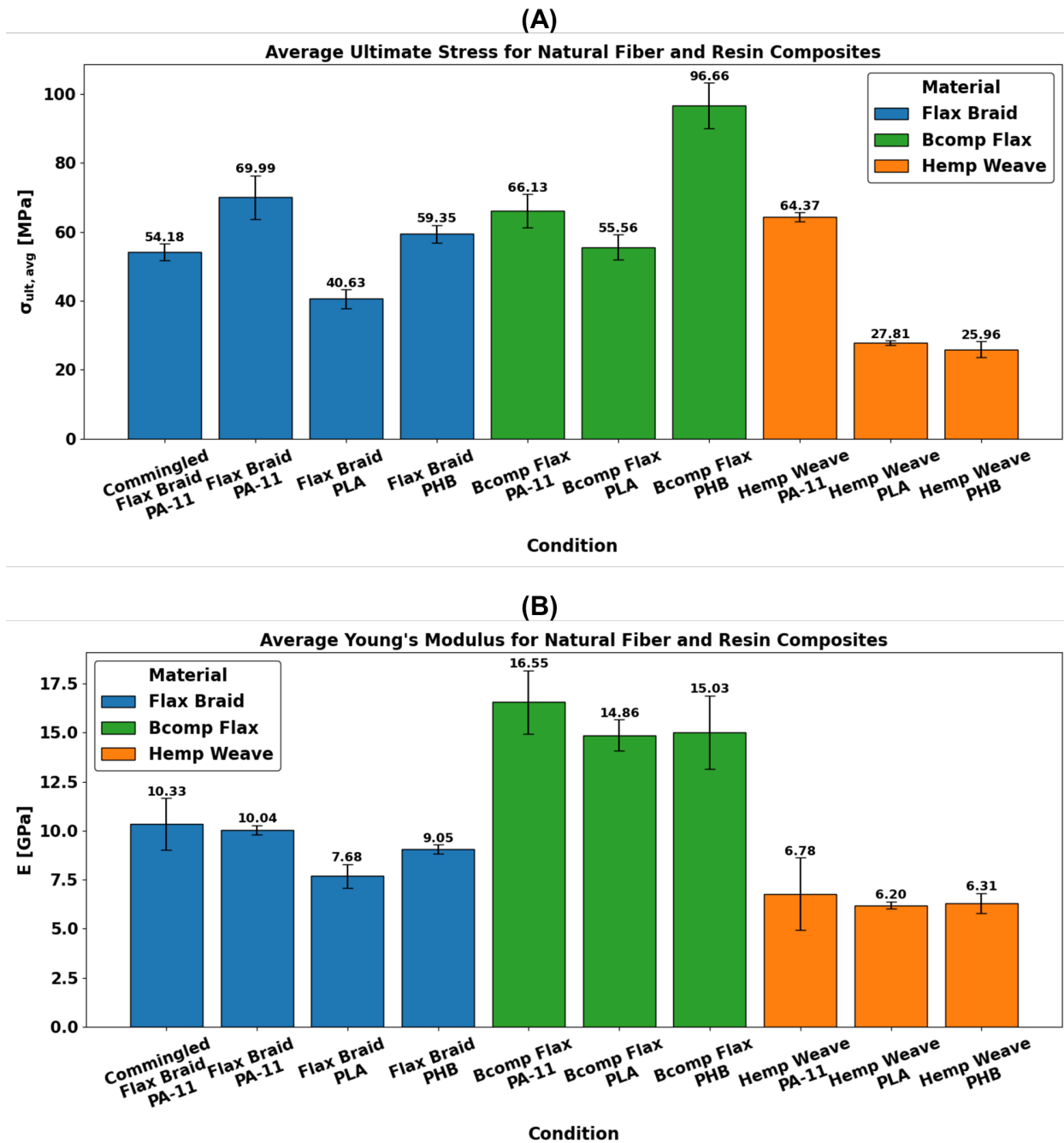


Figure 4.76 Results from tensile testing of flax braid, flax weave (Bcomp), and hemp weave with PA11, PLA, and PHB resins: (A) Average ultimate tensile strength, denoted as σ , and (B) Average Young's modulus, denoted as E. One standard deviation is marked. Blue - flax braid; Green - flax weave; Orange - hemp weave; Resins include PLA, PHB, PA11, and a commingled flax braid PA11.

Since PA11 generally exhibited the highest tensile performance among the resins evaluated, the weight ratio study (representative of fiber volume fraction) was conducted using this

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matrix with both hemp and flax fibers. Figure 4.77A and Figure 4.77B present the average UTS and Young's modulus for hemp weave-PA11 composites at varying fiber-to-resin ratios. The 50:50 ratio (43% VF) achieved the highest average tensile strength, outperforming the 60:40 (53% VF), 65:35 (59% VF), and 70:30 (64% VF) ratios. Among the intermediate ratios, the 65:35 composition exhibited slightly higher strength than the 60:40, but remained within one standard deviation of each other. Overall, these results suggest that the 50:50 ratio is optimal with respect to tensile performance. In Figure 4.77B, Young's Modulus had a slight negative linear correlation with increasing fiber content, but also exhibited large variation for each condition. The 65:35 ratio exhibited the largest modulus (7.5 GPa) followed by the 50:50 ratio (6.78 GPa) despite its marginally higher tensile strength. The 60:40 and 70:30 ratio each exhibited a lower modulus, 5.9 GPa and 4.9 GPa respectively, further emphasizing the optimal performance of the balanced fiber-to-resin weight ratio. These findings are consistent with microscopy observations, which revealed that increasing fiber content beyond a balanced ratio generally leads to reduced material quality and strength due to void formation, limited resin infiltration, and other consolidation defects.

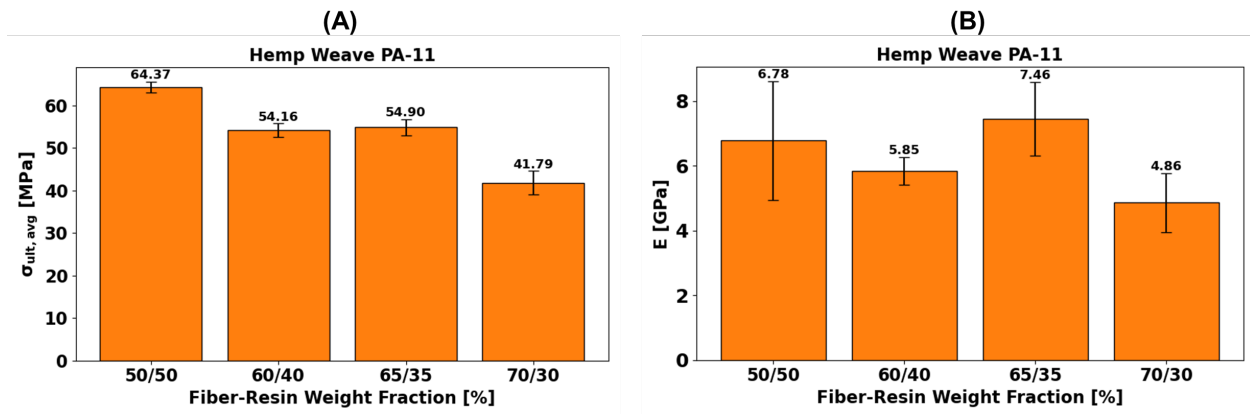


Figure 4.77 Tensile test results for hemp weave - PA11 fiber volume fraction study: (A) Average tensile strength and (B) Average Young's modulus. One standard deviation is marked.

The tensile behavior of flax weave-PA11 composites with varied fiber volume fraction is presented in Figure 4.78A and Figure 4.78B. Across the range of fiber volume fractions evaluated, no significant variation in average tensile strength was observed, with all values clustering around 65.6 MPa and overlapping within standard deviation. A similar trend is evident in Figure 4.78B for Young's modulus, where values remained near 17.4 GPa despite minor fluctuations. Since both tensile strength and modulus fell within overlapping statistical bounds, the results indicate that these properties are governed primarily by the intrinsic strength of the flax fibers rather than the resin content, with fiber volume fraction exerting minimal influence.

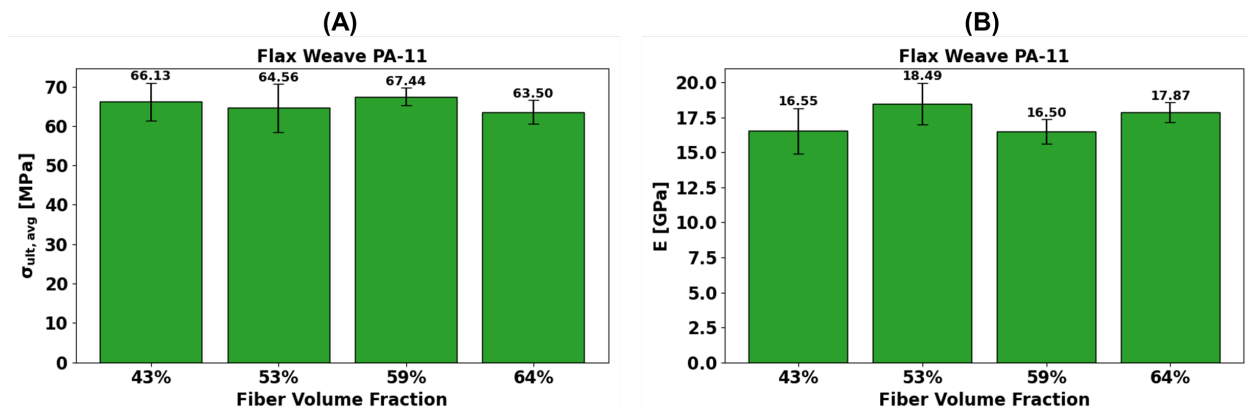


Figure 4.78 Tensile test results for flax weave - PA11 fiber volume fraction study: (A) Average tensile strength and (B) Average Young's modulus. One standard deviation is marked.

Representative failure modes for hemp weave - PLA and flax braid - PHB composites are shown in Figure 4.79A and Figure 4.79B, respectively. The hemp weave PLA specimens exhibited delamination within the gauge section, likely due to poor consolidation between plies. In contrast, the flax braid - PHB specimens failed by lateral fracture through the gauge section, indicative of a stronger fiber-resin interface. These distinct failure patterns highlight the influence of fiber architecture and resin type on composite performance.

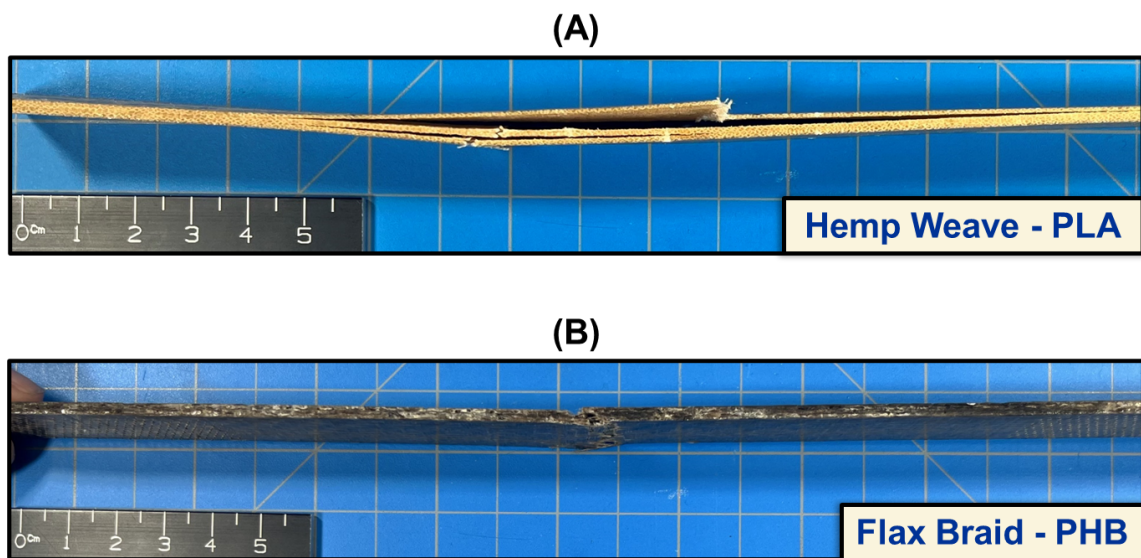


Figure 4.79 Failure of natural fiber composites resulting from tension testing: (A) Hemp weave - PLA experienced delamination of the plies; (B) Flax braid - PHB experienced through-thickness fracture.

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4.3.4.5 Vibration Damping

Vibration testing was performed using the cantilever beam test method according to ASTM E756. Vibration testing is specifically important because it plays a crucial role in the realm of aerospace, ensuring the safety and reliability of aircraft. The schematic of the vibration testing is shown in Figure 4.80. For this testing, a log-sweep-sine signal (from 1 to 5000 Hz) is output from LabVIEW and sent through the DAQ board (DAQ, NI USB-6356), which is sent to the amplifier (Data Physics, DSA1 power amplifier). The amplified signal is then sent to the shaker (Data Physics, Model V301). The accelerations on the shaker and on the tip of the cantilever beam are measured using two light weight accelerometers (PCB Piezotronics, Model 352C22). A signal conditioner (PCB Piezotronics, Model 482C) is also used to increase the amplitude of the accelerometers, which are sent back to the DAQ and collected by LabVIEW software.

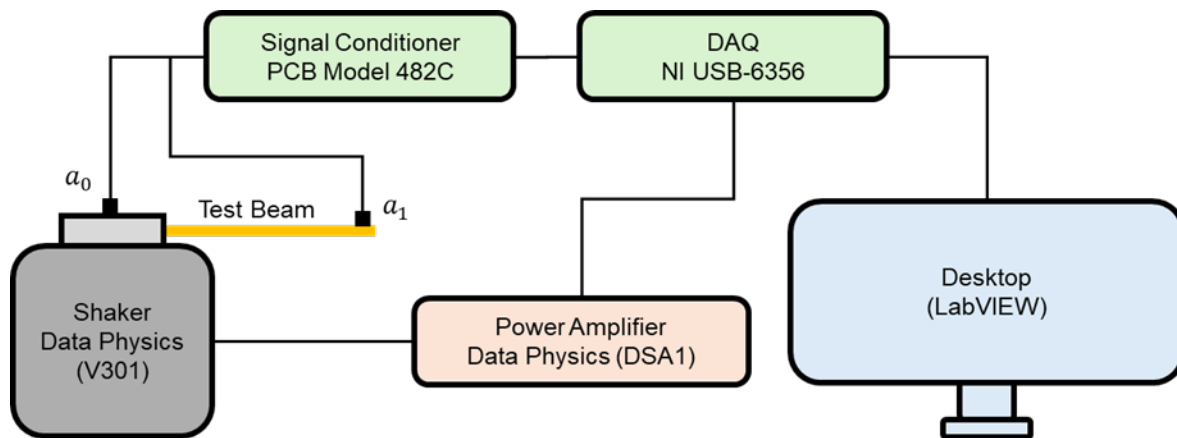


Figure 4.80 Overall schematic for the vibration test setup.

Samples had nominal dimensions of 10 x 0.75 x 0.12 inches, with 2 inches of the sample being clamped in the fixture. Through vibration testing, transmissibility defined as $20 \log(|a_1|/|a_0|)$, in dB was measured. Each material's loss factor, which is used to quantify the material's damping, was measured using the equation, $\eta = \Delta f / f$ where f is a resonance frequency (Hz), and Δf (or f_0) is the 3 dB bandwidth (Hz) of the resonance frequency. For these measurements, the frequency resolution was set at 0.5 Hz.

Resins were tested with various fibers including carbon fiber as a baseline for comparison of their vibration damping properties. Figure 4.81 shows the PA11 loss factor as a function of frequency with different fibers.

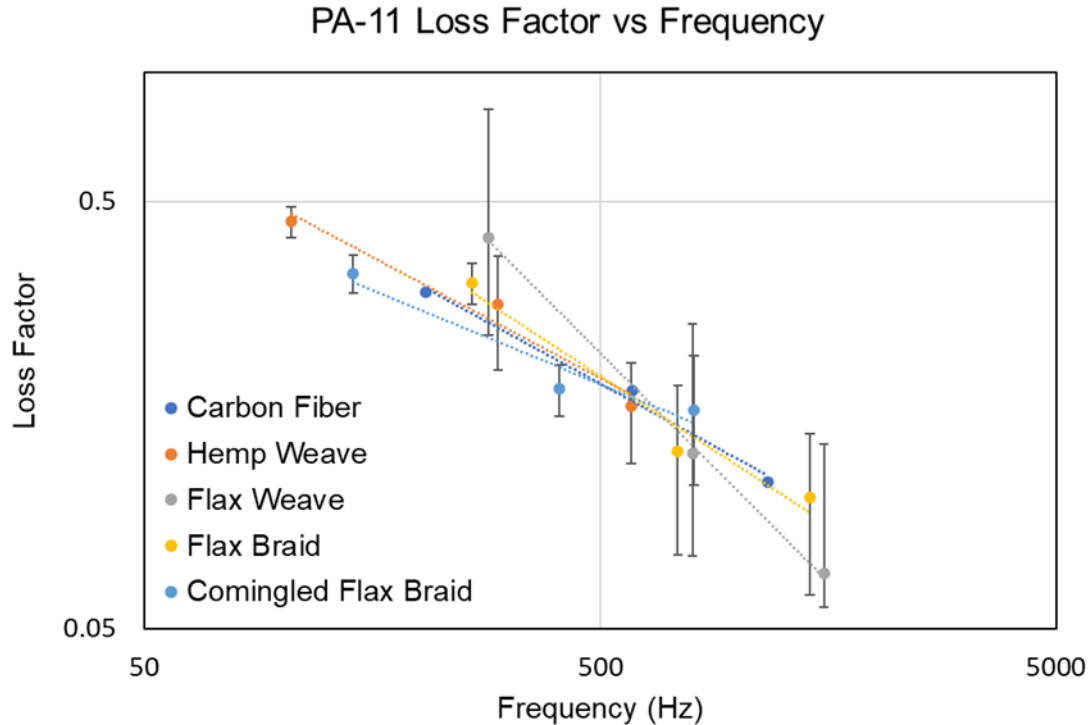


Figure 4.81 The loss factor of PA11 based composites as a function of frequency with different fiber reinforcements.

Consistent with all the bio-composites, as frequency increases, the loss factor decreases. The commingled flax braid maintains the lowest slope, meaning it has the most consistent damping properties and performs the best at higher frequencies. Higher standard deviation for flax based composites might be a sign of manufacturing inconsistency.

Figure 4.82 shows the corresponding results for PLA material system using both carbon fiber and hemp weave. The main difference between the two would be that the carbon fiber tests were considerably more consistent with a near-zero standard deviation as opposed to the flax weave. Other fibers, such as the hemp weave, initially have high loss factor values but decreases significantly as the frequency increases.

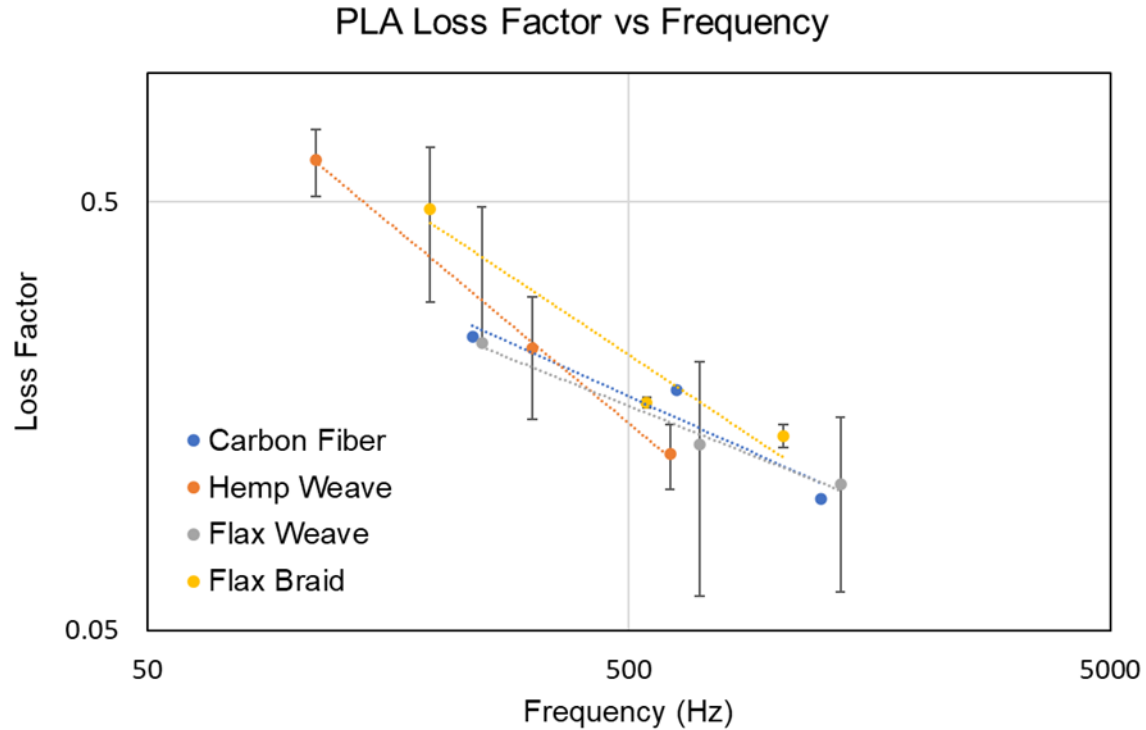


Figure 4.82 The loss factor of PLA based composites as a function of frequency with different fiber reinforcements.

Lastly, the data for PHB with the varied fibers shown in Figure 4.83 shows that carbon fiber, flax weave, and flax braid all have very similar trendlines. They do differ in the sense that the flax weave ultimately has the highest loss factor, followed by flax braid, and lastly carbon fiber. The hemp weave in this plot acts as an outlier, as the only one with a differing trendline, performing the worst as the frequency increases.

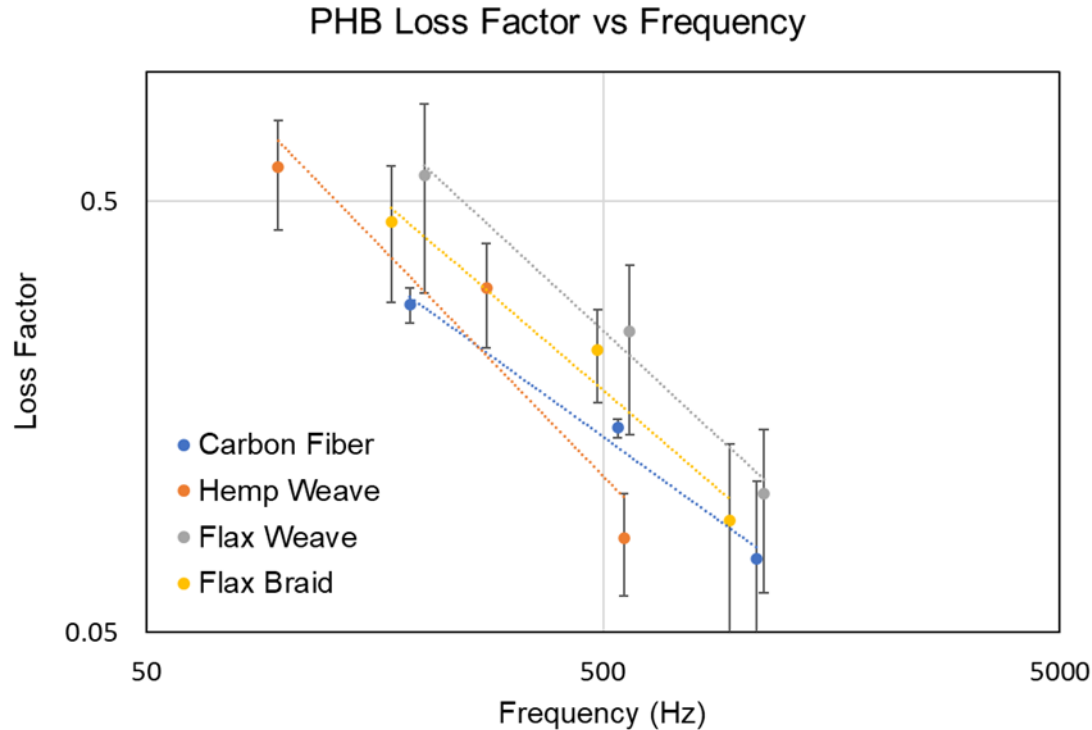


Figure 4.83 The loss factor of PHB based composites as a function of frequency with different fiber reinforcements.

4.3.5 Joining – Conduction and Ultrasonic

One of the benefits of thermoplastic composites is their ability to be reheated and remelted above their glass transition temperature which allows joining by reheating under pressure. Compared to traditional thermoset resin composites that require bolts or dissimilar adhesives to join, thermoplastic joining has the potential to reduce weight, parts, and stress concentrations at the bonding region. The purpose of the joining effort within the SUMAC project was to explore conduction welding of bio-based thermoplastic composites through compression molding and joining through an ultrasonic welding method.

4.3.5.1 Materials

Bcomp 2x2 twill and PA11 thermoplastic with a 53% fiber volume fraction was selected for joining studies. In total, three, 12 in. x 12 in. panels were manufactured to provide adherends for joining and included: one for conduction welding and two for ultrasonic welding. Shims were required for conduction welding the panel for single lap shear (SLS) coupons. These were made of carbon fiber (CF)/ polyether ether ketone (PEEK) composites with a $[0/90]_{2s}$ lay-up configuration. This shim material was chosen due to its high melting

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point (343°C/649°F) compared to PA11 (186°C/367°F), so it would not melt during the conduction welding.

4.3.5.2 Conduction Welding

Conduction welding in the hydraulic press proceeded with the flax/PA11 panel overlaid inside a 12 in. x 12 in. frame with a 1 in. x 12 in. overlap in the center. Two layers of additional PA11 film with an approximate combined thickness of 0.12 mm were placed at the bond line. This additional resin was used for consistency with the ultrasonically welded coupons, where a film energy director is needed at the bond line. The layup prior to compression molding is shown in Figure 4.84, and a cross-sectional view of this same layup is illustrated in Figure 4.85.

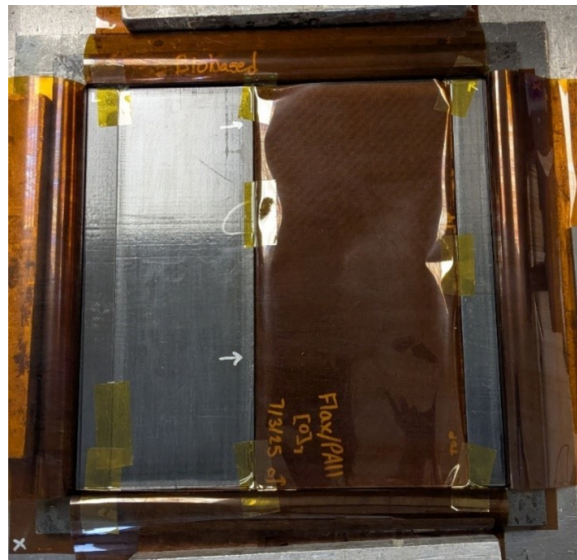


Figure 4.84 Layup of flax/PA11 panel with PEEK shims prior to conduction welding process.

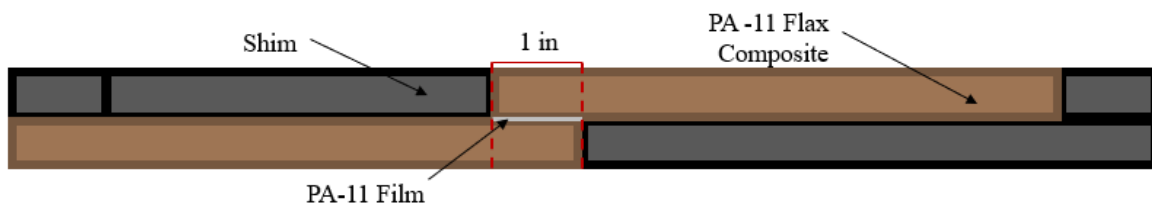


Figure 4.85 Cross-sectional view of the flax/PA11 panel layup inside frame prior to being compression molded.

The mold was placed in the hot press for conduction welding. The panel was held under pressure at 7 psi until the temperature reached 210 °C (410 °F). The pressure was increased to 17.5 psi and held for 20 min. The panel was cooled under pressure. The

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finished conduction welded panel is shown in Figure 4.86. The red lines indicate laser cutting lines to create 1 in. x 7 in. single lap shear coupons.

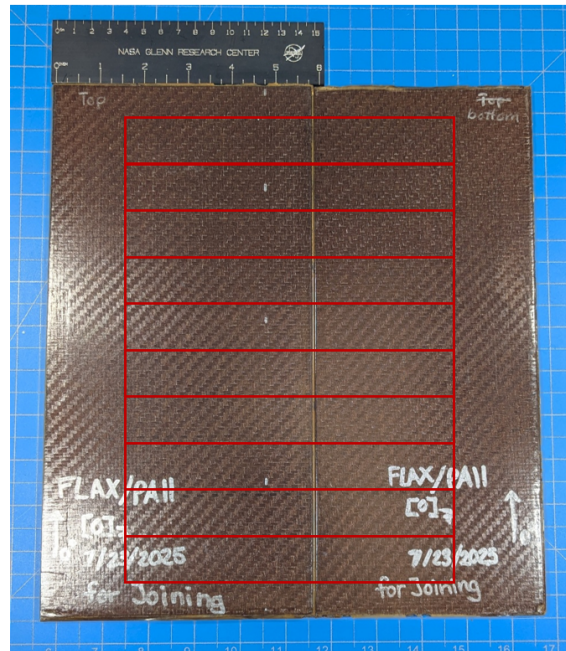


Figure 4.86 Conduction welded panel. Red lines mark laser cut path to create single lap shear specimens.

4.3.5.3 Ultrasonic Welding

Individual single lap shear coupons were joined by ultrasonic welding. A handheld ultrasonic welder (USW) from Sonitek was mounted to an arbor press. Coupon adherends were held down with a custom-made adjustable base plate to fit various coupons widths and lengths, as shown in Figure 4.87.

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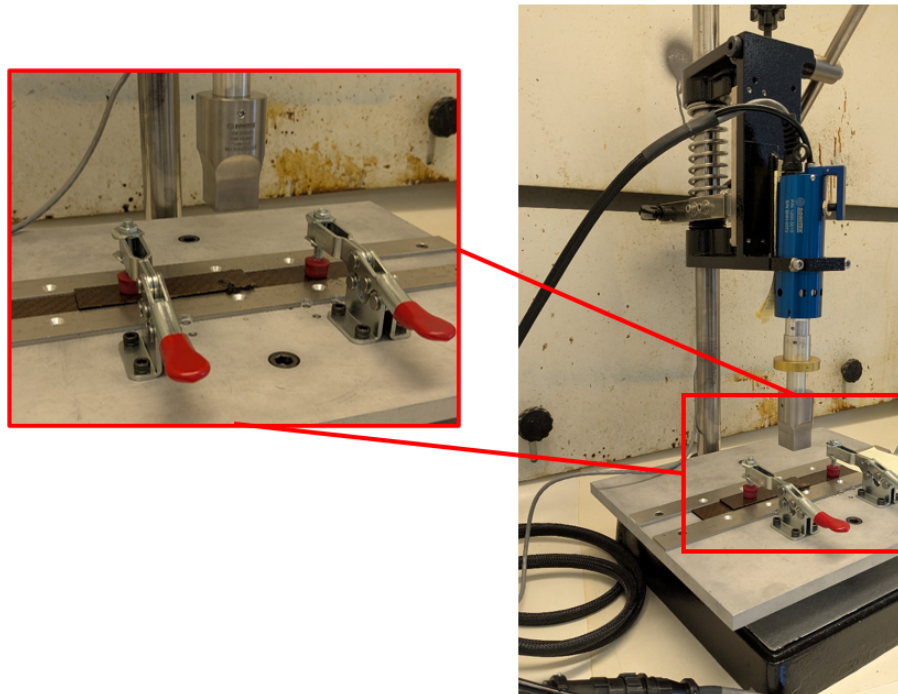


Figure 4.87 Ultrasonic welding setup mounted to an arbor press with an adjustable base clamp system to hold single lap shear coupons.

Prior to joining, two 1 in. x 1 in. films of PA11 were cut and placed at the bond line for each pair of adherends. The adherend and film configuration is shown in Figure 4.88, with the head of the ultrasonic welder applied directly to the 1 in. x 1 in. overlap area of the SLS coupon. The shim that was used here was a 4 in. x 1 in. adherend of Flax/PA11 as only the bond region would be heated.

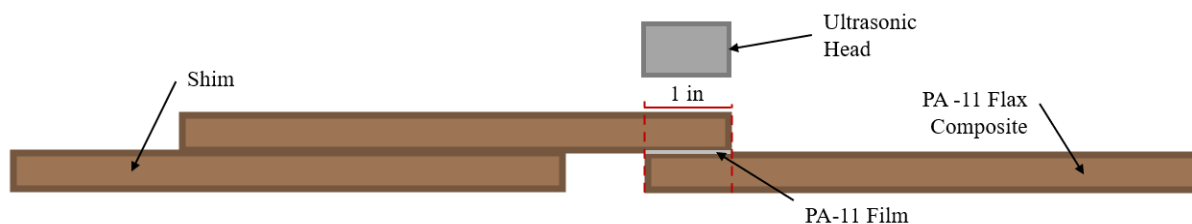


Figure 4.88 Cross-section view of flax/PA11 adherends being ultrasonically welded.

The head that was used for the ultrasonic welding had a knurled surface with a square area of 1 in. x 1 in., see Figure 4.89. The purpose of using this head was to increase surface area in contact with the adherend and to increase friction with the top interface so that the head does not slide during USW as compared to a flat surface. This helped to focus the kinetic energy from the ultrasonic head into the lap shear coupon towards the interlayer boundary.

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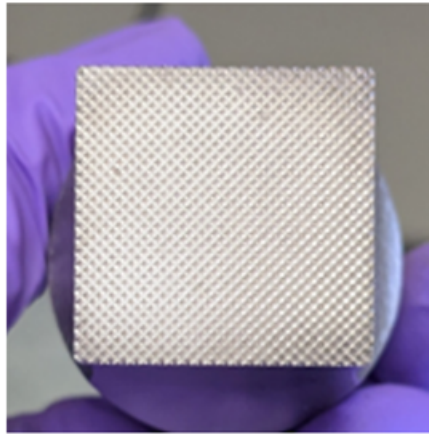


Figure 4.89 Knurled surface finish of the ultrasonic weld head.

Once the adherends were in place, each single lap shear specimen was welded using the same parameters. The frequency of 40.1 kHz with an amplitude of 96% was selected based on process development trials. Each weld was held for 11 seconds. The max power applied for each weld was approximately 270 W with a total energy applied of approximately 2170 W-s per weld. It was difficult to accurately measure force applied due to the manual operation and equipment setup, but a force transducer load cell was used and estimated that between 30-50 lbs of force was applied to each coupon throughout the weld. Using this process, six ultrasonically welded single lap shear coupons were manufactured, see Figure 4.90.

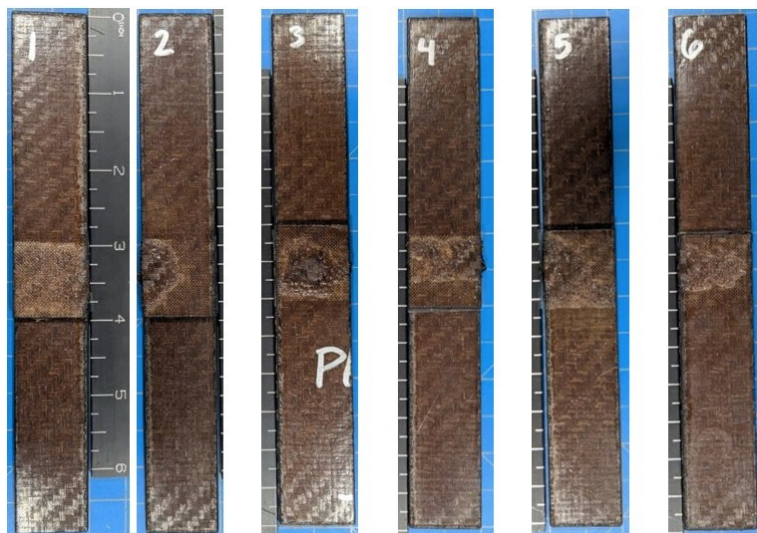


Figure 4.90 Ultrasonically welded flax/PA11 single lap shear coupons.

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4.3.5.4 Mechanical Testing Results

Single-lap-shear coupons were loaded into an Instron and tested according to ASTM Standard D5868 with a 2 mm/min crosshead rate as seen in Figure 4.91. The top grip was a self-aligning fixture which ensured the specimen was only pulled in tension, inducing a shear load at the joining interface. This minimized any out-of-plane loading. The specimen was gripped in a 1 in. x 1 in. cross-section on both the top and bottom grip heads, and crosshead displacement was used to measure displacement of the coupon during testing. Six specimens were tested for each the conduction welded and ultrasonically welded joining methods.

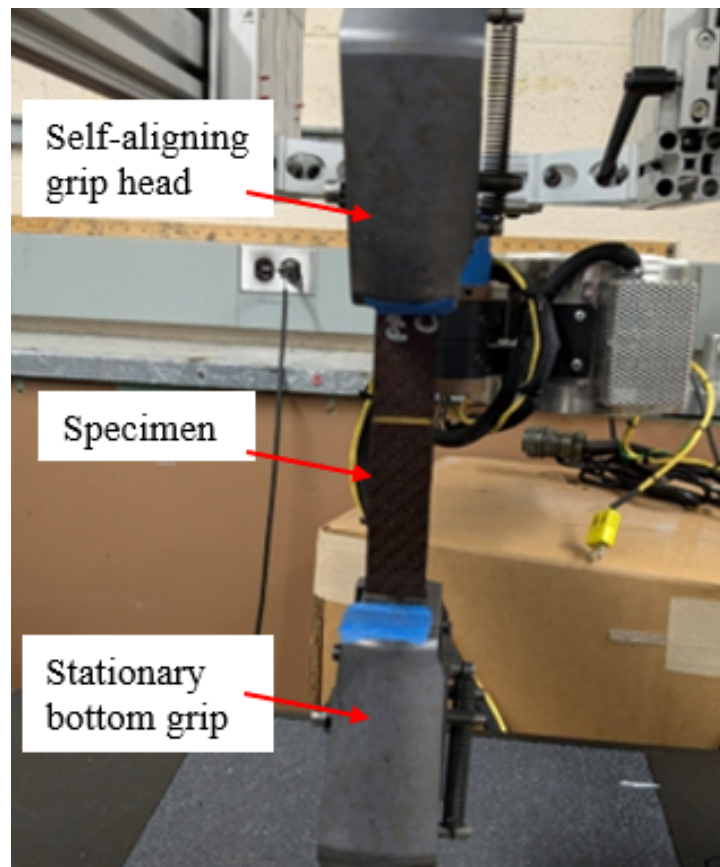


Figure 4.91 Single-lap-shear specimen loaded into test fixture prior to test.

In accordance with common practices for testing bonded lap-shear coupons, the force [kN] vs. displacement [mm] curves for each specimen were plotted in Figure 4.92.

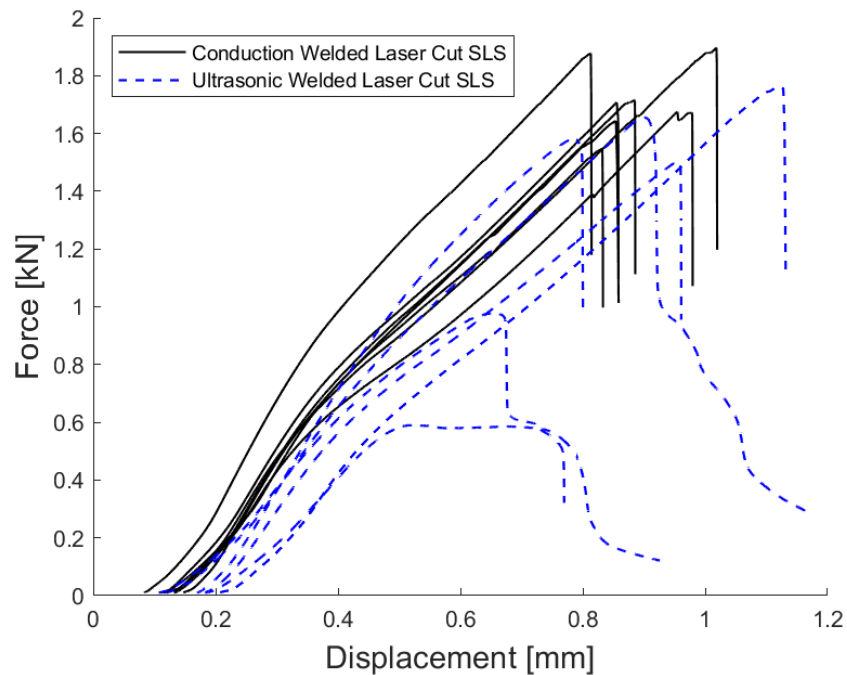


Figure 4.92 Force [kN] vs. Displacement [mm] curves for the conduction and ultrasonic welded SLS specimens.

From Figure 4.92, the ultrasonically welded SLS coupons had a similar force-to-failure to the conduction welded SLS coupons, excluding two outliers. The two outliers were not bonded and therefore broke at an unusually low force. However, this does highlight the fact that ultrasonic welding of composite coupons is difficult to replicate even if the same process parameters are used, regardless of material system.

Table 4.13 Mechanical data summary for conduction and ultrasonic welded SLS coupons. Ultrasonic SLS data is presented both including and excluding outliers (non-bonded coupons).

	Average Displacement to Failure	Average Force to Failure
Conduction Welding	1.06 mm	1.72 kN
Ultrasonic Welding (including outliers)	0.82 mm	1.34 kN
Ultrasonic Welding (excluding outliers)	0.94 mm	1.63 kN

Excluding outliers, the ultrasonically welded SLS coupons performed similarly to the conduction welded SLS coupons. The average force-to-failure and displacement were 95% and 89% that of the conduction welded coupons, respectively. This demonstrates the feasibility of joining bio-based thermoplastic composites through ultrasonic welding.

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Additional parameter and process development are required to increase bond quality and repeatability.

4.3.5.5 Failure Mode Analysis

Each conduction welded specimen failed in the adherend rather than failure at the bond line, indicating a bond strength greater than the adherend strength. Figure 4.93 illustrates the location of adherend failure as adjacent to the bonded region.

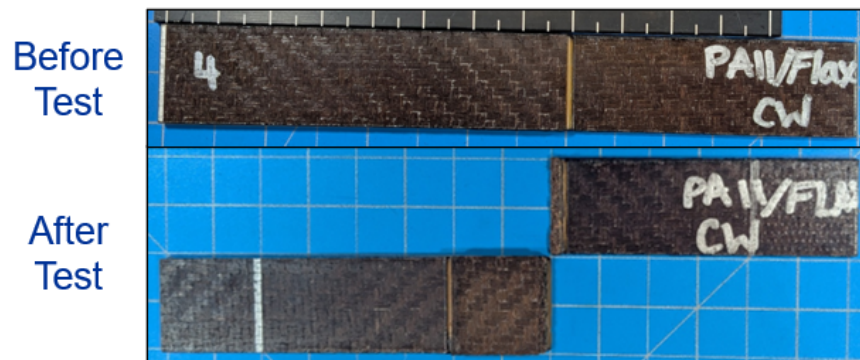


Figure 4.93 Failure of the conduction welded SLS coupons. Horizontal break occurred on edge of welding region as a horizontal break in adherend.

The failure mode of the ultrasonically welded coupons was varied. The lowest force-to-failure corresponds to specimen 2 which failed at approximately 0.6 kN. The top surface of the specimen indicates the resin only partially melted. The post-test interface of specimen 2 shows the unmelted resin at the bond line in Figure 4.94.

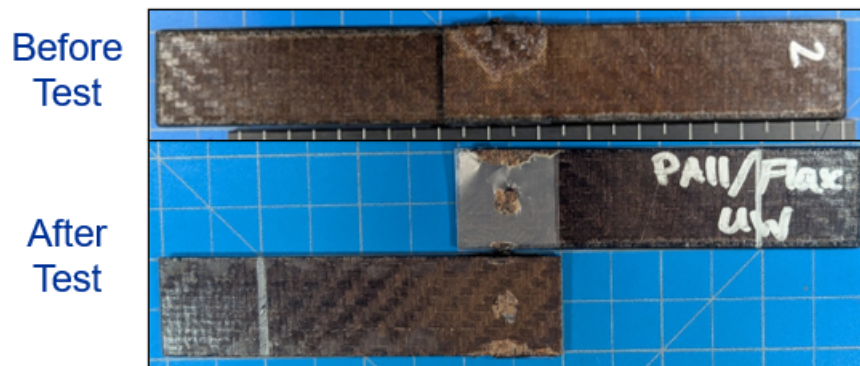


Figure 4.94 Failure surface of ultrasonic welding coupon that is not fully bonded.

Ultrasonic welding coupons, with a higher strength, failed either at the bond line through horizontal adherend breaking (left) or adhesive failure (right). These failure modes are shown in Figure 4.95.

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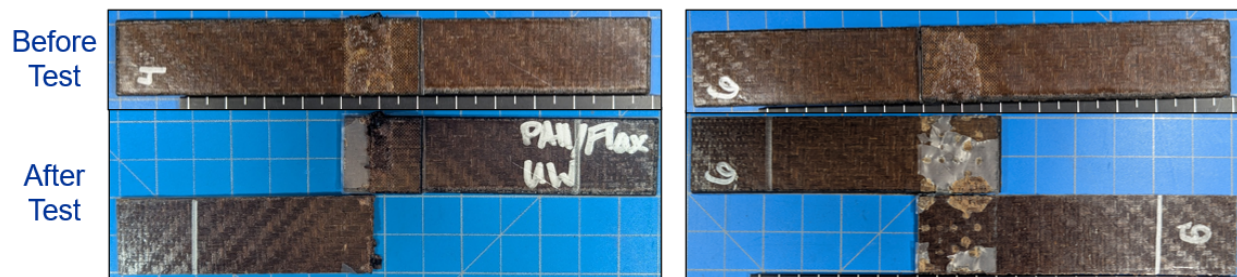


Figure 4.95 Failure surfaces of better consolidated ultrasonic welding coupons with adherend break (left) and adhesive failure (right).

As can be seen, the adherend break was located where the bonding occurred between the two composites. This is similar to the break shown in Figure 4.95 with the conduction welded coupons. However, the break occurred inside the 1 in. x 1 in. interface showing that the whole area was not bonded. Instead, failure was confined to the strip where the fracture took place. The adherends that adhesively split did not have full bonding across the entire surface but instead had small spots throughout the 1 in. x 1 in. interface which helped to distribute the load and allowed for a similar failure to the conduction welding.

4.3.6 Fabrication Demonstration

Leveraging knowledge gained throughout the manufacturing and testing procedure, the design and development of a propeller skin for an electric vertical take-off and landing (eVTOL) propulsion system was pursued. Due to time constraints, no additional mechanical or environmental testing was performed as part of this effort. Instead, emphasis was placed on optimizing layup methods and processing parameters to achieve consistent quality and scalability of parts. For each component, commingled flax braid PA11 was used due to its drapability, ease of handling, and strong mechanical performance. Although not discussed in full here, a separate technical report detailing the fabrication process of these demonstration articles will be made available.

The high-rate manufacturing facility located at NASA Ames Research Center was leveraged in conjunction with a Joby Aviation (Santa Cruz, CA) propeller mold to manufacture a representative eVTOL propeller skin of approximately 4 ft. (1.22 m) length (see Figure 4.96).

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Figure 4.96 Hot press with propeller mold at NASA Ames Research Center High-Rate Manufacturing facility.

An iterative process optimization allowed for variation in parameters including load and hold temperature, dwell time, pressure, and interface material between the mold and fabric. Due to time constraints, variations were limited by maintaining a constant number of plies and a single fiber-resin combination. The final optimized settings included 4 plies of the commingled flax braid with several additional sheets of PA11 on top and bottom. This bundle was placed between Frekote-coated Kapton films and placed in the mold at $\sim 180^{\circ}\text{C}$ (see Figure 4.97). This temperature was held for 25 minutes at ~ 300 psi (10000 kN), after which the test article was cooled under pressure before being removed from the mold.

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Figure 4.97 Propeller mold with Kapton wrapped commingled flax braid PA11 plies prepared for pressing.

One of the manufactured propeller skins is shown in Figure 4.98. A video of the manufacturing procedure may be accessed the following: [Bio-Composite Propeller Manufacturing Video](#). These fabricated skins demonstrated a successful campaign for the scalability of the natural fiber composites with strong consolidation and minimal defects. A lack of resin infusion was observed in a small edge region of the propeller skin, likely due to non-uniform pressure stemming from defects in the mold. Additionally, it is likely a temperature gradient exists between the center and edges of the mold due to its reliance on convective and conductive heating. These factors impact production quality and can be further addressed through a combination of additional layup optimization and by improving the quality of the mold and heating elements.

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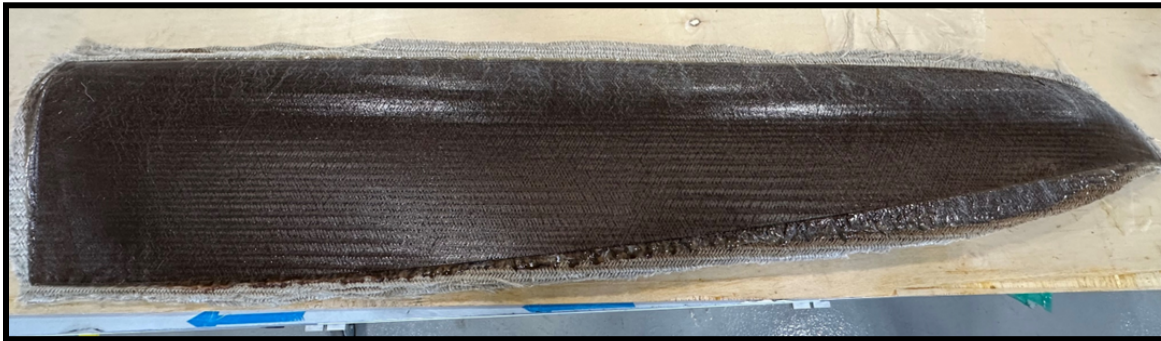


Figure 4.98 Fabricated Joby propeller skin made from commingled flax braid/PA11 composite, approximately 4 ft (1.22 m) in length.

4.3.7 Key Takeaways

- The processing window for the biobased resins was smaller than for engineered thermoplastics and all resin exhibited degradation when hold time or temperature exceeded prescribed processing constraints.
- Individual processing profiles were required for each resin and natural fiber composite system due to unique properties of the constituents
- The pressure required for consolidation was greater than require for engineered carbon fiber/thermoplastic prepreg
- The fibers used in this study were unsized and untreated leading to a poor fiber/matrix interface. This is an area of development that would greatly benefit the use of natural fibers/biobased resins
- Increasing the fiber volume fraction of these composites did not increase the strength of stiffness in either tension or compression
- Conduction and ultrasonic welding of flax/PA11 composites is feasible, with additional development work required to optimize the process parameters for ultrasonic welding.

4.3.8 References

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4.4 Integrated Sensing for Material State Awareness

4.4.1 Introduction

Natural fiber reinforced composites (NFRCs) offer a potential alternative to carbon fiber reinforced polymers (CFRPs) for some aircraft applications. They can be produced sustainably using bio-based resins and natural fibers (e.g., flax, hemp, jute), and can be efficiently decomposed or recycled at the end of life. NFRCs have advanced in the past decade and found applications in high-performance automotive components and sporting goods industries, among others [1]. However, limitations prevent broader use in the aviation industry, especially in structural applications. For example, NFRCs are susceptible to environmental degradation such as moisture and UV exposure that cause material property changes [2, 3]. They also have lower strength and stiffness than state-of-the-art CFRP.

Structural Health Monitoring (SHM) offers benefits for conventional aerospace materials by allowing reduced operating costs and weight. This is because SHM can decrease the safety margins (i.e., "knock-down factors") that engineers typically include during aircraft design to account for potential barely visible impact damage (BVID) or other undetected damage [3]. When applied to NFRCs, an SHM approach could reduce the required strength specifications for certain components. With lower knock-down factors needed, NFRCs (with SHM) could potentially replace CFRP (without SHM) while adding minimal additional weight. Sensors targeting specific degradation mechanisms associated with NFRCs are needed to fully realize their potential in aviation applications. Monitoring moisture and mechanical properties over the lifetime of NFRC parts could enable condition-based replacement and more accurate digital twins for understanding structural response to various flight conditions. El-Saggagh et al. studied the effects of humidity and stress state on the speed of sound in chopped fiber NFRCs [4] and found strong correlation between wave speed and both humidity and fiber fraction. Moisture and associated material property variation also influences the dielectric properties of materials as shown for glass fiber composites [5] and polymers [6], which offers another possibility for monitoring these materials.

The Integrated Sensing task within the SUMAC project has been exploring sensing techniques that would help to enable broader application of NFRCs. This aspect of the project is developing tailored sensing techniques that can be used to assess manufacturing quality and provide material state awareness for NFRC-specific degradation mechanisms to enable use in AAM and other emerging aerospace applications. Sensing methods are being optimized to address two primary challenges for long-term use of NFRCs, namely moisture absorption and mechanical property variation.

This work has been broken up into six sections. In 4.4.2, the methods explored for manufacturing quality control measurements are discussed. Then 4.4.3 goes over bulk ultrasonic and dielectric property assessments made both in the baseline (dried) state, and

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as a function of moisture uptake. The results show sensitivity to elastic property changes and dielectric property changes using lab-based techniques. Building on these early efforts, 4.4.4 discusses in-situ measurements made using ultrasonic guided wave sensors intended for on-aircraft elastic property evaluation. 4.4.5 discusses ongoing and future work in this area in which inverse modeling approaches will be used to extract elastic stiffness matrices from the materials as a function of moisture. 4.4.6 discusses the development of wireless moisture monitoring technologies that leverage the changes in the relative permeability reported from bulk dielectric measurements. Specifically, it discusses microwave sensing approaches being explored for both mapping moisture content and quantifying moisture uptake. 4.4.7 discusses future work in this area, where the team is exploring advanced frequency selective surface (FSS) configurations and using computational modeling to optimize sensors for this application. This work is the first step toward optimization and design of a sensing architecture for monitoring NFRCs in service. Such a sensing architecture could make NFRCs viable and cost-effective alternatives to conventional aerospace materials in some applications.

4.4.2 Exploration NDE Approaches for Natural Fiber Composites

The Integrated Sensing task was led by the NASA LaRC Nondestructive Evaluation Sciences Branch (NESB). NESB's breadth of expertise in various NDE methods was leveraged to address challenges with manufacturing quality control during early production SUMAC materials. Due to the unique properties of NFRCs relative to other composites (e.g., high acoustic attenuation and water absorption), standard quality control processes using ultrasonic immersion testing are infeasible. As an alternative, air-coupled ultrasonic inspections were explored using low-frequency transducers capable of penetrating through the attenuative composite materials. A pair of 500kHz focused air-coupled ultrasonic transducers were used to inspect a panel of braided flax-PA11 (or Rilsan) composite embedded with Teflon inserts of various sizes to simulate delamination (Figure 4.99). While the air-coupled ultrasonic results showed sensitivity to embedded flaws, it lacked the detail needed to resolve fiber orientation and other fine features of interest to the manufacturing team.

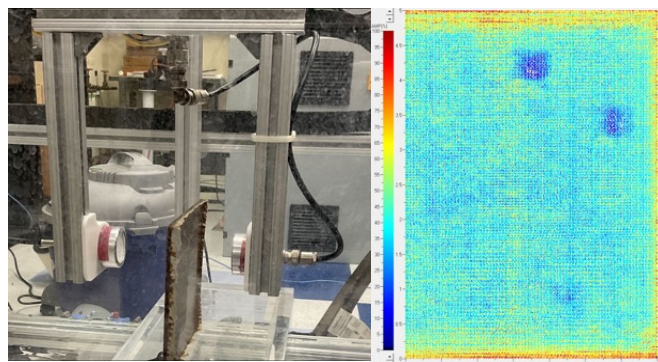


Figure 4.99 Air coupled ultrasonic inspection of a flax-PA11 panel with embedded Teflon inserts (Left). The amplitude C-Scan (Right) showed indications from flaws of various sizes, but a lack of resolution of the fiber structure within the material.

Other approaches considered for inspection included electromagnetic techniques (THz and microwave inspection) and thermography (Figure 4.100). Electromagnetic techniques worked especially well due to low electrical conductivity in the NFRCs relative to carbon-

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based composites. A range of electromagnetic frequencies were considered for inspection, including those in the microwave range (1-50 GHz) and those in the THz range (0.5-1.5 THz). Higher frequency THz inspections provided the best resolution to fiber structure, while lower frequency microwave inspections showed enhanced sensitivity to moisture uptake as well as more rapid inspection results.

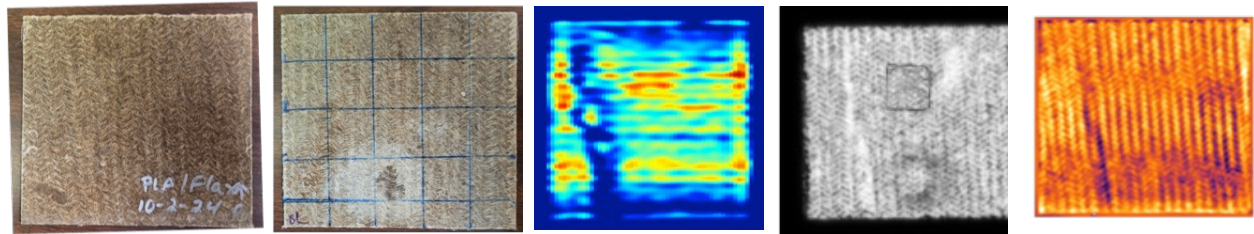


Figure 4.100 Example NDE inspection performed on a braided flax/PLA composite early in the manufacturing process. From left to right: Images of the front and back of the composite panel; Microwave NDE image of the composite panel showing a region of irregularity aligned vertically on the left side of the panel; THz image of the same composite panel showing the same region of irregularity as well as highlighting the fiber structure, resin loss at the bottom of the panel, and an area where Kapton tape was placed on the surface; Principal Component Analysis (PCA) image collected from flash thermography data collected on the same panel showing same region of irregularity and some spatial variation in thermal conductivity.

4.4.3 Characterizing Moisture-dependent Properties in Natural Fiber Composites

The long-term goal of the Integrated Sensing task was to develop sensing technologies that provide the material state awareness data required to address unique challenges associated with NFRCs. The first step toward developing sensing approaches was to characterize the material properties that are relevant to the sensing modes of interest, and to determine how those properties change in the operating environment. Dielectric and acoustic properties were the focus of this analysis since early brainstorming by the Sensing team identified ultrasonic and electromagnetic techniques as the most promising candidates for monitoring elastic property changes and moisture uptake in natural fiber composites.

4.4.3.1 Experimental Methods

Materials: Flax fiber composite laminates were produced at NASA Glenn Research Center using three different bio-derived thermoplastic resins – Pond Global bio-based Pond Cycle IMF 101 HT polylactic acid (PLA), Mango Materials YOPP ST-101 poly-3-hydroxybutyrate (PHB), and Arkema Rilsan bio-based Polyamide11 (PA11)¹. Resin sheets were laid up with

¹ Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the methods used in this study. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified material/equipment is the best available.

fiber mats at a mass ratio of approximately 1:1 and were pressed using parameters optimized for each material system. For the PLA and PHB laminates, eight layers of a 2x2 twill of flax (Bcomp Ltd.) were used as the fiber reinforcement. For the PLA composites, laminates were preheated without pressure for 15 min at 380°F, then pressed at 278 psi at 380°F for 10 minutes, pressed at 556 psi at 380°F for 5 minutes, and slowly cooled to room temperature. For the PHB composites, laminates were preheated without pressure for 10 min at 370°F, pressed at 222 psi at 370°F for 10 minutes, pressed at 444 psi at 370°F for 10 minutes, and then slowly cooled to room temperature. For the Rilsan PA11 composite, 6-layers of braided flax fiber (A&P Technology) reinforcement was used. The material was preheated for 30 minutes at 248°F, then pressed at 100 psi at 410°F for 30 minutes, and allowed to slowly cool to room temperature. Square 0.75" x 0.75" coupons were cut from each material using a laser cutter. The edges of the specimens were sealed with epoxy prior to environmental exposure.

Dielectric Measurement: Dielectric properties of NFRC coupons were measured using an Agilent 4192A LF impedance analyzer and Agilent 16451B dielectric test fixture (Figure 4.101a). For each test, specimens were placed on the bottom plate of the test fixture and centered. The top electrode was placed on the surface and was tightened to a preset torque level for the fixture. A logarithmic sweep was performed from 1kHz to 13MHz while recording capacitance. The dielectric constant was calculated from capacitance, C , as

$$\epsilon'_r = \frac{tC}{\pi \left(\frac{d}{2}\right)^2 \epsilon_0} \quad (4.9)$$

Where ϵ'_r is the dielectric constant, t is the thickness of the test coupon, d is the diameter of the guarded electrode, and $\epsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of free space. The right side of Figure 4.101b shows a schematic of the capacitance measurement configuration. Figure 4.101c shows baseline dielectric measurements for Flax-PHB twill, Flax-PLA twill, and Flax-PA11, which were calculated as described previously.

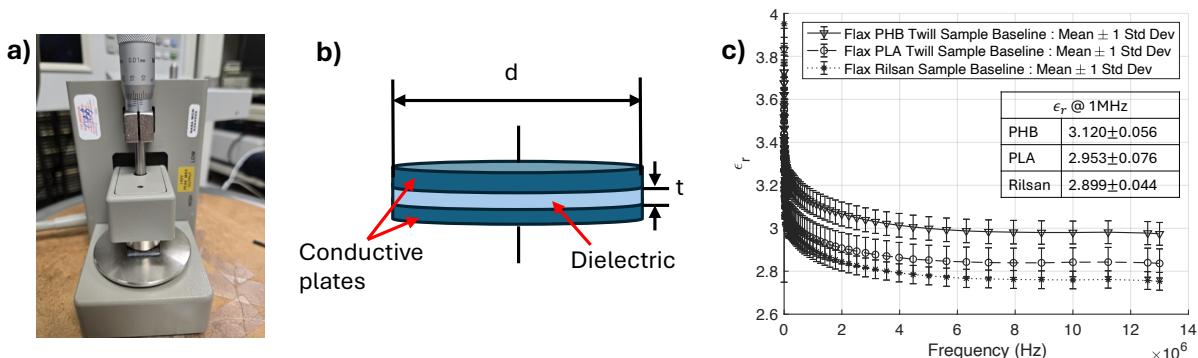


Figure 4.101 Dielectric test fixture used during the measurement for measuring capacitance. (b) Schematic showing key parameters associated with calculating relative permittivity from capacitance. (c) Results from dielectric property measurements for PHB, PLA, and PA11 composites.

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Ultrasonic Measurement: Ultrasonic measurements were made using a pair of 500 kHz transducers coupled to the samples using Aqualene dry couplant. The transducers were excited with a 500 kHz tone burst using a Ritec RAM-5000 high-power ultrasonic instrument and data was captured using an oscilloscope. The received waveforms were enveloped using a Hilbert transform, and the amplitude and time of arrival of the peak of the envelope were measured. Data was also collected for a reference measurement taken with only the dry couplant and no sample present (Figure 4.102).

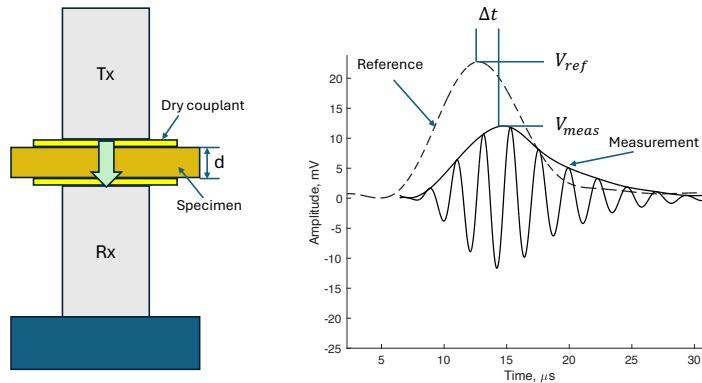


Figure 4.102 Ultrasonic measurement process. (Left) Illustration of the experimental setup showing the transmitter (Tx), receiver (Rx), polymer dry couplant, and specimen. (Right) Representative data showing the measurement signal, the signal envelope, and the envelope of the reference signal collected without the specimen present.

The relative change in peak time of arrival and amplitude between the reference and specimen measurement were used to calculate relative wave speed and attenuation metrics as

$$c_{rel} = \frac{d}{\Delta t}, \quad \alpha_{rel} = \frac{1}{d} \ln \left(\frac{V_{meas}}{V_{ref}} \right) \quad (4.10)$$

where d is the specimen thickness, Δt is the difference in peak time of arrival between reference and measurement signals, V_{meas} is the peak amplitude of the measurement signal, and V_{ref} is the peak amplitude of the reference signal.

Accelerated Environmental Exposure: Dielectric and ultrasonic measurements were made as moisture was absorbed during accelerated aging experiments. The experimental setup consisted of a temperature control chamber that was fed compressed air bubbled through a Erlenmeyer flask of distilled water. The resulting condition inside the chamber was approximately 99% relative humidity and 77°F. Coupons were placed in the chamber for a period of 1 week and were then allowed to dry outside of the chamber for a period of 1 week in a desiccator at room temperature (approximately 72 °F).

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The dielectric and acoustic properties of each material were measured daily along with their thickness and weight. In addition, the density was calculated in the dry state using weight and volume measurements of materials cut from the same region as the coupons. The effective density as a function of moisture content was calculated by assuming that any change in volume was due to the addition of water in the microstructure.

4.4.3.2 Results

Figure 4.103 shows moisture absorption in the NFRC coupons versus cycle of exposure for Flax-PHB twill, Flax-PLA twill, and Flax-PA11, presented as both percentage weight gain from water uptake (left) and thickness strain (right). Water uptake of up to 20% was observed in the PLA composite, with the PHB gaining approximately 15%, and the PA11 gaining the least moisture at 5%. These relatively high values of moisture uptake are attributed to composite samples fabricated during the initial stages of process development, prior to optimization. It should be noted that the moisture uptake results presented in Figure 4.11 (flax-PA11) and Figure 4.112 (flax-PHB) correspond to composites manufactured using the optimized fabrication process. The thickness strain measurements follow similar trends, with maximum values reaching about 25% for PLA. Swelling in the thickness-direction was observed in proportion to the increase in moisture. All specimens retained approximately 2% moisture after moisture exposure and several cycles of drying, but varying levels of residual strain remained, with the most being observed in the PLA indicating potential irreversible swelling in the microstructure.

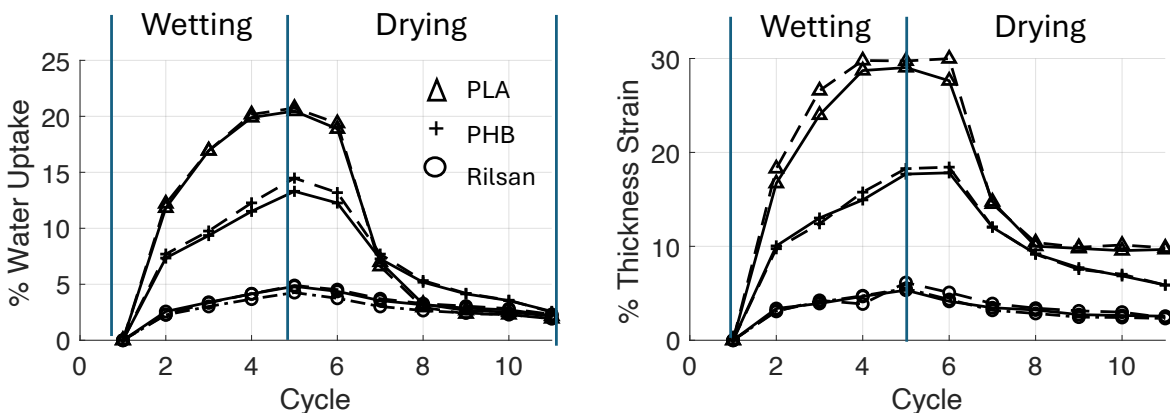


Figure 4.103 Wetting data for NFRC specimens subjected to one week of humidity exposure (Wetting) followed by one week of drying in a desiccator (Drying).

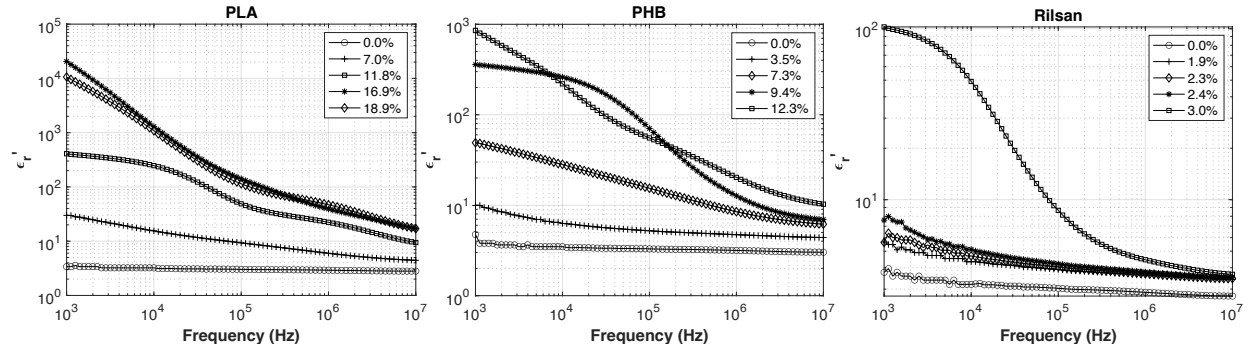


Figure 4.104 Frequency dependent dielectric constants measured for flax composites having PHB (Left), PLA (Middle) and PA11 (Rilsan) (Right).

The dielectric constant as a function of frequency is displayed in Figure 4.104, which mostly increased with moisture over the whole frequency range for all three material systems with some exceptions. The growth in dielectric constant measured at 1 MHz showed generally a nonlinear trend (Figure 4.104). The volume percentage of water was related to theoretical models representing the water and the composite material as capacitors in series or in parallel [6]. The volume percentage of water in the microstructure was calculated assuming that increased mass due to water absorption (Δm) lead to an increase in volume, (ΔV), given as $\Delta V = \Delta m / \rho_w$, where ρ_w is the density of water. The resulting dielectric constant under the series and parallel capacitance approximations, are given, respectively, as

$$(\epsilon_r)_{Series} = \frac{\epsilon_w \epsilon_{Comp}}{\frac{\rho_{Comp}}{\rho_w} \phi_w^m \epsilon_{Comp} + \left(1 - \frac{\rho_{Comp}}{\rho_w} \phi_w^m\right) \epsilon_w} \quad (4.11)$$

$$(\epsilon_r)_{Series} = \frac{\epsilon_w \epsilon_{Comp}}{\frac{\rho_{Comp}}{\rho_w} \phi_w^m \epsilon_{Comp} + \left(1 - \frac{\rho_{Comp}}{\rho_w} \phi_w^m\right) \epsilon_w} \quad (4.12)$$

where ϕ_w^m is the mass fraction of water in the material and ρ_{Comp} is the density measured for each material system in the baseline state while ϵ_w and ϵ_{Comp} are the dielectric constants measured at 1 MHz for water and the dry composites, respectively. The result of these models is also shown in Figure 4.105.

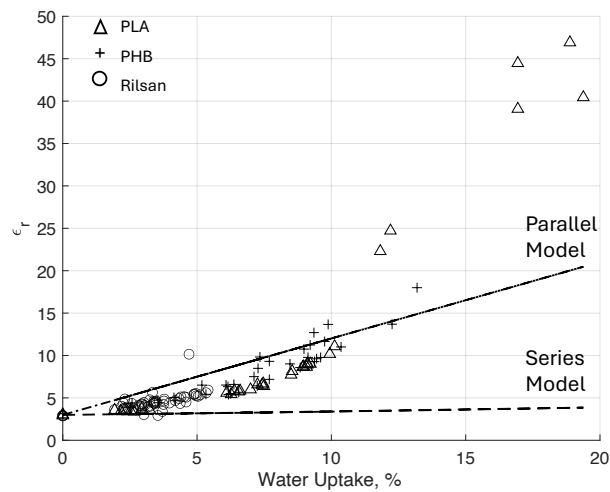


Figure 4.105 Dielectric constant measured at 1MHz as a function of percent volumetric moisture uptake of water overlaid with series and parallel equivalent capacitance approximations.

The data in Figure 4.105 follows most closely with the parallel capacitance model, indicating uniform distribution of moisture within the microstructure rather than more localized at edges or within the microstructure [6]. This is especially true for the PHB material, while the PLA material seems to exhibit much larger change in dielectric constant than predicted by either model at relatively higher moisture levels.

Ultrasonic measurements on the samples also showed significant change as a function of moisture uptake. The signal envelope from measurements taken for each of the NFRC materials at varying moisture levels is shown below in Figure 4.106. A clear reduction in the peak amplitude and increase in the peak time of arrival is observed as the moisture level increases. This trend is shown more directly in Figure 4.107, which is a plot of moisture exposure, in number of cycles, versus wave speed and attenuation of the ultrasound signal.

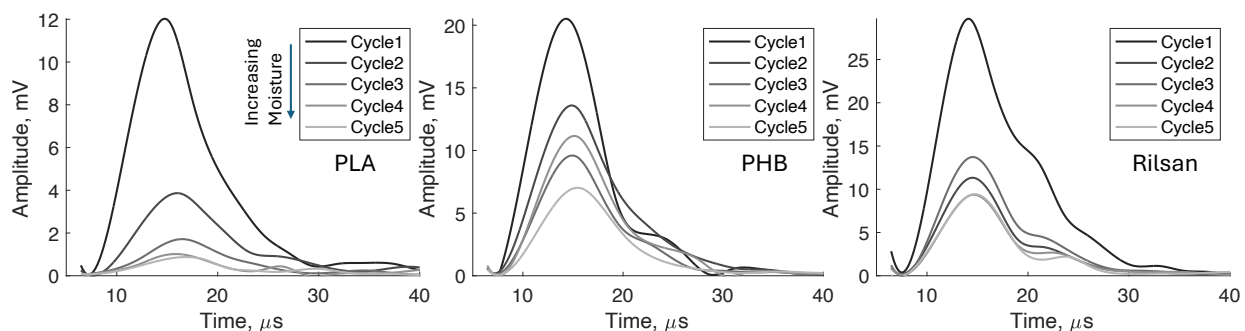


Figure 4.106 Ultrasonic signal envelopes during the first five wetting cycles. Each shows a reduction in amplitude and increase in peak time of arrival as moisture increases. (Left) PLA, (Middle) PHB, and (Right) Rilsan PA11.

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As the material absorbed moisture, attenuation increased significantly, and the speed of sound decreased. Wave speed is influenced by both the increased density as water is absorbed and potential reduction in Young's modulus previously reported for NFRC materials exposed to moisture [2].

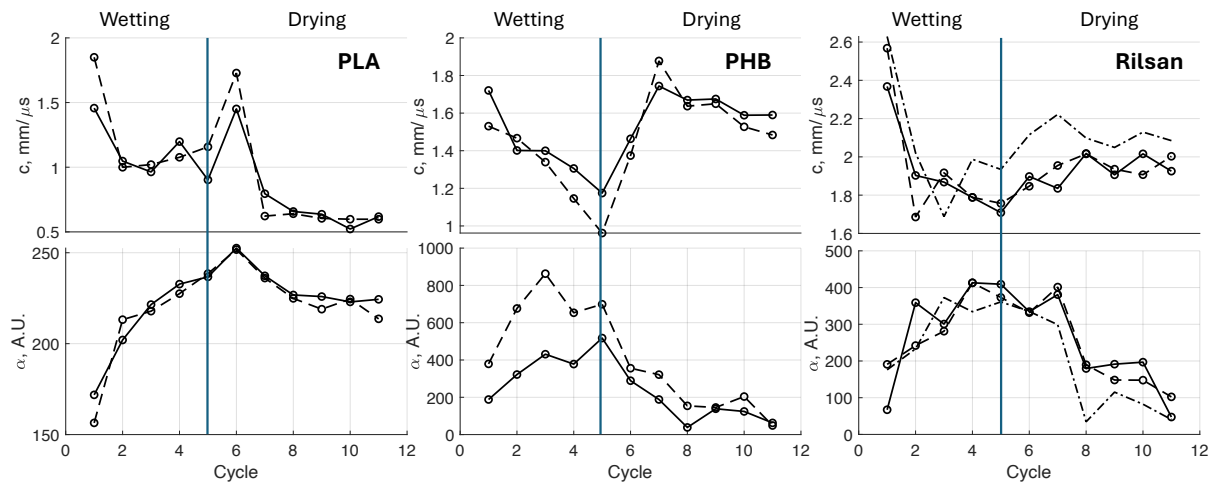


Figure 4.107 Relative wave speed and attenuation throughout the accelerated moisture exposure and drying cycles.

The effective change in Young's modulus in the direction of wave propagation can be estimated assuming conservation of volume and the relationship between the wave speed, Young's modulus, and density, ρ given by

$$c = \sqrt{\frac{E}{\rho}} \quad (4.13)$$

Approximations for the Young's modulus calculated by rearranging Equation (4.13) (Figure 4.108) show values that are close to those reported for natural fiber composites in the dry state [3]. Reduction in Young's modulus of as much as 80% in PLA and 50% in the PHB and Rilsan composites are observed. While such large changes in properties could be due to damage in the microstructure [12], it is also possible that there are changes in bulk density caused by fiber swelling that is not accounted for under the assumptions applied in these calculation (i.e., that only moisture changed the material's density).

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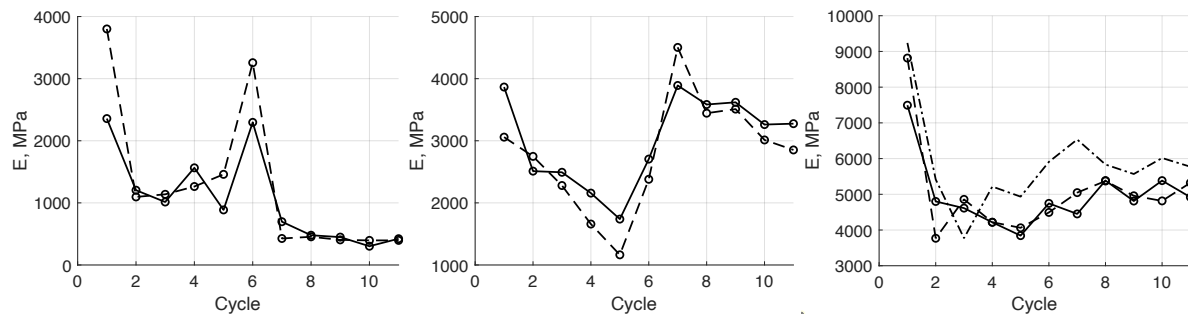


Figure 4.108 Young's modulus, E , approximated from ultrasonic data throughout the accelerated aging experiment.

4.4.3.3 Discussion

The work presented here is a necessary first step toward development of surface-mounted sensors for monitoring degradation in NFRCs. It is shown that dielectric and acoustic properties are both sensitive to moisture uptake. The dielectric constant measured for these materials increases at a rate that is closest to the parallel capacitance mixture model, indicating a more even distribution of moisture than has been observed for some polymers [6]. In the flax-PLA material the increase is greater than the parallel capacitor model at the highest moisture levels. Further study of the chemical composition and microstructure of the aged flax-PLA is needed to determine the underlying cause of the high changes in dielectric properties.

Acoustic properties change significantly as NFRC materials are wetted and dried. All materials studied had an increase in attenuation and decrease in wave speed with moisture uptake. For the PHB and Rilsan-based composites, changes in properties were mostly reversible, while the PLA showed irreversible and significant change, especially in wave speed. Due to the high levels of moisture uptake and brittle nature of PLA resin observed during manufacturing, irreversible change in wave speed could be due to resin cracking caused by fiber swelling in the matrix and increased void content around the fibers after drying [3].

In addition, dielectric measurements made on these materials feed directly into this goal by providing input into simulations aimed at optimizing printed sensors that are under development. Likewise, the bulk wave ultrasonic measurements aid in developing an understanding of the impacts of moisture on the acoustic response (e.g., the level of attenuation observed at high levels of moisture) as well as providing an initial assessment of the sensitivity of ultrasonic approaches to the magnitudes of elastic property variation that may be expected in service. Both the dielectric moisture sensing and guided wave based ultrasonic material property characterization will be pursued in future work.

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4.4.4 In-Situ Measurement of Moisture-dependent Properties

Building on measured changes in the acoustic and dielectric properties of NFRCs following moisture exposure, experiments were conducted to measure moisture-induced property changes using sensors applicable to in-service monitoring. In plate-like composite structures, surface guided ultrasonic waves, or “guided waves”, are ideal for broad area monitoring. Guided waves are vibrational modes excited in plates subjected to local surface vibration (e.g., from an ultrasonic transducer on the surface). Unlike bulk ultrasonic waves, guided waves are dispersive, meaning that multiple different wave modes are excited at different frequencies and their speed is a function of frequency. The dispersive behavior of the material is complex and is influenced by the elastic stiffness matrix of a material, making this measurement method ideal for tracking the moisture-dependent changes in elastic properties that have been reported for NFRCs [1]. Guided wave measurements have been used to characterize natural fiber materials using a shear deformable plate theory analysis [7], and more recently has been used extensively with a more robust frequency wavenumber analysis and model inversion to characterize damage on the basis of changes in elastic constants [8]. The goal of this work would be to track changes in the elastic properties as a function of time. As a starting point, changes in the wave speed of a specific wave mode at a specific frequency was analyzed to assess sensitivity to moisture-induced changes.

4.4.4.1 Experimental Methods

Experiments were conducted on Bcomp Flax twill/PHB laminates manufactured by the Manufacturing team at GRC as described in the section above. A set of seven 5.5” x 5.5” coupons were laser cut from two 12” x 12” Bcomp Flax/PHB panels. After laser cutting, the specimen edges were sealed with epoxy to minimize water uptake at the edges. The specimens had a piezoelectric wafer active sensor (PWAS) bonded to the lower right corner at a distance of 1” from the bottom and right edge (Figure 4.109). The PWAS on each specimen was excited during experiments using a 5-cycle sinusoidal tone-burst at 50kHz. The resulting guided wave propagation was measured using a laser doppler vibrometer (LDV) positioned above the panel. Line scans were taken with the LDV starting at a distance of 1” from the PWAS transmitter and moving at 0.1” increments to a total distance of 2” from the PWAS. The results below are for line scans conducted along the 0 degree direction, defined as the vertical edge of the laminate in Figure 4.109.

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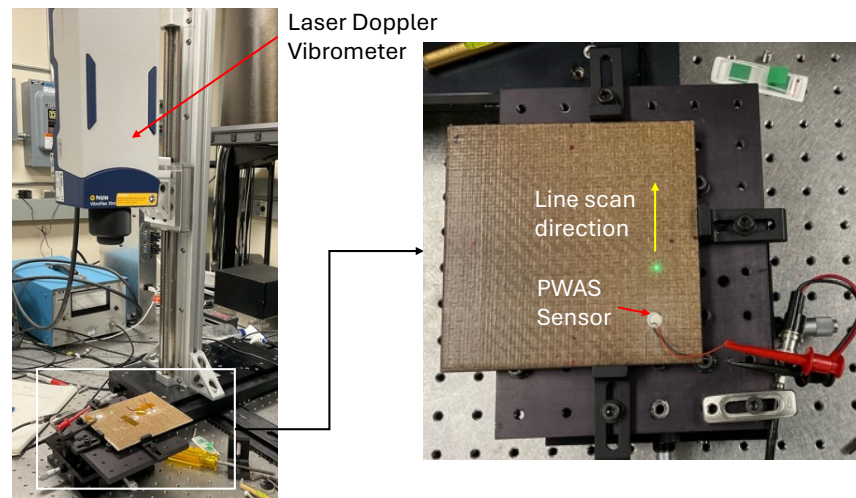


Figure 4.109 Setup for guided wave line scans on the Flax/PHB composite panels. (Left) A laser doppler vibrometer (LDV) is positioned above the composite panel during measurement. (Right) Close-up view of the composite panel on the rotating test stage. A surface bonded PWAS sensor excited vibration in the panel and the vibration is measured along a line by the LDV.

Ultrasonic time-domain data was collected at each scan point and stored in a data array for post processing in Matlab. From the received waveform at each scan point, the time at which the ultrasonic signal exceeded a threshold of 20% of its maximum was recorded, as was the maximum amplitude of the signal recorded at a distance of 1.5" from the PWAS sensor, and the time location of the first three peaks of the wave packet (Figure 4.110- Left). The group velocity (the speed at which the entire wave packet is traveling) and the phase velocity (the speed at which specific phase points like peaks or zero crossings are traveling) could be calculated by tracking the time of arrival of either the threshold crossing (for group velocity) or the peaks (for phase velocity) as a function of the scan location. A linear fit applied to this data was used to extract a velocity illustrated below (Figure 4.110-- Right).

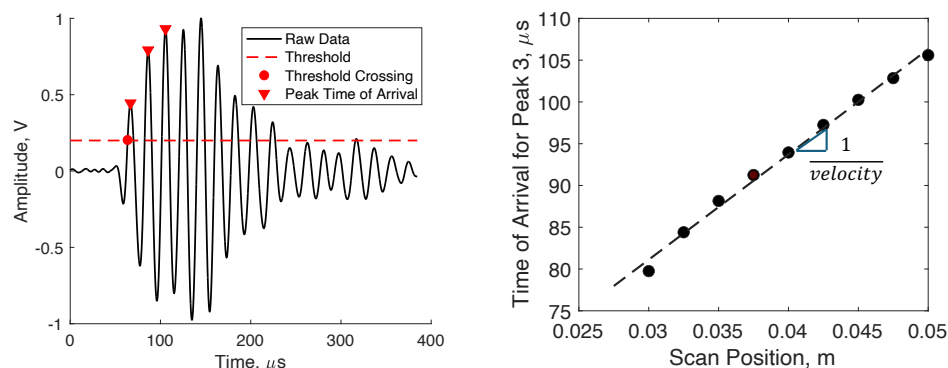


Figure 4.110 Illustration of guided wave processing. The threshold was set on raw data collected at each scan point (Left). The time at which the threshold was crossed and the time of arrival of multiple

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peaks in the wave packet were tracked as a function of location. The linear fit to the time of arrival versus scan position data (Right) enabled robust extraction of wave speed, c , from the data.

Controlled environmental exposure experiments were used to assess changes in guided wave response as a function of moisture content. All specimens were first dried in a vacuum oven at a temperature of 40°C and a vacuum pressure of 35 in Hg. The specimens were then weighed using a mass balance, their average thickness was calculated from four measurements along the perimeter of the specimens, and their width and height were measured. Each time the specimen weight and dimensions were measured ultrasonic measurements were also made using the protocol described above. Six of the seven specimens were placed in a Thermotron chamber at 85% RH and 29.4°C for one month during the experiment. The environmentally exposed specimens were inspected daily along with a single reference specimen that remained in a desiccator throughout the experiment. Moisture uptake rates and deformation in the specimens throughout testing were calculated using the measured mass and dimensions. Specifically, the percentage of moisture uptake was calculated from the relative change in mass while deformation was measured using linear strain metrics in the width, height, and thickness directions.

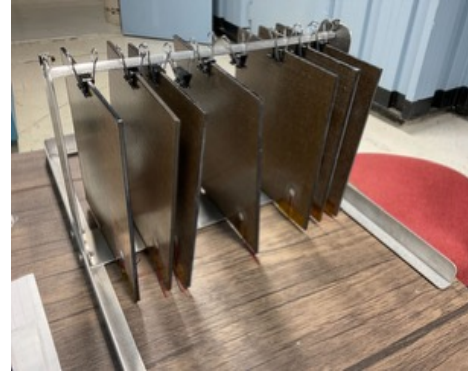


Figure 4.111 Specimens prepared for moisture exposure in the Thermotron chamber following drying in the vacuum oven.

4.4.4.2 Results

The environmentally exposed specimens showed a rapid initial uptake in moisture, which plateaued after approximately one week into the experiment. The maximum level of moisture uptake observed for any specimen was approximately 6%. Deformation in the specimens occurred primarily in the thickness direction, with a maximum thickness-direction strain (ϵ_{zz}) of 8%, while maximum strains in the height and width directions were on the order of 0.1%.

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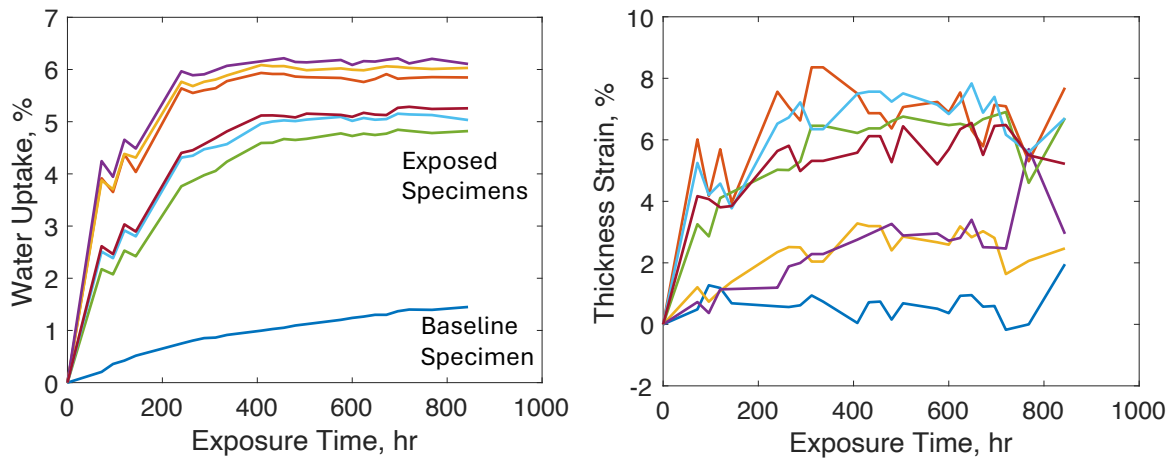


Figure 4.112 (Left) Moisture uptake in the specimens calculated as the percentage of mass change from the dried state. (Right) Strain in the thickness direction as a function of exposure duration.

Phase velocity, group velocity, and amplitude at 1.5" propagation distance are given below in Figure 4.113. The results in Figure 4.113 show consistent and significant change in the phase velocity with a strong correlation with moisture uptake. Similarly, the group velocity appears to change significantly with moisture uptake, but with more variability and less overall change than observed in the phase velocity. The amplitude recorded at 1.5" from the PWAS sensor shows some reduction as the moisture level in the specimens increases, but the correlation with moisture content is less clear.

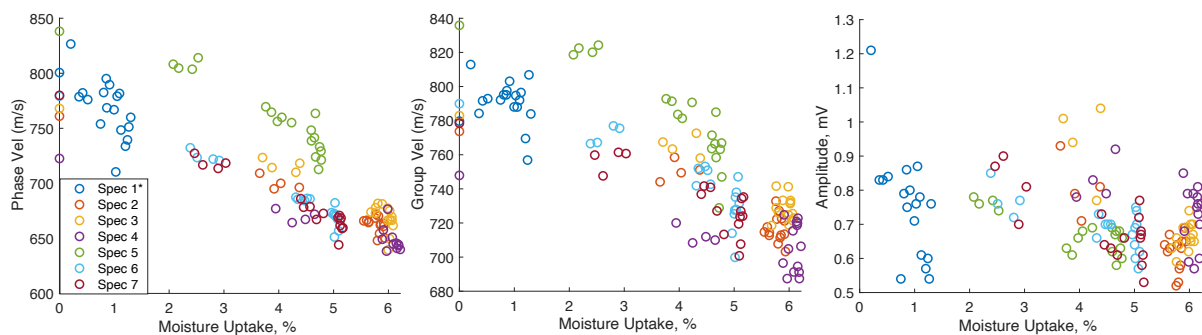


Figure 4.113 Results from guided wave line scans of the flax/PHB composite subjected to controlled moisture exposure. Note that, in all results, Specimen 1 was not exposed to elevated temperature/humidity conditions. (Left) Phase velocity as a function of moisture uptake showing a strong negative correlation between phase velocity and moisture. (Middle) Group velocity as a function of moisture showing a negative correlation with moisture, but also significant scatter in the data. (Right) Amplitude measured at 1.5" from the PWAS transmitter as a function of moisture. While some decrease in amplitude is observed, the trend is not clear.

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The results from guided wave velocity measurements show sensitivity to moisture uptake, but it should be noted that material thickness also affects phase velocity. However, initial analysis during experimental setup showed that the fundamental antisymmetric, or A0, wave mode is what is being excited and measured. At low frequencies the phase velocity of the A0 mode is roughly proportional to the square root of thickness. For a thickness increase of 8% (Figure 4.113– Right), we expect a ~4% increase in wave speed if there were no other changes in properties. So the total change in phase velocity due to moisture-induced changes in the elastic constants is likely larger than measured here. Accounting for thickness variation in future work will enable better quantification of elastic property changes.

4.4.5 Model Inversion for Elastic Property Characterization from Guided Wave Data

Since the material anisotropy of NFRPs produces directionally varying wave propagation characteristics (group velocity, phase velocity, wavelength, etc.) that change with material and damage state, a full stiffness matrix characterization can provide diagnostic information to gauge vehicle health. A full anisotropic material characterization provides better understanding and higher sensitivity to signals that relate to defects or material state changes. There has been a significant body of work characterizing mechanical properties in anisotropic carbon fiber reinforced composites, for example [9-13]. In contrast, mechanical characterization of NFRCs has received little attention despite challenges from high attenuation, environmental influence on mechanical properties, and propensity for heterogeneity.

Presented here is a modeling pipeline with verification and validation for the use of ultrasonic guided waves to characterize NFRP anisotropic stiffness matrix. The methodology for stiffness matrix characterization was approached via the way directional dependence of wave propagation relates back to stiffness matrix components. In a flight vehicle, such material property characterization may be performed by placing piezoelectric transducers at known distances and varying propagation angles within a region of interest, such as a likely location of emerging damage or in a sparse area coverage approach. Prior to deployment in a vehicle or for offline analysis, further line scan or full-field measurements may be obtained via scanning LDV for detailed guided wave propagation characterization.

4.4.5.1 Methods

The material model used for woven NFRPs was orthotropic, with nine independent components: three elastic moduli (E_1 , E_2 , E_3), three shear moduli (G_{23} , G_{31} , G_{12}), and three Poisson ratios (ν_{23} , ν_{31} , ν_{12}). To characterize anisotropic material properties, we needed: (1) experimental data at a sufficient number of propagation angles, (2) a forward model capable of simulating ultrasonic guided wave propagation at these angles, (3) a post processing methodology capable of producing wave propagation metrics from experimental and simulated data, and (4) an inverse modeling driver that minimizes residuals between experimental and simulated propagation metrics.

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For experimental data, we acquired LDV line scan data on the Bcomp Flax Twill/PHB laminates previously described in Section 4.4.4.1, again using a PWAS for excitation. A linear chirp function was used to excite across a broadband frequency range: $A(t) = A_0 \sin(2\pi f(t) * t)$, $f(t) = \frac{f_1 - f_0}{T}t + f_0$ where $A(t)$ is the voltage with peak amplitude A_0 , f_0 is the start frequency, f_1 is the end frequency, and T is the duration of the sweep. The chirp was excited over a 100 μ s duration between 50-300 kHz. Six LDV line scans were acquired at 15-degree increments, each line scan 37.4 mm in length with 0.2 mm spatial discretization. Using the symmetric S_0 and antisymmetric A_0 wave mode in each line scan, we may obtain 12 parameters to support characterizing the 9 orthotropic stiffness matrix components.

Wavenumber (with units in cycles per meter) was chosen as a propagation metric due to its ability to measure aggregate propagation characteristics across a region. To obtain wavenumber values, we followed a standard approach [14], applying a 2D fast Fourier transform (FFT) to the LDV out-of-plane velocity data $v_z(x, t)$ with a Tukey window function and a taper length parameter α via $w(x, t; \alpha)$. That is, $V_z(k_x, f) = FFT(w(x, t; \alpha) * v_z(x, t))$. We plot $|V_z(k_x, f)|$ to obtain a 2D amplitude map of wavenumber k_x with frequency, where peaks which may be connected to obtain wave modes within a dispersion curve.

4.4.5.2 Results

Figure 4.114 shows an exemplary LDV chirp response (Figure 4.114a) and wavenumber amplitude (Figure 4.114b). A monotonically increasing wavenumber may be seen across the measurement frequency range, associated with the A_0 wave mode which has out-of-plane dominant amplitude (in line with the LDV, which picks up out-of-plane velocity). Characteristic peaks and valleys across frequency are observed, typical of a finite transducer effect where wavelengths constructively and destructively interfere with the diameter of the PWAS.

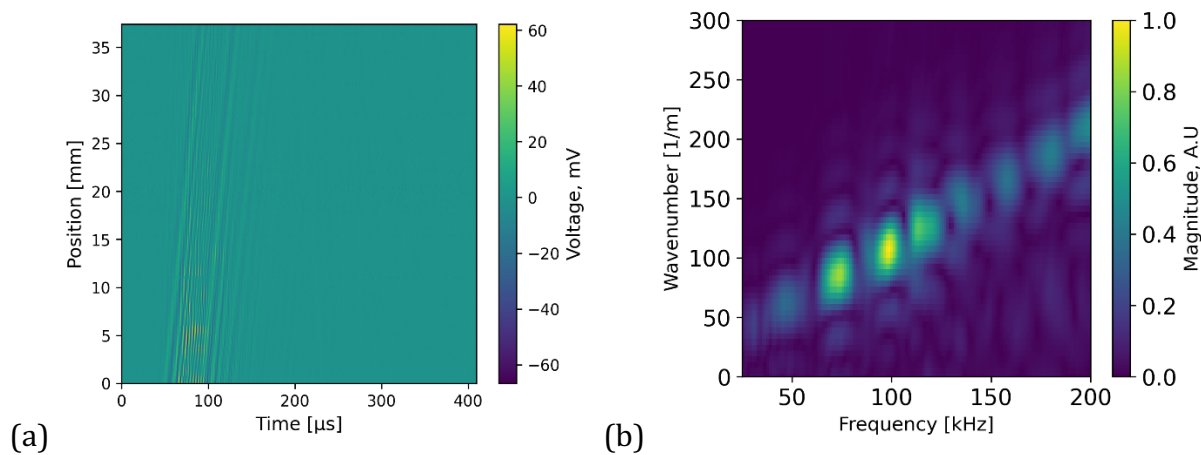


Figure 4.114 (a) Chirp response of Bcomp Flax Twill/PHB LDV line scan taken at 45 degrees, and (b) frequency-wavenumber results showing an upwards trend of peak FFT magnitude across frequency due to an out-of-plane dominant A_0 wave mode.

Next, a forward ultrasonic guided wave model was created to estimate wavenumber dependence on propagating angle. Initially a semi-analytical finite element (SAFE) method was assessed, since this method runs relatively fast and is a common forward model for optimization tasks. However, for computational speed we pivoted to a 3D finite difference model PanNDE [15]; previous optimization work meant that the 3D finite difference model ran in under 5 minutes per set of elastic constants across a sweep of propagation angles. Figure 4.115 shows simulated wave propagation and a wavenumber amplitude map, using a CFRP test case made from IM7-8552 [16]. Since the 3D wavenumber plot involves an additional dimension (k_x and k_y directional wavenumbers), wavenumber peaks were converted to polar coordinates and sampled at 15-degree increments to correspond to the line scan data.

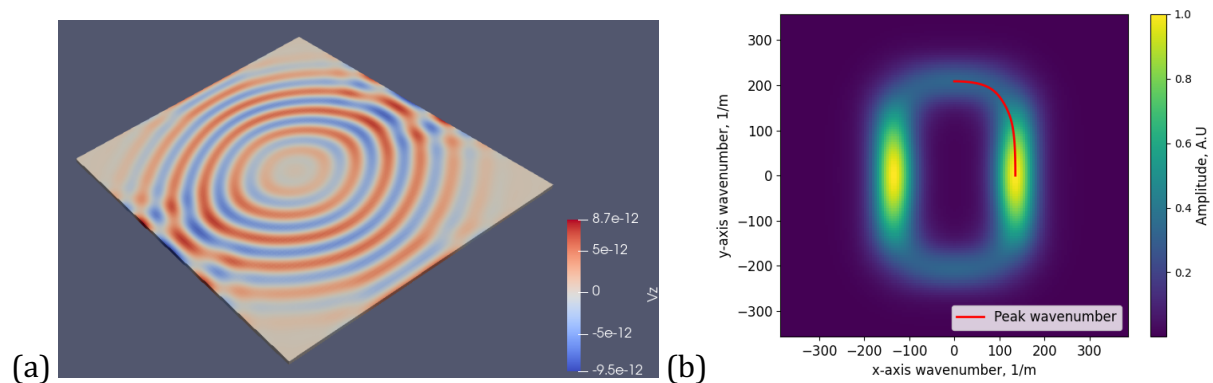


Figure 4.115: Optimization pipeline verification and validation case using IM7-8552 CFRP. (a) Time-domain snapshot of out-of-plane velocity wavefield (in arbitrary units) rendered in ParaView, (b) wavenumber plot with peak A_0 mode wavenumber plotted in a red line between 0 and 90 degrees.

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The verification and validation work, and the modeling pipeline is complete. The forward model has been linked with parametric exploration and inverse modeling software Dakota developed by Sandia National Laboratories. The pipeline uses the sum of squared residuals between simulated and experimental wavenumber metrics for each line scan as an objective function. And, the pipeline is staged to find the optimized material properties by minimizing this objective function. Plans for future work involve demonstrating how a nondestructive material characterization procedure will work for heterogeneous and highly attenuative NFRPs, with the procedure and pipeline remaining as capabilities applicable across a variety of material systems.

4.4.6 Demonstration of Frequency Selective Surface (FSS) enhanced Moisture Sensing

Microwave-based measurement methods, including reflection-based techniques, have been used in the past to measure changes in material properties including changes due to moisture uptake [9, 10]. Frequency selective surfaces (FSSs) are arrays of electromagnetically resonant elements, which act as filters, typically having relatively narrow bandwidths [11]. The FSS response is affected by changes in the dielectric constant of the surrounding medium, such as when moisture is present in or behind the panel. More recently, FSSs and other resonant type electromagnetic structures have also been used to detect moisture at microwave frequencies [12,13].

In terms of measuring moisture content in non-conductive Natural fiber reinforced composites (NFRCs), moisture content can be determined with microwaves alone, but in this work, it was experimentally found that adding an FSS enhances the response by ~7 dB. Regardless, a strong microwave response from moisture is expected because of the significant difference between the dielectric constant of NFRC composites (~5) and the dielectric constant of water (~80). Further, spectral centroiding (SC), cross-correlation (XC), principal component analysis (PCA), and Delta Summation (DS) are useful methods for analyzing various types of data, which have been demonstrated in microwave sensing applications [14, 15, 16, 17]. This work also investigates the application of these four post-processing methodologies to analyze the reflected electromagnetic (EM) response data from FSSs on NFRC specimens when exposed to moisture.

4.4.6.1 Methods

Experimental Setup for Microwave Sensing: Figure 4.116 shows the experimental setup used for measuring moisture utilizing microwave radiation. The setup consists of a frame that holds the flax-Rilsan composite panel vertical and a linearly polarized, dual ridged horn antenna positioned 58 mm from the sample, which operates in the Ku band (12.4 GHz ~ 18 GHz) and is used to interrogate this sample. The FSS is placed in front of the sample as shown. The S11 response is measured using a Planar R180 vector network analyzer (VNA)

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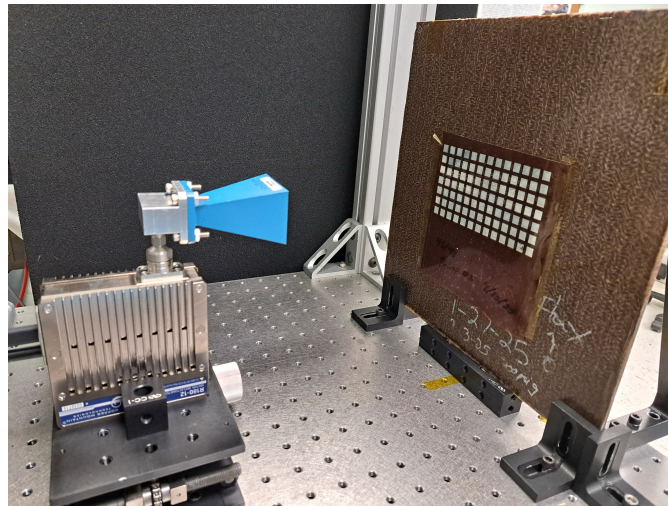


Figure 4.116 Experimental setup: polarized horn antenna, and network analyzer, FSS, and flax-PA11 non-conductive panels.

and the data is analyzed mostly in the Ku band. The Ku band was selected because the resonant frequency of the FSS is outside of this band, which means that more of the microwave energy can pass through the FSS to interact with the composite material

To simulate moisture within the composite panel, a Kapton strip with a circular absorbent paper was placed behind the composite panel with different volumes of water injected into it (Figure 4.117). The absorbent material is 0.3mm thick. Cellophane was used to encapsulate



Figure 4.117 Experimental setup: Backside of the non-conductive composite panel with a Kapton/absorber/cellophane test specimen.

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the absorbent material to keep the moisture from entering the composite or evaporating out of the absorbent paper. Also, a control measurement was performed utilizing this configuration where no moisture was injected into the absorbent paper and it was kept dry.

Printed FSS Development: The silver nanoparticle-based printed FSSs were fabricated via inkjet printing using a FUJIFILM Dimatix Materials Printer (DMP-2850). NovaCentrix JS-A191 silver nanoparticle ink was used to make the structures, which were printed on a Kapton substrate after it was cleaned using isopropyl alcohol. To ensure a relatively high, uniform conductivity and reduce gaps in the print, at least three layers of ink were deposited. The square patch FSS consists of a 13 x 7 array of unit cells of 10.5 mm, which resulted in a total array size of 123.5 mm × 66.5 mm (Figure 4.118). Each square patch had an edge length of 7 mm and was surrounded by uncoated Kapton. After printing, the FSS was sintered using a PulseForge photonic sintering tool (IX2-521), which illuminates the print with high-intensity visible light pulses to evaporate the solvent and sinter the silver ink to form a conductive structure. Once an optimized sintering process was developed, the patch was printed on Kapton. Following sintering, electrical characterization was conducted using a four-point probe system with an applied current of 100 mA. Voltage measurements were then taken at various locations across the FSS. The resistivities were found to be $1.304 \times 10^{-5} \Omega \cdot \text{cm}$, assuming a rough print thickness of 4 μm , which is typical for structures printed under these conditions.

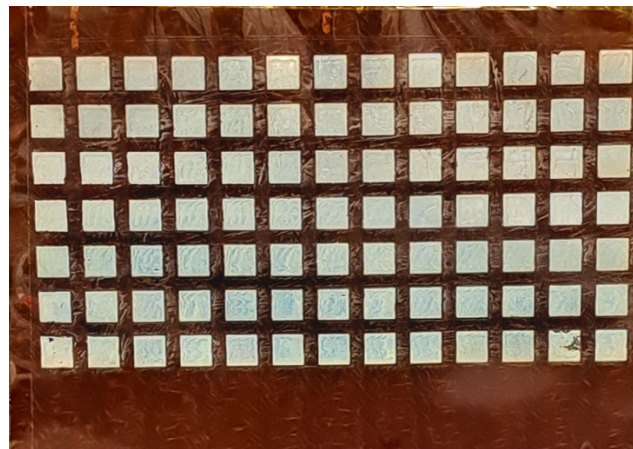


Figure 4.118 Printed FSS patch, 7 x 7 mm squares with 2.5 mm spacing.

The raw spectral data collected with the VNA from the setup described above consists of 10001 measurement points of S11 coefficients. Dimensionality reduction can be used to produce a single value from this relatively large number of values per data set. The four methods of dimensionality reduction investigated were SC, XC, PCA and DS.

Spectral Centroid: The spectral centroid (SC) is defined as the center of mass of the spectrum power and is defined as

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$$SC = \frac{\sum_{n=1}^N f_n m_n}{\sum_{n=1}^N f_n} \quad (4.14)$$

where f_n is the n th frequency value, m_n is the n th log magnitude value of the EM response and is the number of points collected across the frequency sweep. The feature of interest for this effort is the shifting of the spectral centroid as a function of the moisture level. The spectral centroid algorithm is implemented using MATLAB.

Cross-Correlation: Cross-correlation is defined as the measure of similarity of two series as a function of the displacement of one relative to the other. The circular cross correlation ($f * g$) is given by

$$(f * g) = \sum_{m=1}^N \overline{f[(m-n)_{mod N}]} g[m] \quad (4.15)$$

where f is the initial data set and g is a measurement data set, $\bar{f}$ is the complex conjugate of f , n is the displacement, and N is the number of points in each data set. The displacement of the maximum correlation is directly dependent on spectral shift between the two data sets, and, in this case, the spectral shift between a baseline response and the response as the moisture within the panel varies. The cross correlation is found using the `xcorr` function in MATLAB and is scaled according to the frequency band of the EM response.

Principal Component Analysis (PCA): PCA is a method of reducing high dimensional data sets to a number of principal components that retain as much of the variance of the data sets as possible. In sensing applications, the data set variance corresponds to measurement values, with a small variance corresponding to a small measurement value and large variance corresponding to a large measurement value. For this work, the only principal component that is retained is the one associated with the largest amount of variance, and it corresponds to the relative shift of the EM response across the frequency band of the spectrum analyzer. Using this method, the microwave response data consisting of 10001 points each can be reduced to a single measurement value, and later converted to spectral shift, for each measurement. The PCA operations in this work are conducted using MATLAB's `pca` function, which employs singular value decomposition (SVD) given by:

$$X = U \Sigma W^T \quad (4.16)$$

where X is the singular value decomposition matrix, U is the left singular vectors of X , rectangular diagonal matrix called the singular values of X , W is the right singular vectors of X , and T is the transpose operator.

Delta Summation: A simple summation of the delta impedance across the frequency range can provide acceptable results with less computation than other post processing methods.

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The summation of the delta impedance across 10001 points of a data set is given by:

$$SZ = \sum_{i=1}^{10001} (|Z_i - Z_{0i}|) \quad (4.17)$$

where Z_i is the current data set and Z_{0i} is the reference or first data set. Each of the four post processing methods will be evaluated for data reduction.

4.4.6.2 Results

The raw data is the complex S11 values from the VNA, which can be converted to the S11 log magnitude response as shown in Figure 4.119. The S11 log magnitude response is taken from 10001 points between 12.6 GHz to 13.6 GHz for 105 runs. Further, using the S11 data, the phase and the impedance (Z) can be calculated. The Z form of the data is used here to investigate the different postprocessing methods mentioned above since it was found to be most sensitive to changes in moisture content (not shown). Each test condition set consists of seven measurements from the VNA where each data set consists of alternating a dry test specimen and wet test specimen until the seven measurements are captured. This sequence is repeated for three different circular absorbent material of diameters: 7mm, 9mm, and 11mm. The three sizes of absorbers were all subjected to five different amounts of water, 1 μ L, 2.5 μ L, 5 μ L, 10 μ L and 20 μ L. With seven runs per set, three absorber sizes, and five different moisture levels, a total of 105 different measurements were made. Both a spectral shift and a change in amplitude are clear in Figure 4.119. Further, using the S11 data, the phase and the impedance (Z) can be calculated. The Z form of the data is used here to investigate the different postprocessing methods mentioned above since it was found to be most sensitive to changes in moisture content (not shown).

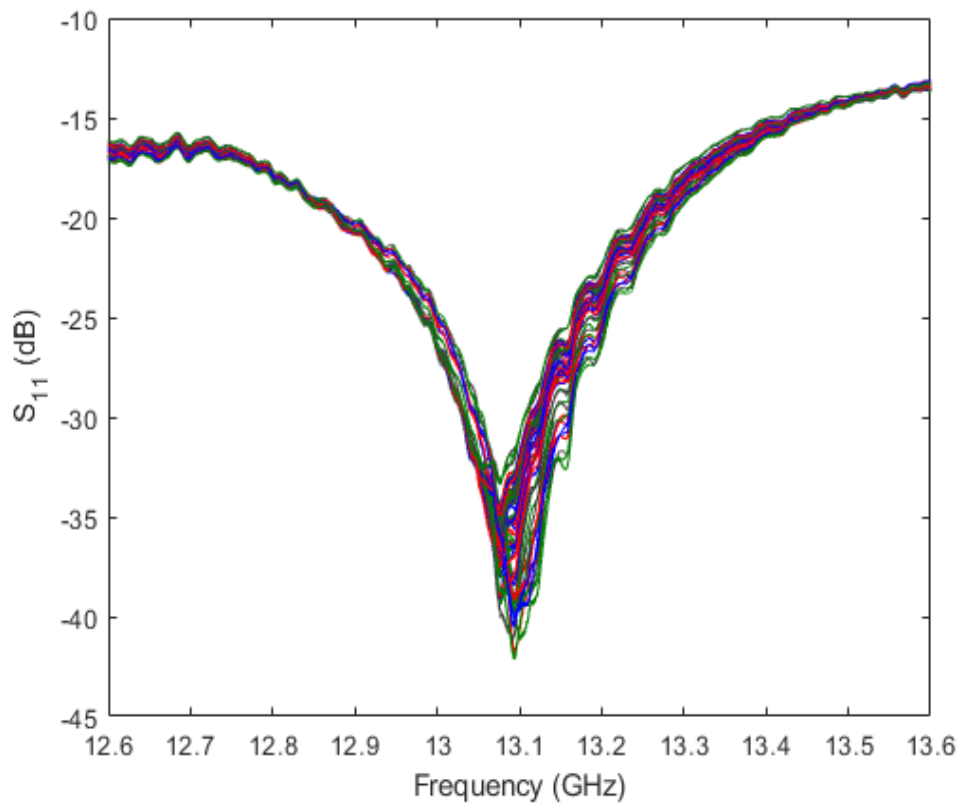


Figure 4.119 The S_{11} EM response for all 105 data sets.

Next, the DS method was applied to the data in Figure 4.119 and is presented in Figure 4.120 as the magnitude of the delta sum of the Z versus trial number. The peaks correspond to the cases where moisture is present while the troughs correspond to the dry cases and the noise level. The magnitude of the different peaks is a function of the amount of moisture in the absorbent material and the size of the absorbent material.

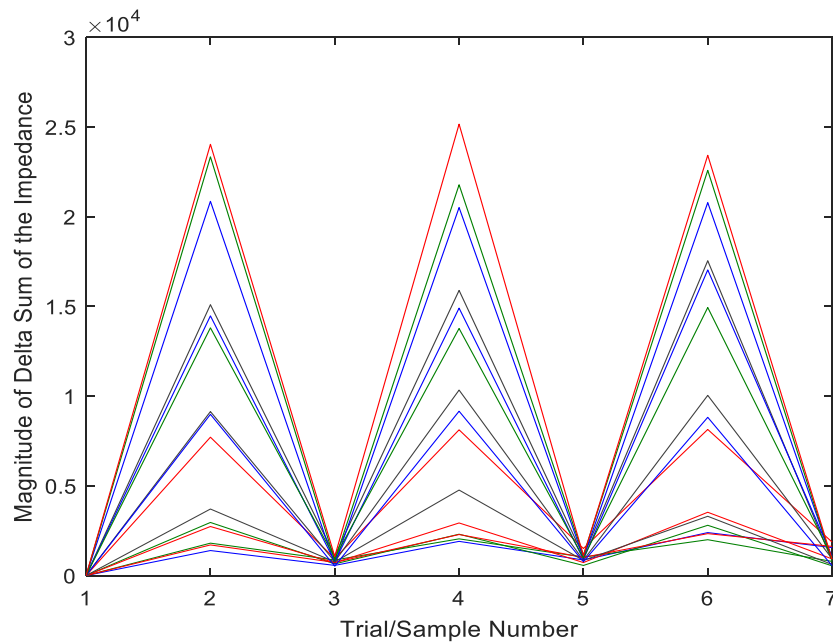


Figure 4.120 The delta sum values for all 105 runs. The dry, wet, dry pattern is evident.

Similarly, each of the four postprocessing techniques were applied to the Z form of a subset of data and this subset was fitted versus volume of the fluid. Specifically, in order to relate the microwave response in the form of Z to the level of moisture, the data is fitted with a cubic equation:

$$Fit = \alpha X^3 + \beta X^2 + \gamma X + \delta \quad (4.18)$$

where Fit is the estimation for the moisture level, and α , β , γ , and δ are the cubic fit coefficients, and X is the EM response data (the impedance (Z) data using the DS technique). The r^2 value was used as a goodness of fit, the closer to a value of one the better the fit. In Figure 4.121, the largest r^2 value, 0.9861, is found for the case using the DS method.

Since, the DS postprocessing method was found to be most sensitive to moisture content in these samples, this method was applied to all 105 data sets. The averaged fitting parameters are given in Table 4.14. When this equation is applied to the Z form of the EM response for the dry specimen measurements, a detection limit of 1 μL of water is implied. The fit parameters from Table 4.14 can then be used with equation (4.18) to relate the measured DS of the impedance to water content for unknown amounts of moisture absorbed in the absorbent material behind the NFRC samples.

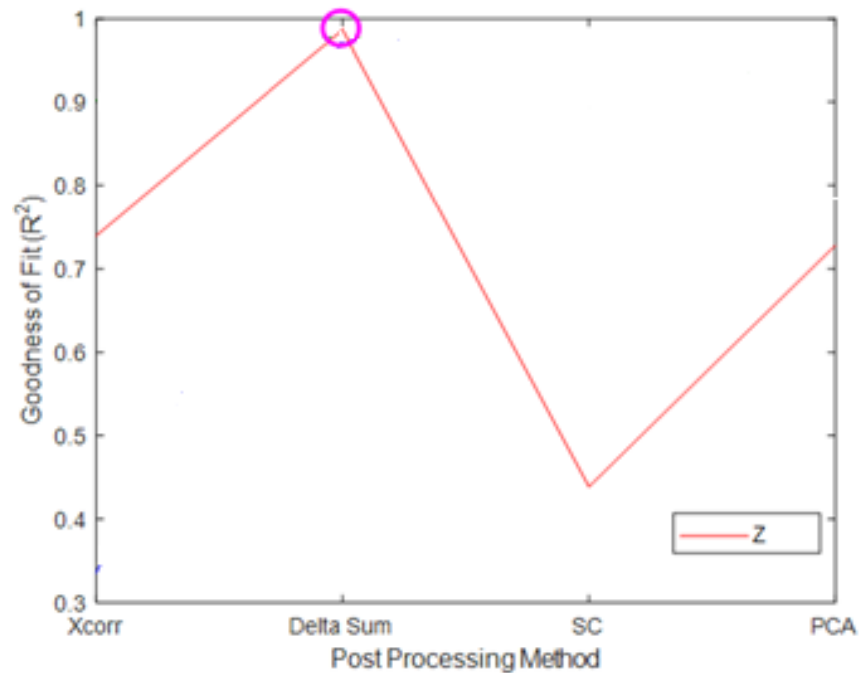


Figure 4.121: The r^2 value for the four postprocessing techniques applied to the impedance (Z) form of the data. The circle indicates the highest value which is from the DS technique.

Table 4.14 Fit Averaged Quadratic Parameters from data that is postprocessed with the DS method

Averaged Quadratic Parameters	α	β	γ	δ
Values	-3.119e+9	8.988e+04	0.4266	8.47e-07

4.4.6.3 Conclusion

A microwave interrogation system has been used to demonstrate the sensitivity of microwaves to moisture within an absorbent material behind a non-conductive flax-Rilsan composite panel where a FSS is used to enhance this sensitivity. A detection limit of 1 μL is suggested for water when applying a DS postprocessing method towards the Z form of the EM response. Further optimization of the method may be able to improve the sensitivity. It should be noted that the method presented here should apply to all non-conductive composite materials that are not very lossy at these frequencies.

This initial effort measures moisture behind the panel, however future work will focus on the way to improve this method to allow measurements to be made on the amount of moisture that is absorbed inside a non-conductive composite.

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4.4.7 Key Takeaways

- Natural fiber reinforced composites possess unique properties that require tailored sensing approaches both for in-service monitoring and NDE. Electromagnetic and thermal techniques proved particularly useful for quality control during manufacturing.
- NFRCs exhibit significant changes in acoustic and dielectric properties when subjected to moisture exposure, which provides a strong basis for in-situ monitoring of degradation in the service environment
- Ultrasonic methods are sensitive to changes in elastic properties both when used in a bulk wave inspection mode and in a guided wave mode. The guided wave mode providing the richest data for fully characterizing elastic constants
- Phase velocity changes in the fundamental antisymmetric (A0) guided wave mode are among the most promising for sensing changes in elastic constants. Single line scans showed empirical evidence of changes in properties and line scans along multiple material directions would allow for more quantitative analysis through inverse modeling.
- Microwave sensing showed sensitivity to moisture uptake and was further enhanced by the use of a frequency selective surface (FSS) to enhance the microwave response to changes in composite dielectric properties.
- Data reduction through delta summation produced a statistically significant fit with experimental data and enabled calibration of the microwave response for use in predicting moisture uptake.
- Future work will focus on optimizing the FSS design for maximal response to moisture uptake and in applying FSS measurements to other sensing modes of interest for health monitoring of NFRC materials – including monitoring strain, impact, and vibration events.

4.4.8 References

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4.5 Computational Materials for Composite Design Optimization

4.5.1 Introduction

SUMAC's computational materials task aimed to develop a computational material model of each composite component, resin and fiber, capable of resolving key microstructural features, mechanical deformation, and fracture. This task grew to include segmentation and analysis of fibers from optical microscopy and computed tomography (CT) scans, informing this and the other tasks. Changes to the plan are reflected in the timeline for activities associated with this focus area, shown in Figure 4.122.

Analysis of composite images made key contributions to various SUMAC efforts. Quantification of void fraction from CT scans indicated the need for improved resin infusion in the PA11 composites. The hollow cores of natural fibers contribute many technical advantages for composites, such as vibration dampening. Hollow core size, fiber size and shape distributions were calculated for 7 composites. The ability to compare across composites allows assessment of the role of weaving on fiber deformation and sourcing on fiber variability.

Component models for fiber, resin and fiber-resin were developed to simulate yarn, rein and weave behavior, and in preparation of the full composite simulations planned for the second project year. The fully explicit simulations identified the importance of initial slack and twist on single yarn tensile behavior, of both dry and infused yarns. PA11, PHA, and PLA bonded network models capture manufacturer mechanical properties and can resolve failure and microstructure. A tool was developed to reliably go from manufacturer weave pattern, yarn twist, spacing and ply number to explicit fiber simulation that agrees with real weaves. Fully explicit dry and infused yarns of different fibers will improve coarse-grained models. Key takeaways are listed in Section 4.5.4.

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	Pre-Year		FY25				FY26			
Task	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
CM1: Component and Composite Model Development								★		
Develop dry fiber model										
Develop resin model										
Develop composite model with fiber-resin interactions										
CM2: Dry Weave Pattern Assessment										
Generate relaxed plain weave configuration										
Generate relaxed non-plain weave configurations										
Simulate dry weave tensile and flexural deformation										
report/presentation/article on the role of weave pattern										
CM3: Composite Simulation and Microstructural Analysis										★
Simulate composite tensile and flexural deformation										
Characterize composite microstructure from microscopy and tomography										
Analyze microstructural contact and stress behavior during deformation										
Simulate deformation in interlaminar configuration										
Vary resin and fiber composite properties and simulate deformation										

Figure 4.122. Computational materials activity timeline, including completed planned (blue cells) and unplanned activities (purple). Events cancelled due to premature project ending are stricken through, including report out events (orange) and “nice to have” activities (yellow).

Each subsection of Section 4.5 is reasonably self-contained with methods, results, and technical conclusions. Fiber size, shape distributions in the different composites are reported in Section 4.5.2.1 from segmented and instantiated optical microscopy (OM) of 2D composite. As discussed in Section 4.5.2.2, flax and hemp fibers are hollow. Section 4.5.2.2 reports the core perimeter distribution for flax also from 2D OM. Voids in composites are segmented from computed tomography (CT) in Section 4.5.2.3. Material simulations are reported in Section 4.5.3 using a particle-based method that resolves fiber diameter distribution, yarn twist, ply and weave pattern. Small-scale simulations that model each fiber in a yarn cross sections are discussed in Section 4.5.3.1. A bonded network model of PLA, PA11 and PHA capable of simulating mechanical, viscous and fracture of resins is reported in Section 4.5.3.2. Dry weave simulations, using a coarse-grained yarn model are demonstrated in Section 4.5.3.3.

4.5.2 Microstructural Analysis

Segmentation and instantiation of optical microscopy in Sections 4.5.2.1 and 4.5.2.2 are used to analyze fiber-scale microstructure and calculate fiber feature distributions. Segmentation of computed tomography (CT) scans in Section 4.5.2.3 is used to calculate 3D, whole composite features.

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4.5.2.1 Fiber Analysis

Greater variability in properties is typically observed for natural fibers compared to synthetic fibers, which may result from differences in fiber source and plant location, soil quality, climate, harvest timing, fiber extraction technique, and fiber processing, among others [1, 2, 3]. Optical microscopy images of cross-sections of SUMAC composites reveal a significant variation in fiber sizes and shapes for the natural fibers. Quantitative analysis of the fiber sizes and shapes was sought by the project to provide thorough microstructural characterization of the composites and their constituents. Among other things, this type of analysis is valuable to inform the construction of material models, informing the model descriptions of the fibers.

To extract fiber metrics from a cross-sectional image of the composite, the image first must be segmented into regions associated with each fiber. It's important to distinguish between semantic segmentation, which classifies pixels into categories (e.g., fiber or matrix), and instance segmentation, which differentiates objects—instance segmentation is necessary to obtain fiber metrics. Thresholding is a simple semantic segmentation approach that assigns classes to pixels based on the intensity value. Further processing is necessary to obtain an instance segmentation, such as through application of the watershed algorithm. Attempts to segment fiber objects in the SUMAC images with a thresholding/watershed approach were not successful due to poor fiber/matrix contrast (problematic for thresholding) and complex fiber geometries (leading to oversegmentation by the watershed algorithm).

Manual segmentation of the images is tedious and labor intensive, so AI-enhanced capabilities were sought. The recent release of the Segment Anything Model (SAM) [4] from Meta AI has led to significant improvements in object detection and instance segmentation tasks across various types of datasets. SAM enables promptable segmentation, meaning that objects can be detected through interactive prompts in real time by the user, such as positive/negative points placed on regions belonging to the object or not (i.e., point prompts), or boxes drawn around the object (i.e., box prompts). Real-time interaction is made possible by separating the model into an image encoder, which runs only once per image prior to prompting, and a lightweight mask decoder that runs quickly with each user prompt. SAM was trained on a large dataset with more than 1.1 billion segmentation masks collected on ~11 million images to provide generalization, meaning that it works well out of the box on many images without additional training.

Since SAM's release, many tools have been introduced that implement SAM with capabilities or models suited for specific applications and image types [5, 6, 7]. Among them, Segment Anything for Microscopy (micro-SAM) [8] offers (i) a Python library to apply SAM to 2D or 3D data or fine-tune the models with user-provided data, (ii) a set of models fine-tuned for light microscopy, electron microscopy, medical (e.g., X-Ray, CT, MRI, Ultrasound), or histopathology images, and (iii) a plugin to napari [9], a Python viewer, for interactive data annotation. Due to its apparent usability and versatility, micro-SAM was

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chosen for segmentation of fiber cross-sections in a selection of available SUMAC optical microscopy images. The micro-SAM fine-tuned models were not anticipated to yield significantly improved performance for the composite images, as they were trained on biological images, but the goal here was to evaluate the effectiveness of the annotation capabilities within the napari plugin and the model fine-tuning workflow for material image datasets commonly generated within NASA projects like SUMAC.

The out-of-the-box micro-SAM segmentation functionalities were evaluated first for an image at 1000× magnification, providing the highest quality fiber cross-sections. To baseline the capabilities, the original SAM model (listed as ‘Natural Images’ in the micro-SAM plugin) was chosen, which uses a masked autoencoders (MAE) pre-trained Vision Transformer (ViT). Various model sizes are available (‘tiny’, ‘base’, ‘large’, and ‘huge’), which require increasing computational resources. The micro-SAM documentation notes that the tiny model (ViT-t) often yields inferior quality and that the huge model (ViT-h) doesn’t offer any advantages, so the large model (ViT-l) was chosen for testing. Because SAM scales inputs to a shape of 1024 pixels × 1024 pixels, segmentation performance can suffer when images deviate significantly from these dimensions. To handle other input dimensions, micro-SAM implements tiling. Generally, for SUMAC images deviating significantly from 1024×1024, a tile shape of 1024×1024 and halo size of 256 was found to work well.

The baseline SAM performance with the ViT-l model is demonstrated for an optical microscopy image of a Braided Flax/Rilsan composite at 1000× magnification in Figure 4.123, with examples of fiber object masks obtained from SAM box prompts within different regions of the image overlaid (labeled a-d). Not surprisingly, SAM performed well when fiber boundaries were distinct and very clear (Figure 4.123a). It performed well even with more poorly defined boundaries (Figure 4.123b), but it struggled when boundaries between fibers became indistinguishable to the human eye (Figure 4.123c). The presence of surface defects, such as scratches from sample preparation, also presented issues for segmentation (Figure 4.123d). Correction of such segmentation errors could be accomplished effectively and efficiently using additional point prompts or manual adjustment of masks using napari’s brush and eraser tools.

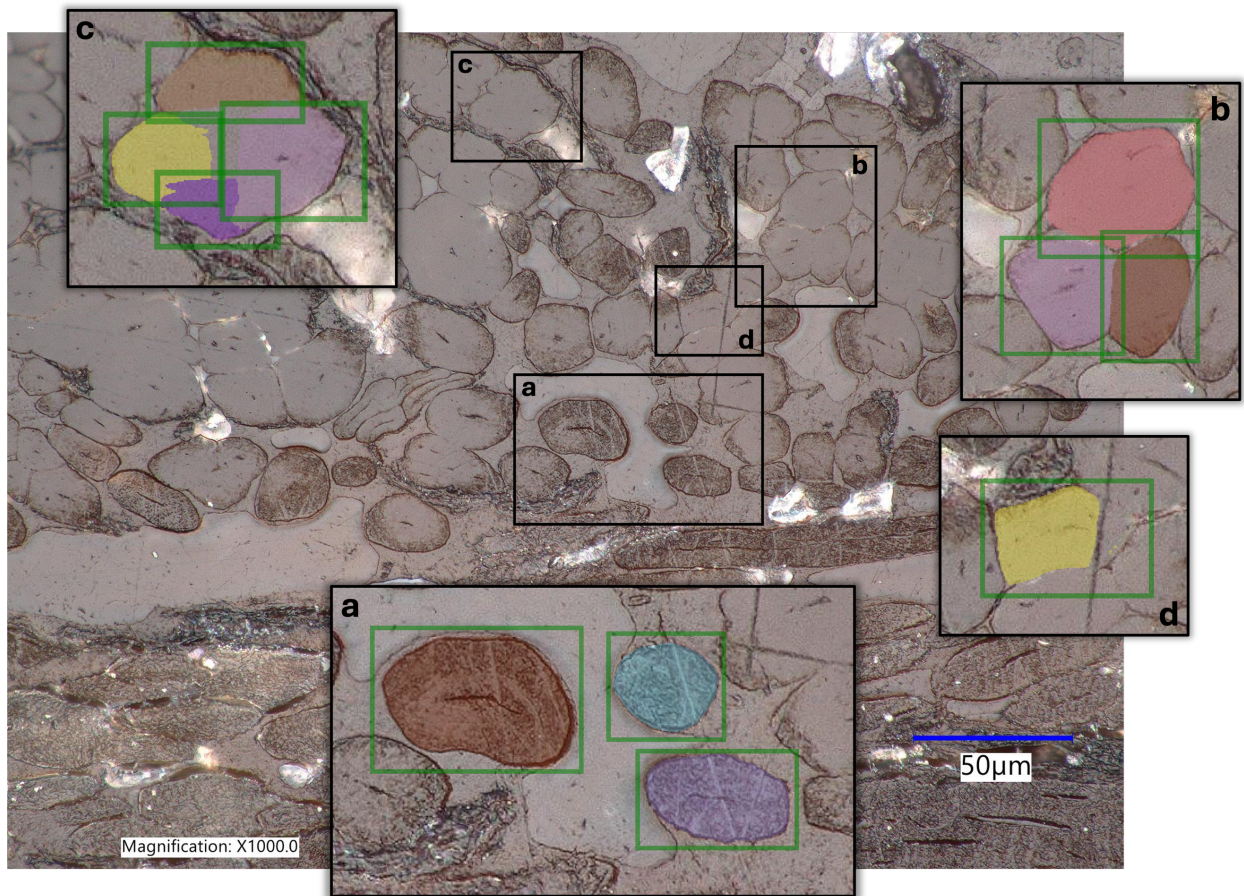


Figure 4.123. Optical microscopy of Braided Flax/Rilsan composite at 1000× magnification with regions overlaid (a-d) showing examples of box prompt segmentations obtained with micro-SAM napari plugin using SAM’s ViT-l model.

The performance of the SAM ViT-l model was assessed next for an optical microscopy image of a Braided Flax/PHB composite at 400× magnification, shown in Figure 4.124 with examples of fiber object masks obtained from SAM box prompts within different regions of the image overlaid (labeled a and b). Even at the lower magnification, SAM performed reasonably well. Similarly to the high magnification image, performance was best when fiber boundaries were well defined (Figure 4.124a) and struggled more with less distinct boundaries (Figure 4.124b).

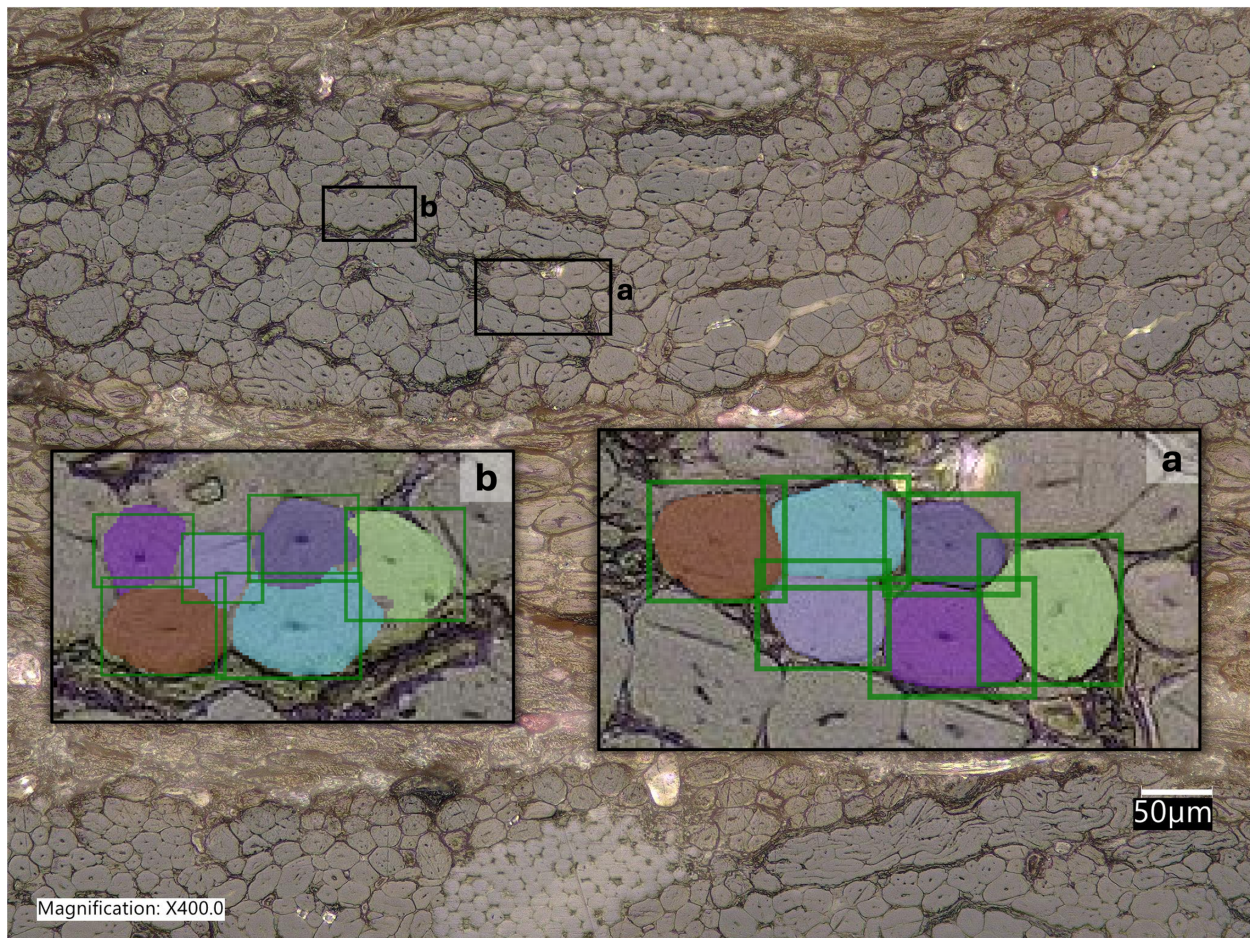


Figure 4.124. Optical microscopy of Braided Flax/PHB composite at 400× magnification with regions overlaid (a, b) showing examples of box prompt segmentations obtained with micro-SAM napri plugin using SAM's ViT-l model

In an ideal situation, the automatic segmentation capability in micro-SAM would be used to segment the full image in one click without the need for user prompts and with little need for manual correction of segmentation errors. The performance of the SAM ViT-l model on the region of interest from the optical microscopy image of the Braided Flax/Rilsan composite at 1000× magnification is shown in Figure 4.125. Although many fiber objects are segmented correctly, there are many instances of fibers being oversegmented or groups of fibers that have been segmented as one. Additionally, many regions of the matrix were incorrectly marked with masks. Overall, however, the performance of the automatic segmentation is surprisingly good given that no training data was provided.

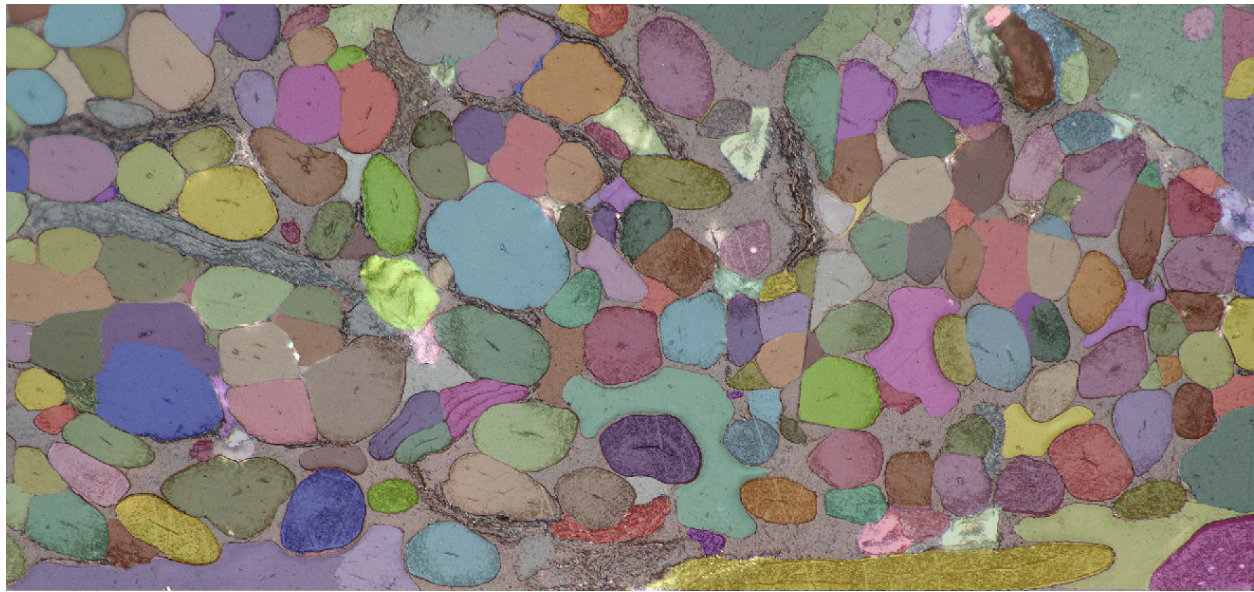


Figure 4.125. Fiber object masks obtained with micro-SAM using the automatic segmentation function with SAM's ViT-L model. Many fiber masks are determined correctly, while many other regions are labelled incorrectly.

A selection of nine cross-sectional optical microscopy images varying fiber/fabric, matrix material, and magnification were segmented with the use of napari and micro-SAM. The segmentations of fiber object masks are illustrated alongside the original microscopy images as follows:

- Figure 4.126: Flax Twill/PHB composite at 400× magnification
- Figure 4.127: Flax Twill/PHB composite at 1000× magnification
- Figure 4.128: Flax Twill/PLA composite at 400× magnification
- Figure 4.129: Braided Flax/PHB composite at 1000× magnification
- Figure 4.130: Braided Flax/PHB composite at 400× magnification
- Figure 4.131: Braided Flax/PLA composite at 1000× magnification
- Figure 4.132: Braided Flax/Rilsan composite at 1000× magnification
- Figure 4.133: Hemp Weave/PHB composite at 400× magnification
- Figure 4.134: Hemp Weave/PLA composite at 400× magnification

It is important to note that distinguishing unique fiber instances within the images was difficult in many cases due to several factors, such as variations in the image quality, poor contrast between fiber and matrix, low magnification, surface defects or scratches, etc. A best guess was made while performing the segmentations, but a closer inspection of the fiber masks would be warranted.

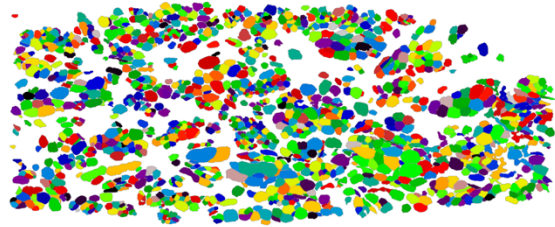
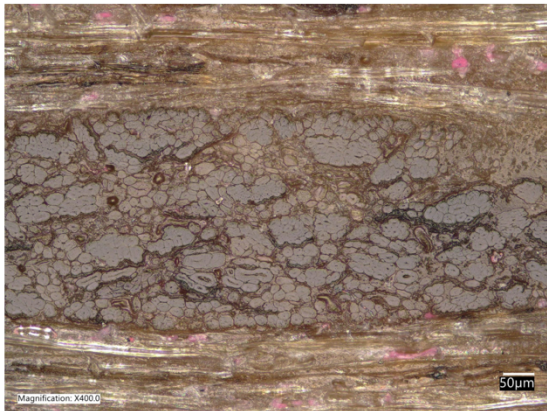


Figure 4.126. Optical microscopy of Flax Twill/PHB composite at 400× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

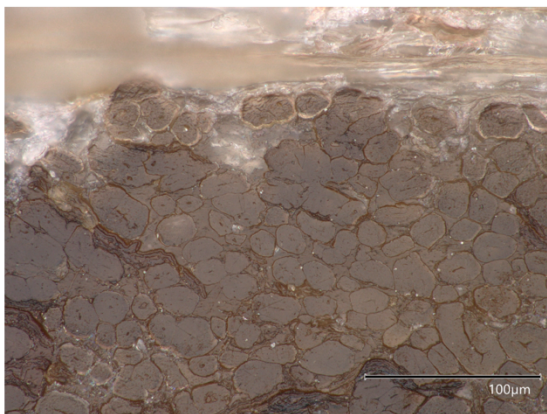


Figure 4.127. Optical microscopy of Flax Twill/PHB composite at 1000× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

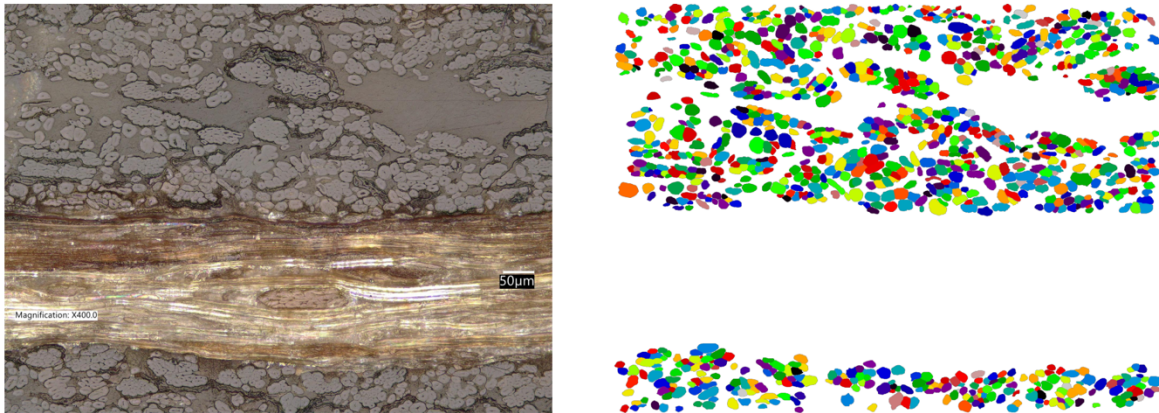


Figure 4.128. Optical microscopy of Flax Twill/PLA composite at 400× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

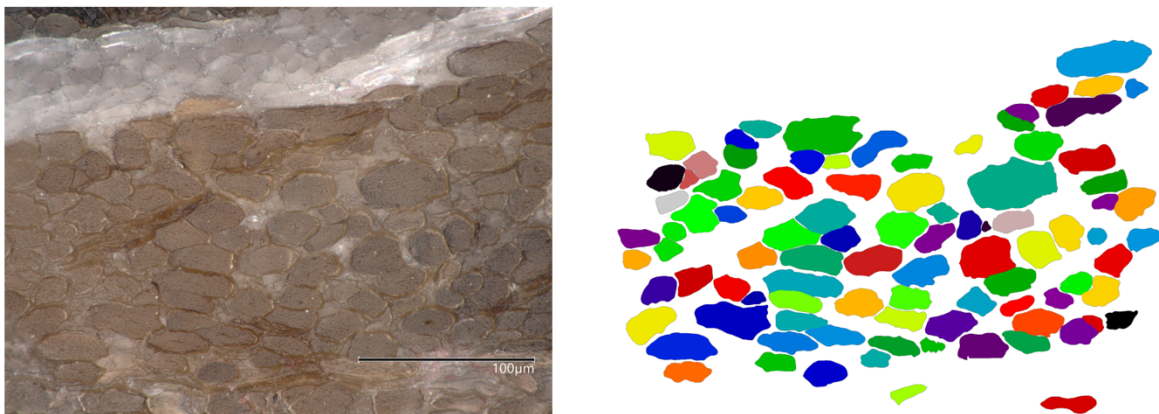


Figure 4.129. Optical microscopy of Braided Flax/PHB composite at 1000× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

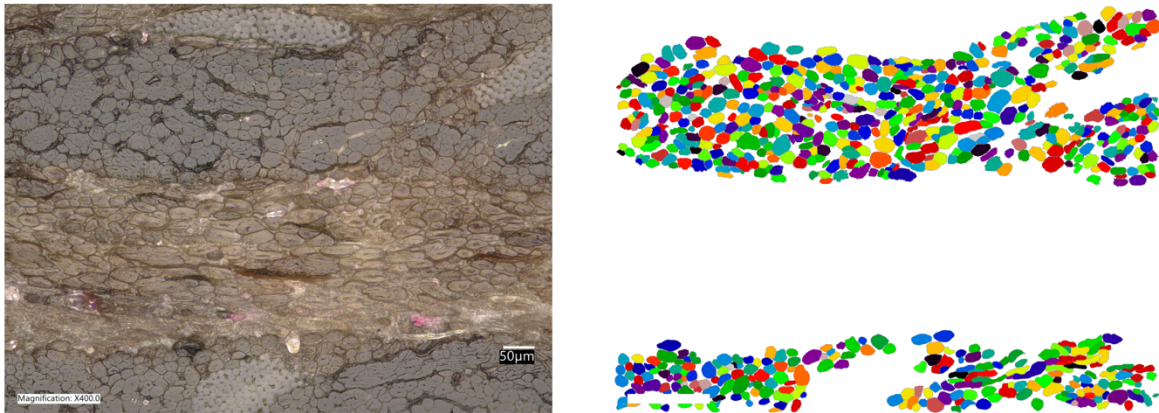


Figure 4.130. Optical microscopy of Braided Flax/PHB composite at 400× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

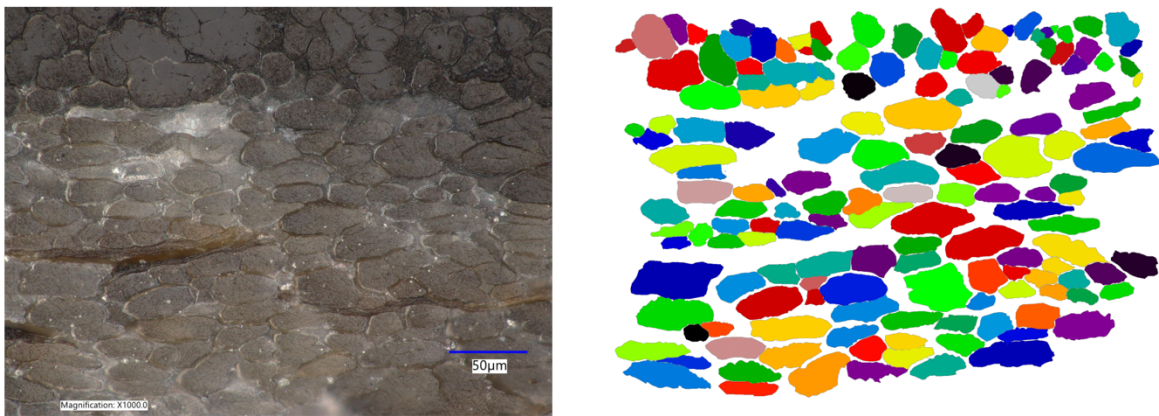


Figure 4.131. Optical microscopy of Braided Flax/PLA composite at 1000× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

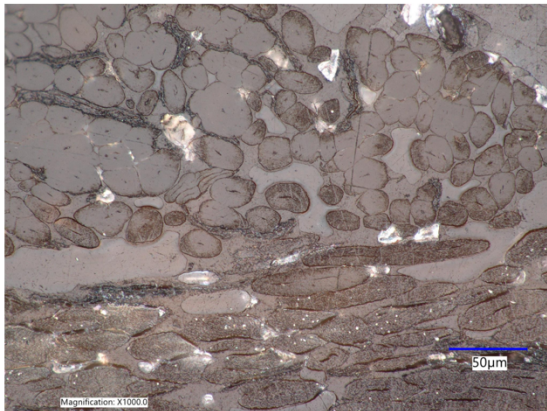


Figure 4.132. Optical microscopy of Braided Flax/Rilsan composite at 1000× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

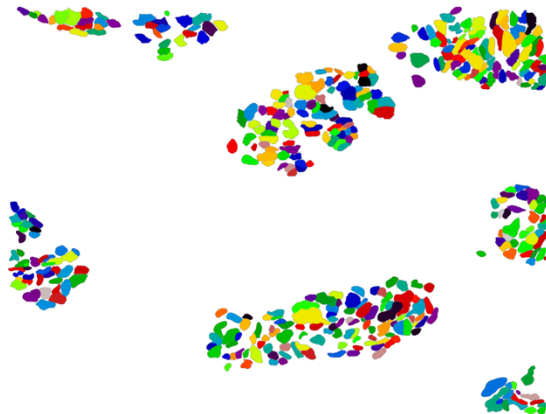
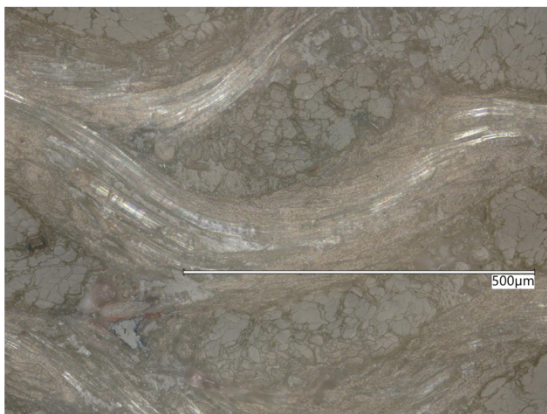


Figure 4.133. Optical microscopy of Hemp Weave/PHB composite at 400× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

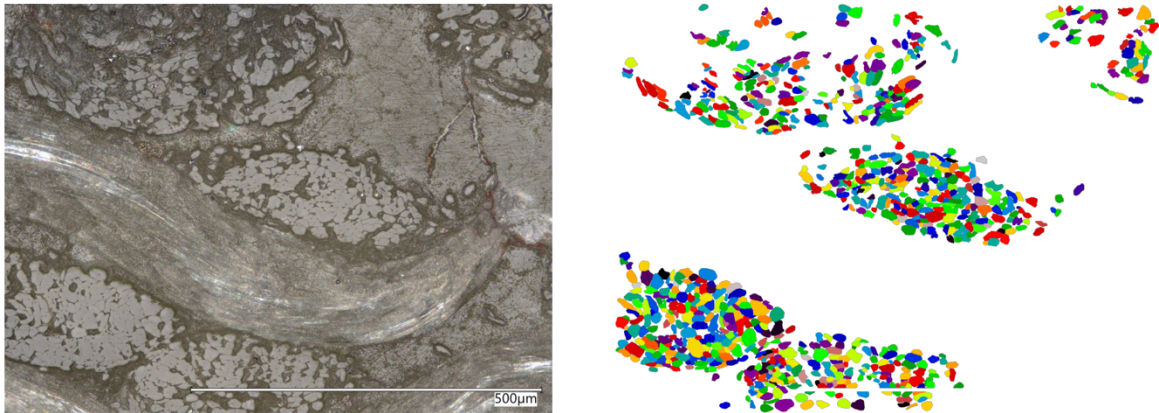


Figure 4.134. Optical microscopy of Hemp Weave/PLA composite at 400× magnification (left) and segmented fiber object masks obtained with micro-SAM (right).

The images at 400× magnification were chosen for analysis as they include a larger number of fibers, allowing for better statistics. The analysis was performed in Python leveraging several packages, including NumPy [10], pandas [11], Matplotlib [12], and Plotly [13]. From the fiber object masks, statistics related to fiber cross-sectional sizes and shapes were extracted. In the interpretation of the data, it is important to keep in mind that the fiber cross-sections observed in the optical microscopy images are influenced by the fabric and composite processing, including any distortions or damage to the fibers in the woven or braided state. Additionally, the sizes and shapes are dependent on the angle of the fibers relative to the surface imaged. A more complete characterization of the fibers could be obtained with three-dimensional data, such as from microtomography or serial sectioning [14, 15, 16].

The distributions of fiber sizes as quantified by the cross-sectional areas and the equivalent diameters are shown in Figure 4.135. Generally, the fiber diameters are 10-20 μm, but broad distributions with many outliers are observed in all cases. The fiber cross-section shapes are described by the circularity in Figure 4.136, which is calculated as $4\pi A/P^2$, with cross-sectional area A and perimeter P . With this definition, larger circularities indicate cross-sectional shapes closer to circular, with 1 indicating a perfect circle. From the distributions, fiber cross-sections typically are more circular in shape, but broad non-circular, elongated shapes are also common. The plot of major and minor axis lengths for ellipses fit to the fiber cross-sections, as illustrated in Figure 4.137, shows a broad scattering of fiber sizes and shapes with aspect ratios typically ranging from 1 to 5. Overall, broad variability is observed in fiber sizes and shapes in all cases, consistent with the variability inherent to natural fibers.

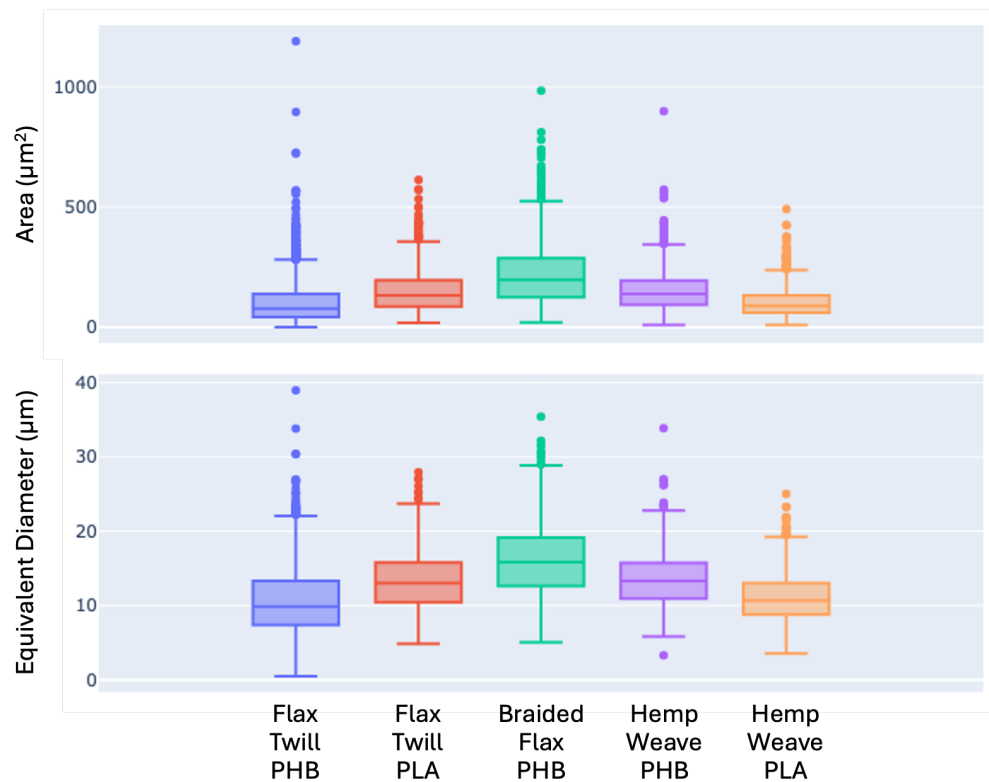


Figure 4.135. Distributions of fiber cross-sectional areas (top) and equivalent diameters (bottom) for Flax Twill/PHB, Flax Twill/PLA, Braided Flax/PHB, Hemp Weave/PHB, and Hemp Weave/PLA composites.

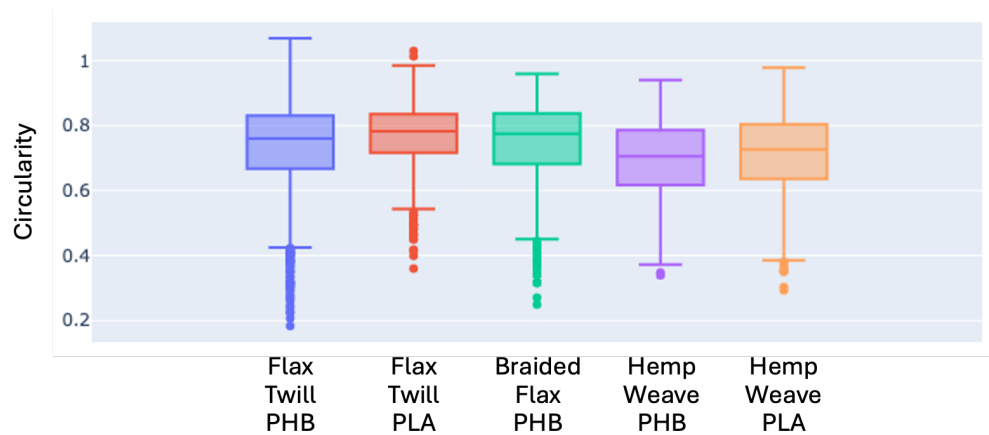


Figure 4.136. Distributions of fiber cross-sectional circularity for Flax Twill/PHB, Flax Twill/PLA, Braided Flax/PHB, Hemp Weave/PHB, and Hemp Weave/PLA composites.

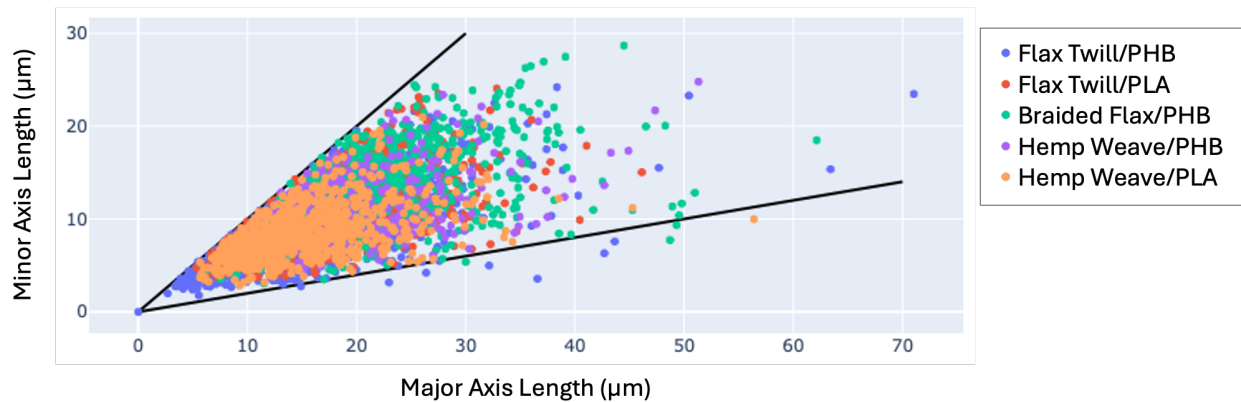


Figure 4.137. Scatter of major and minor axis lengths for ellipses fit to fiber cross-sections for Flax Twill/PHB, Flax Twill/PLA, Braided Flax/PHB, Hemp Weave/PHB, and Hemp Weave/PLA composites. Black lines represent aspect ratios of 1 and 5.

4.5.2.2 Fiber Hollow Core Analysis

It is established that natural fibers have hollow cores, as is apparent in many of the presented figures. A close up of the 3000 flax hollow cores were segmented and are shown in Figure 4.138a. Figure 4.138b shows the probability distribution of hollow core perimeters, ranging from 2 to 20 μm . The perimeter is reported because of the deformed fibers, and is calculated as the largest axis of each core instance. Based on inspection of the microscopy, it is likely that larger hollow cores correlate with larger, less circular, and more deformed fibers. Fiber wall thickness was not calculated, but seems to also have a wide distribution, and would weaken the fiber core-to-size correlation. Correlations were not quantified because cores and fiber are segmented separately and are unconnected. Fibers with no observed hollow core were not segmented, and are excluded from Figure 4.138b. The core size distribution will inform future work simulating the deformation of fibers during tension or torsion, and could be used to understand the role of core sizes on composite performance, particularly moisture uptake and vibrational dampening.

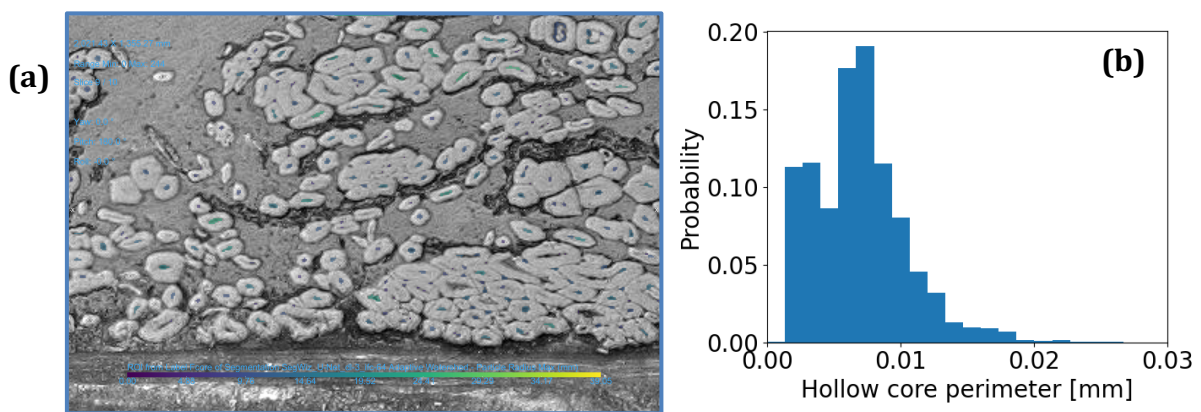


Figure 4.138. (a) Close-up of Flax fibers in a Flax Twill-PLA optical microscopy showing hollow core segmentation. About 3000 cores were segmented. (b) Probability distribution of hollow core perimeter lengths.

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4.5.2.3 Composite Voids Analysis

Figure 4.139 shows a three-dimensional segmentation of voids in braided flax composites. Computed tomography scans of full composite pieces allow visualization of the weave-scale variation of the composite edge effects, and infusion quality certification. The yarns, resin and voids of five composites were segmented. Contrast and resolution limited void and resin segmentation precision. For example, an early version of flax-PA11 had poor infusion quality and about 20 vol% void content, see Figure 4.139b. This analysis helped direct manufacturing changes, to improve infusion. Well-infused samples are estimated to have less than 2 vol% void content, but quantified comparisons were not possible at these resolutions. Two types of voids, linear cracks and fiber-resin gaps in Figure 4.140, were identified. We expect that the number of linear cracks more closely tie to the material brittleness, *e.g.*, PLA will likely have more linear cracks. The frayed voids may be improved with sample preparation and manufacturing. Small voids may be beneficial for certain applications, like vibration dampening.

The segmentation and analysis performed for Figure 4.138, Figure 4.139, and Figure 4.140 used Dragonfly 3D World, which is developed with biological and composite structure analysis in mind. Dragonfly includes tools to assist manual segmentation, to train AI models, instantiate and analyze scans. The void, resin and yarns of about 40 out of 4000 CT slices were manually segmented. Those segmented slices were used to train a 5-level “U” neural network with 64 initial filter count. Data was augmented with flips, rotations, shear and zoom. After 6 epochs, and a 0.986 training score, the segmentation was reviewed.

The accuracy and speed of composite-scale image analysis would benefit from higher resolution and contrast scans which would enable multiple future directions. Future work could utilize instantiation techniques, as used in Section 4.5.2.1, to analyze the void type, size, shape, and number distributions in the full composite. Scans taken before different performance test, could be used to correlate resin, weave deformation, and void content with properties. Yarn instance segmentation could be used to generate configurations for as-manufactured computational materials modeling.

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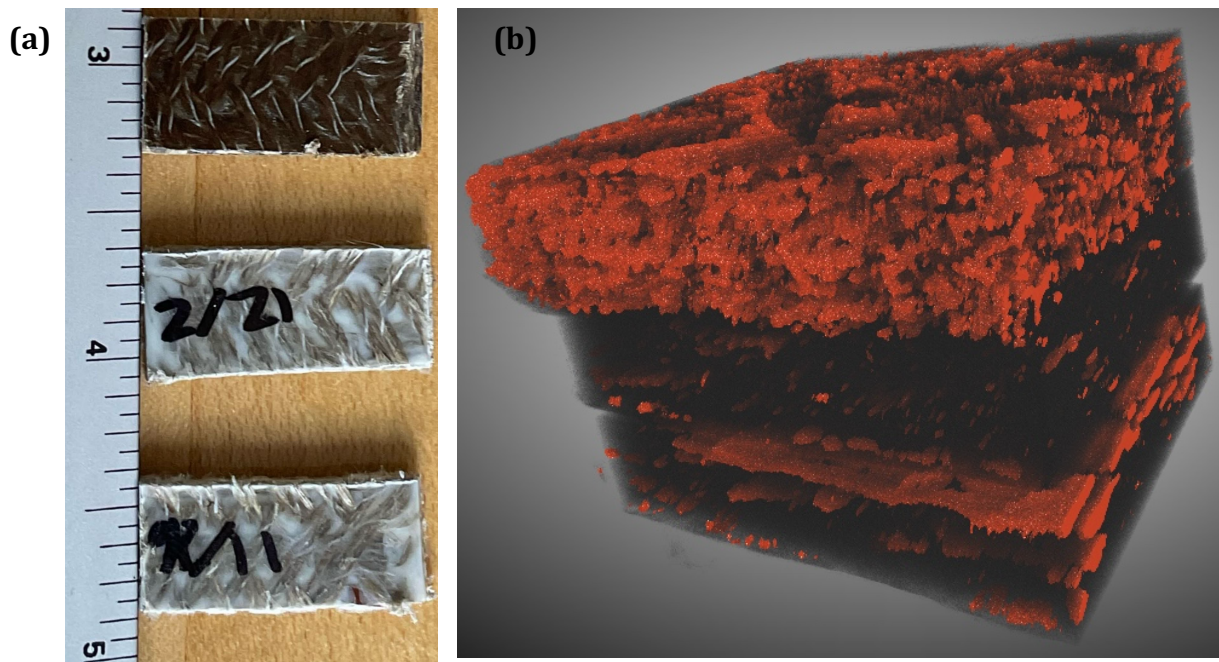


Figure 4.139. Braided flax composite (a) images and (b) of 3D rendering of voids (red) overlaid on CT scans (dark) of PA11 (top) and PHB (middle and bottom). Large voids detected in the PA11 composite informed manufacturing improvements. Voids are likely over-estimated due to resolution and contrast. Credit manufacturing team for composites and images, Credit sensing team for CT scans.

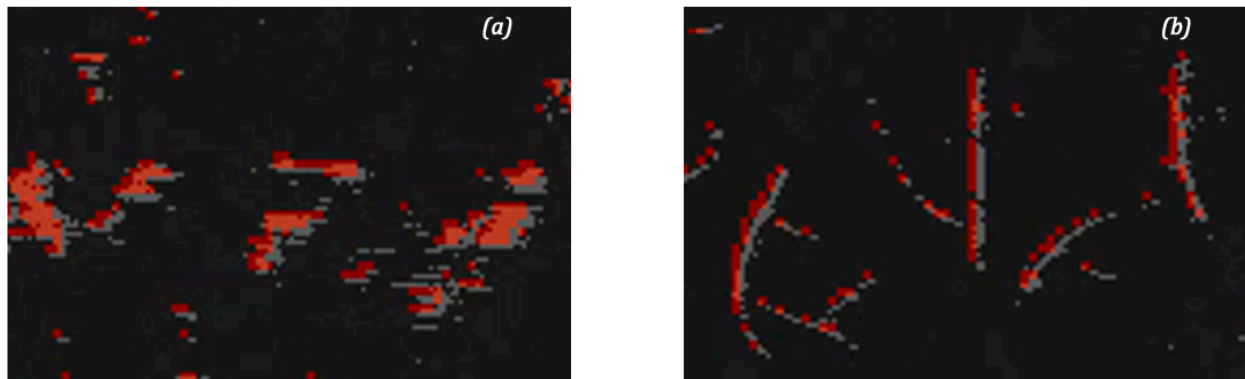


Figure 4.140. Void types observed in twill flax-PLA composite (a) frayed pattern, indicating resin-void-fiber interface, and (b) linear patterns, indicating brittle resin cracks. Red pixels are segmented CT Scan slices.

4.5.3 Material Models

Natural fiber are great performers in composites for sports, automobiles and some aviation components. SUMAC is targeting US-sourced materials, often developed for non-composite applications for more ambitious aviation components. This required opening the design space to different materials and microstructures. Design and diagnosis via computational

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methods requires material models that can resolve and vary components and microstructures. A bottom-up simulation workflow (characterized from single-component, single-fiber and resin, experiments) is needed to mix and match different materials. Lagrangian methods can capture the large deformations for bio-sourced resins and natural fibers. These explicit fiber simulations [17] have been applied to weave impact [18], braiding [19] and woven thermal protection materials [20], among other materials and processes. Microscale bonded particle explicit fiber models resolve micromechanics (friction, viscous damping) and the anisotropic physics of fibers (pull vs push), and complex fracture. All the material models were simulated in LAMMPS [21].

Fiber and yarn experiments parameterized yarn simulations resolving each fiber in Section 4.5.3.1. Those simulations are used to interpret single yarn experiments and for the development of a coarser yarn model for tractable weave-scale simulations. Bonded network resin models and simulations, in Section 4.5.3.2, are needed to match the physics and scale of coarser weave-scale simulations, in Section 4.5.3.3.

4.5.3.1 Fiber Model

To develop a coarse-grained yarn model, yarn cross-sections were simulated to assess their ability to reproduce yarn properties from fiber properties, and to gain insight into resin infused yarn properties. Two types of yarn cross-section simulations were run, “quasi-2D” and “2.5D”. This work shows that fiber packing and boundary conditions play critical roles in simulated yarn’s tensile strength, fiber alignment with respect to the tensile direction influences the yarn’s Young’s modulus. The Young’s and shear moduli of a resin infused yarn are difficult to measure experimentally, and are sensitive to resin-fiber bond modulus and strength.

“Quasi-2D” simulations were run with short fibers comprised of three spheres, where the ends spheres are pulled, sheared, and torqued. The three spheres of each fiber were connected with a modified LAMMPS rotational bonded particle model (BPM). The BPM was modified to consider the radius of each sphere, such that the bond forces represented a cylinder of material between the spheres with material properties set from experimental fiber tests.

These fibers were packed into circular regions with varying amounts of centripetal force, among other packing methods such as a circle cutout of a gravity filled box, and through yarn torquing. A schematic of these 2D yarn simulations can be seen in Figure 4.141.

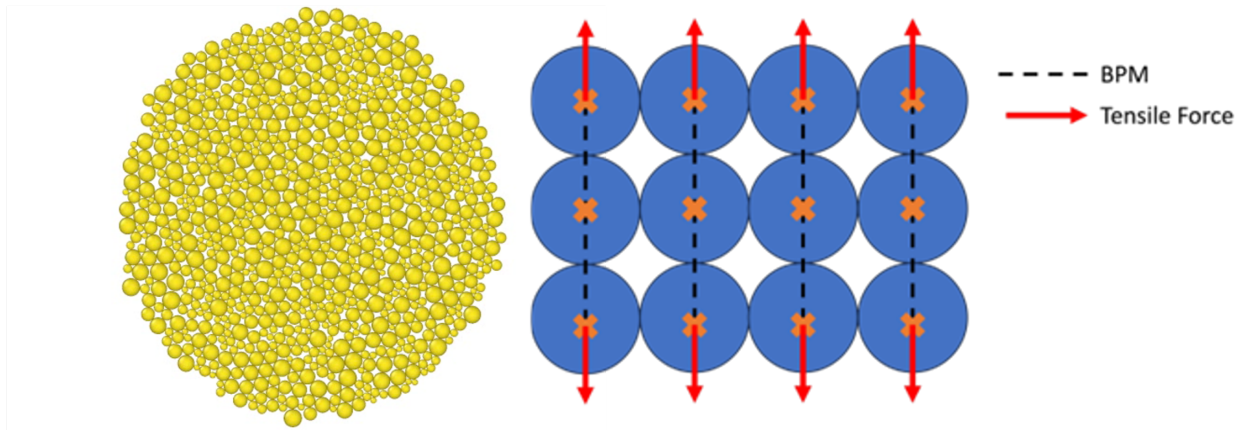


Figure 4.141. Schematic of 2D yarn simulation. Granular spheres are connected using a bonded particle model to form fibers. The top and bottom spheres have fixed radial positions and constant strain rate axial positions.

All packing methods led to similar yarn Young's moduli E_{yarn} , which were all comparable to the fiber Young's modulus E_{fiber} scaled with the area porosity of the specific packing $\frac{A_{\text{fiber}}}{A_{\text{yarn}}} E_{\text{fiber}}$, not the experimental yarn values. This can be seen in Figure 4.142a, a tensile stress-strain plot between different packings with a centripetal force. A more notable result of these fiber packings is the yarn's tensile strength, which decreases as packing force increases. This happens because contact forces between fibers adds additional stress on the BPM of the fiber, which is demonstrated in Figure 4.142b. This result shows that, to accurately model a yarn with contact forces and a BPM, close attention to how the fibers are packed is needed if breakage is of importance.

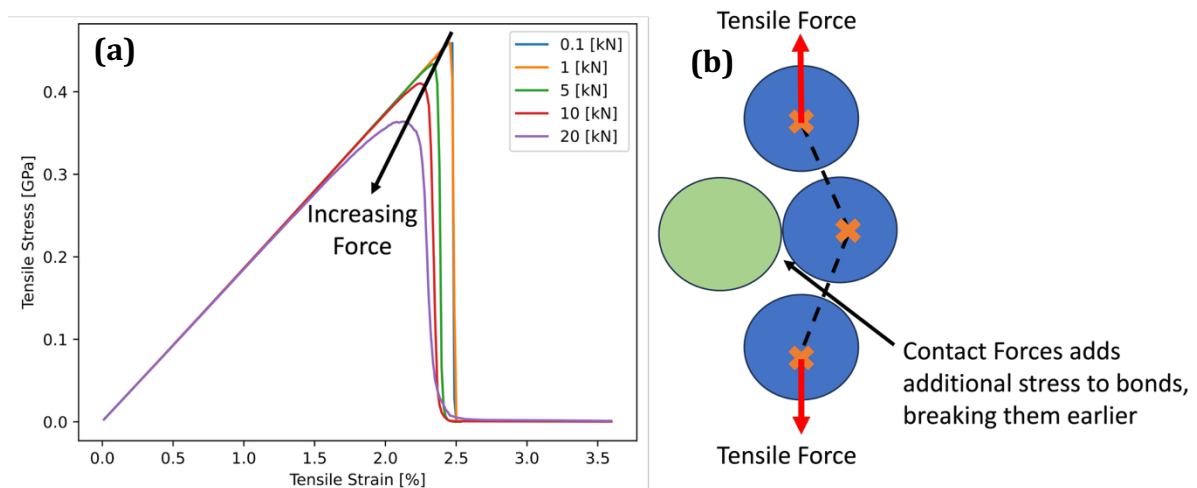


Figure 4.142. (a) Tensile stress-strain graph of increasing packing force. (b) Schematic of contact forces adding additional stress to bonds within fibers.

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From here the 2D fiber was extended slightly into axial direction, “2.5D”, to model more of the physics of a real yarn such as fibers not aligning with the direction of the tensile force and fibers have different lengths within the same length yarn. Notably the “2.5D” model is missing some aspects of a full yarn such as fibers not spanning the full length of the yarn. A side profile of this cross section of the yarn can be seen in Figure 4.143 during a tensile simulation. These yarns were both torqued and compressed with a centripetal force before running tensile deformation simulations.

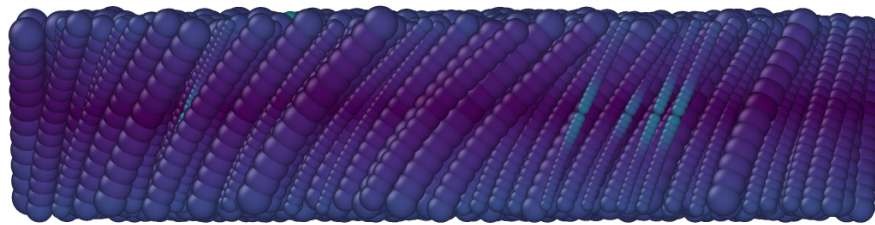


Figure 4.143. Side profile of twisted bonded particle yarn. Variation of color depicts the magnitude of displacement from each sphere’s original position.

Tensile deformation simulations were run for both Hemp 1 and Bcomp flax, as experimental data on both the fibers and yarns were available. Having the fibers not all aligned with the tensile force lead to the stress-strain curve having a strain hardening effect at the start of the simulation as seen in Figure 4.144. This is also seen in experimental yarn tensile tests, which is hypothesized to be caused by loose fibers not aligned with the tensile force. In Table 4.15, Young’s modulus compares well for Hemp 1, which is a twisted yarn. The Bcomp simulation, which used the same twisted packing, had a Young’s modulus outside the experimental error, largely due to Bcomp Flax being an untwisted yarn. Results here imply that yarn twisting, and the 3D structure of the fibers have a significant impact on the yarn’s Young’s modulus as unaligned fibers response to tensile forces depends on not only the fiber’s Young’s modulus, but also the fiber’s shear modulus. It was not expected that percent elongation at break would match as real Hemp 1 and Bcomp flax yarns have fibers which do not span the whole yarn, because strength is the model fracture criteria. Discontinuous fibers in the yarn are a likely cause for higher experimental values of elongation in Hemp 1 yarns.

Table 4.15. Experimental and simulation results for Hemp 1 and Bcomp Flax yarn under tension.

Bcomp Flax	Experiment Yarn	Simulation Yarn
Young's Modulus [GPa]	12.0 ± 1.7	15.78
Tensile Strength [MPa]	143.2 ± 23.0	542.5
% Elongation at Break	1.5 ± 0.1	2.0

Hemp 1	Experiment Yarn	Simulation Yarn
Young's Modulus [GPa]	7.51 ± 3	7.57
Tensile Strength [MPa]	259.7 ± 32.8	233.6
% Elongation at Break	4.5 ± 0.9	~2.0*

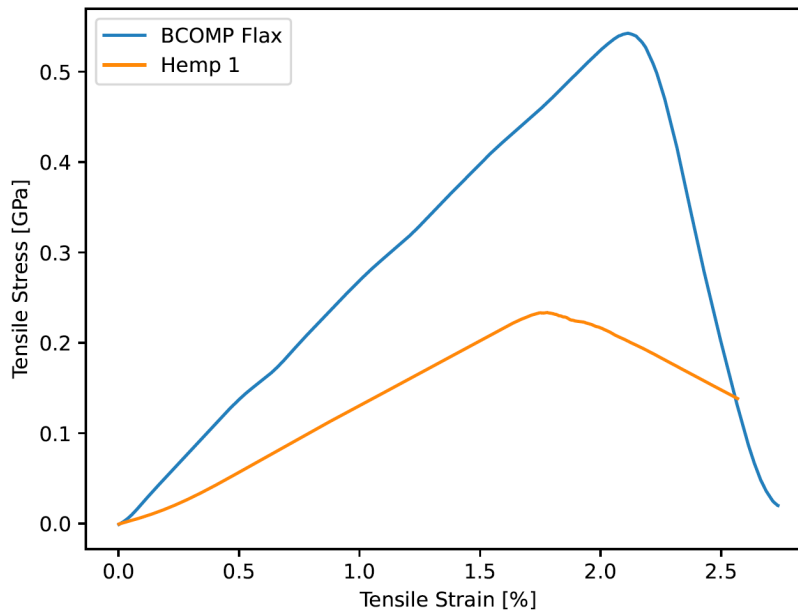


Figure 4.144. Stress-Strain plot of Bcomp Flax, and Hemp 1 yarns.

Final SUMAC composites are infused woven composites, and therefore need an infused yarn model. Experimentally isolating an infused yarn, and measuring fiber-resin mechanical properties is difficult, and, therefore, there is no experimental data to compare. But with the optical microscopy data, a representative microstructure can be simulated to improve typical volume-averaging techniques. Figure 4.145 includes a depiction of the resin infused yarn. This yarn has a fiber volume fraction of 0.67, a resin volume fraction of 0.16, and void volume fraction of 0.17. Using a volume averaged approach, we can expect the tensile Young's modulus to be 28.7 GPa, with approximately 21 GPa from the fibers. A simulation with all contact mechanics disabled also had a Young's Modulus at approximately 28 GPa.

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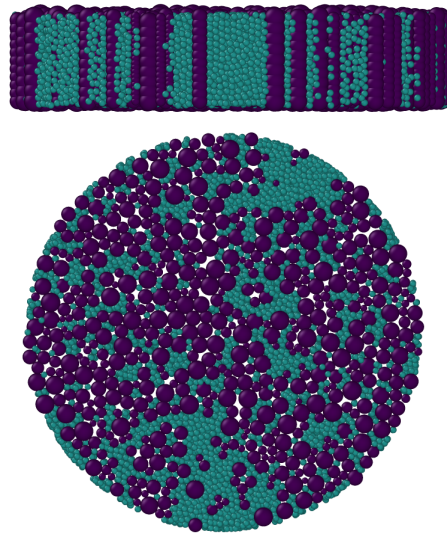


Figure 4.145. Yarn Infused with Resin. Fibers are shown in purple, with resin shown in cyan, white area is void space within the infused yarn.

This resin infused yarn contains three BPM types, fiber-fiber, resin-resin, and resin-fiber, with the latter having no experimental data. However, different resin-fiber bond properties affect both the yarn's shear modulus and Young's modulus. The bond properties were varied from, the fiber-resin average, and pure resin properties. Figure 4.146 shows tensile and shear stress results from these two resin-fiber material properties. A Young's modulus of 16.7 and 19.2 were calculated for 'from resin' and 'from average' resin-fiber material properties. Therefore, the volume-averaged approximation likely overpredicts the modulus. Shear Modulus results for 'from resin' properties and 'from average' properties were 0.25 GPa, and 2.26 GPa, respectively. The fiber-resin bond has a bigger effect on the shear modulus than tensile modulus. All fiber-fiber and many resin-resin bonds are well-aligned to the axial direction and tensile stress. Resin-fiber bonds better align to the radial direction and shear stresses, and thus contribute more to the infused yarn properties. To properly model the shear forces of a coarse grain resin infused yarn, experimental results of resin-fiber bonds strength are needed. This work suggests that composite shear and through-thickness strengths can be improved with fiber-resin wetting, cohesion and bonding.

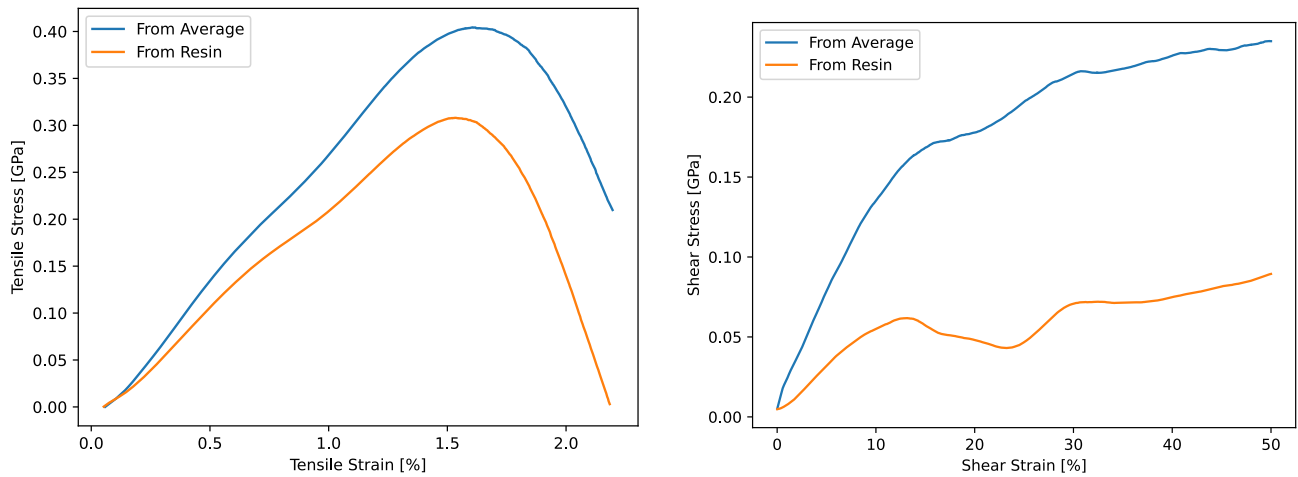


Figure 4.146. Tensile and shear stress-strain of a yarn infused with resin. Resin-fiber bonds material properties were changed between the average of the resin and fiber ('From Average') and using just the resin properties ('From Resin').

4.5.3.2 Resin Model

A bonded particle resin model was developed to model the SUMAC composites. The infused weave, discussed in Section 3.5.2.2, requires a resin model that can reproduce infusion into yarns and weaves, and intra-resin voids. The model is parameterized by performing tensile, shear, and oscillatory simulations of a bulk-like resin sample. Each resin material point represents about 10^5 monomers, and bonds do not represent covalent bonds, but effective interactions at the micron scale.

Figure 4.147 shows the resin configuration process for infusion it is important to have a non-crystalline material point distribution to have unbiased stress development and fiber interfacing. We pack spherical particles at a low pressure with monodisperse diameters, Hertzian contacts and no friction [22]. Bonds are formed between particles with a separation distance of $8.35 D_p$, which results in 11-17 bonds per particle, with an average of about 13.

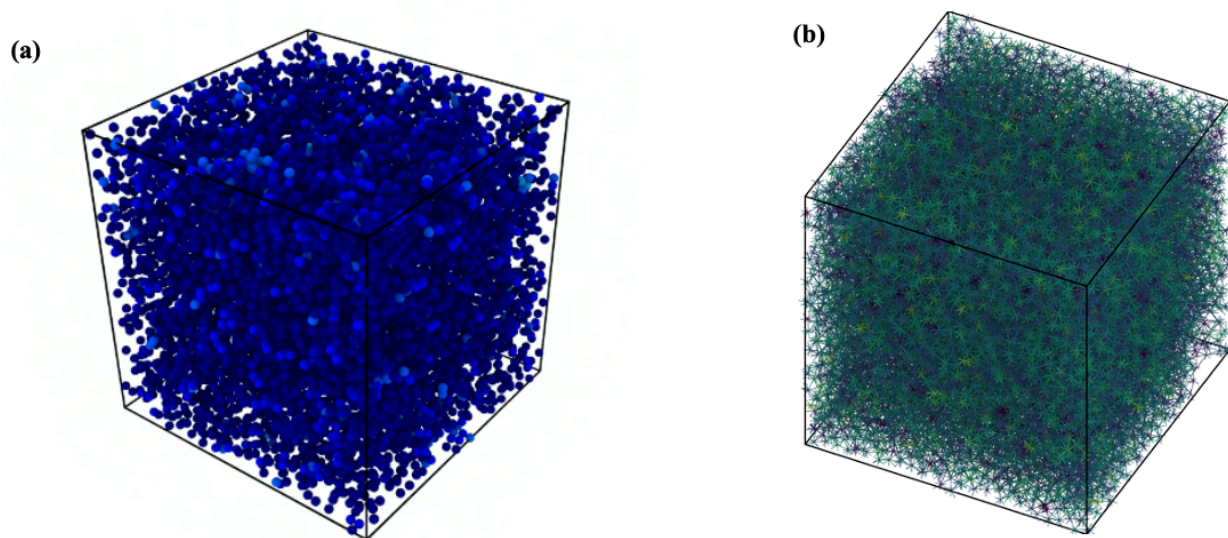


Figure 4.147. Bulk resin configuration generation visualization. (a) A dilute initial configuration is compacted to form a random packing of monodisperse frictionless Hertzian spheres. (b) A bonded network is formed between nearest and next-nearest neighbors, separations less than $8.5D_p\phi$. Colors in (a) are for variation for the eye, and in (b) are the number of bonds per node.

The essential bond model parameters are the bond, tensile, shear, and bending moduli and strength. Each experimental Young's modulus and Poisson's ratio are used to develop those parameters. Figure 4.148 shows the tensile simulations to failure for the different resins. The bond model stiffnesses and strengths are set by the manufacturers' experimental tensile modulus and strength. An example fracture resin network in Figure 4.148a shows the ability of the model to resolve complex fracture paths, which is important for composite failure, and is generally initiated in the resin or at the resin-fiber interface.

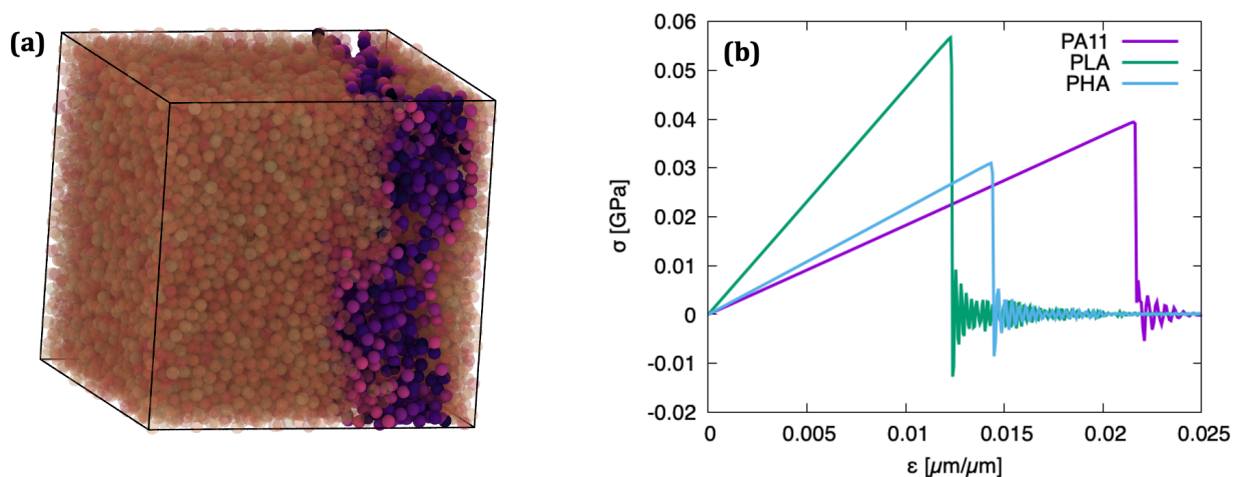


Figure 4.148. (a) Fractured PA11 configuration after a constant tensile deformation at 500 mm/min, the ASTM D638 standard. Particles are colored by number of bonds, black:0, white: 17. (b) The tensile stress-strain curve for the different SUMAC resins.

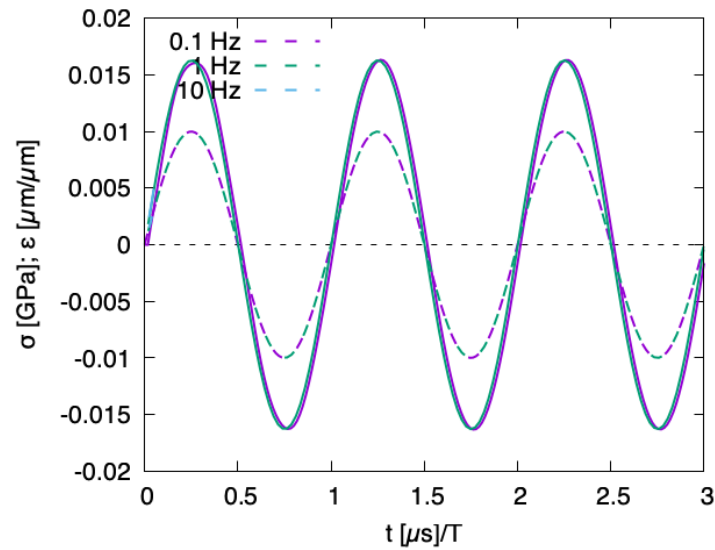
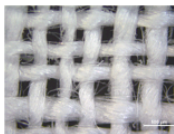


Figure 4.149. Simulation oscillatory shear stress (solid lines) and strain (dashed lines) with respect to period-normalized time at different frequencies for the PLA resin BPM model.

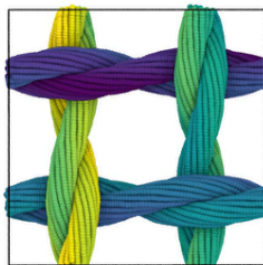
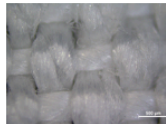
The bond model also has a viscous damping term. To parameterize this property and amplitude, oscillatory shear simulations are performed at different frequencies. Figure 4.149 shows the oscillatory shear simulations.

4.5.3.3 Weave Model

1-ply plain weave (B608)



2-ply plain weave (B601)



Twill weave (Bcomp)



Triaxial braid (AnP)

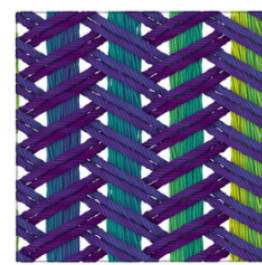
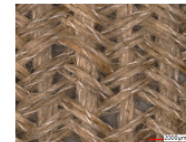


Figure 4.150. Four examples of (bottom) relaxed simulations that match the pattern (including plain, twill and triaxial braid), yarn ply (1 to 2), and yarn twist from visual inspection of (top) optical microscopy.

Simulations of one or more unit cells capable of assessing weave patterns requires a coarse-grained model to be computationally tractable. To simulate a unit cell of triaxial

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braid, for example, at the resolution used in Section 4.5.3.1 would require about 1 million particles and resolve multiple timescales at different orders of magnitude. By contrast each coarse-grained fiber can contain 10-100 fibers. One of the goals of the fiber-scale model shown in Section 4.5.3.1 is to parameterize these coarse-grained fibers, by matching the yarn behavior. Although coarse graining the number of fibers in these weave-scale simulations leads to a loss of resolution, many important phenomena are retained. Coarse-grained yarns capture the differences in tension and compression, and have large deformability, friction, twist, and rupture.

Figure 4.150 shows the matching of different weaves with coarse-grained fiber weaves, showcasing the variety of yarn ply, twist and pattern tested in SUMAC. Relaxation is important for capturing the features of the weaves. Figure 4.151 shows yarns deform and shift due to contacts with other yarns. At the contact points the twisted plies are side-by-side to reduce tension. More locally, fibers spread out near the contact creating a non-circular cross section. Higher-resolution CT scans could be used to validate this intuitive feature.

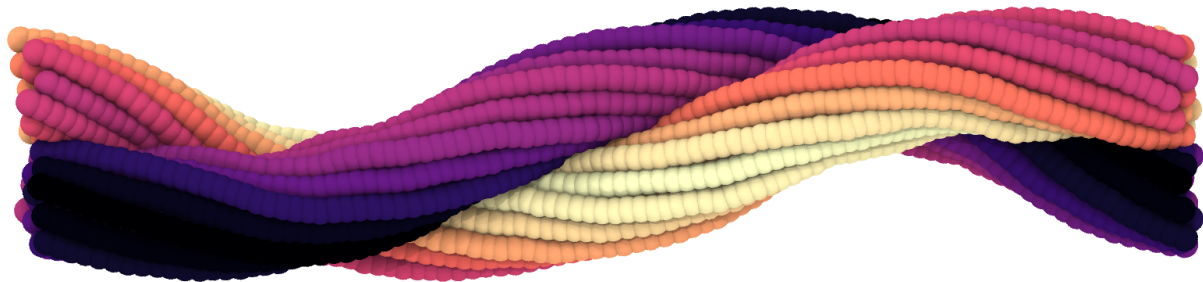


Figure 4.151. Extracted relaxed 2-ply twisted warp yarn from B601. Yarns are deformed where they contact weft yarns. Coarse-grained fibers are uniquely colored.

Coarse-grained, explicit fiber models were simulated using the same discrete element with bonded particle model methodology used in Section 4.5.3.1-2, but with less stiff bonds and fiber-fiber contacts. To simulate a representative weave unit cell required multiple tools. Weave pattern, yarn height, width, and spacing were input into TexGen [23, 24] to generate a meshed weave representation. Tools were developed for SUMAC to convert the TexGen output to a yarn path, and to populate yarns with twist and/or plies along the path. Here, in the context of yarns, plies define the number of yarns that are twisted together to make a tow. In the context of composites, plies defines the number of weave layers. Tools developed for STMD's Entry Systems Modeling Project were utilized for populating fibers along the yarn path. Weaves were relaxed. Warp and weft (in-plane) directions obeyed periodic boundary conditions and were unconstrained in the through-thickness direction.

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There are many promising future directions for coarse-grained fiber simulations. The planned SUMAC work is still very relevant for future natural fiber composite projects. SUMAC planned to apply these simulations to weave patterns outside those tested experimentally; preliminary work on satin patterns was promising. Simulating the full composite, combining Sections 4.5.3.2 and 4.5.3.3, would benefit from more experimental data on dry weaves, and could test hypotheses on the trends observed with different fibers and resin composites. The process to generate configurations of the weaves infused with bio resin models is developed but there was insufficient time to run the simulations. These methods have promise for modeling more traditional aircraft composites, such as carbon and glass fiber-epoxies. For all these directions, future work should automate more aspects of the coarse-graining process from explicit full fiber yarn simulations, to connect Sections 4.5.3.1 and 4.5.3.3.

4.5.4 Key Takeaways

- Fiber cross sectional properties were calculated by segmenting, instantiating and analyzing optical microscopy segmentation to quantify microstructure variation and influence of manufacturing.
 - Fibers are very deformable and non-circular (circularities of 0.2 were observed).
 - Fiber cross-sectional equivalent diameters D range from submicron to 20 μm , where $D_{\text{flax braid-PHB}} > D_{\text{hemp-PHB}} \approx D_{\text{flax twill-PHB}} > D_{\text{flax twill-PHB}} \approx D_{\text{hemp-PLA}}$.
 - Fiber shapes range from flattened, aspect ratios $R_{\text{long}}/R_{\text{short}}$ up to 5, to round, $R_{\text{long}}/R_{\text{short}}=1$.
 - Core perimeter likely drives deformation and were calculated $P_{\text{core}}=7 \mu\text{m}$.
- Segmentation of composite CT scans revealed good infusion quality with less than 2 vol% voids. Two types of voids, linear cracks and fiber-resin gaps, were identified.
- Explicit-fiber yarn simulations, parameterized from single-fiber measurements, resolved and identified slack as a cause for yarn strain-hardening tensile behavior.
- The bonded network model of PLA, PHA and PA11 resins captures tensile behavior, and can model an infused weave.
- Computational models of the weave unit cells matched the pattern (including plain, twill and triaxial braid), yarn ply (1 to 2), and yarn twist from optical microscopy.

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4.6 System Analysis - Life Cycle Analysis (LCA)

4.6.1 Introduction

Environmental impacts and benefits need to be assessed over a product's full lifecycle. This includes sourcing of raw material, processing the material into an end-use product, evaluating the use of the product in service, and considering end-of-life options for the product. Environmental life cycle analysis (LCA) is a formal methodology and modeling tool that can be used to quantify these impacts. This method compiles the input and outputs materials across a product's life cycle and translates these into environmental impacts across a range of environmental categories.

LCA for Transportation Applications: For commercial aircraft, previous LCA studies estimate that approximately 75 - 99% of greenhouse gas (GHG) emissions are due to the use phase of the aircraft [1]. A study focused on advanced air mobility vehicles shows very similar results [2]. These results indicate that the energy used to power aircraft dominate the environmental impact of the aircraft over its lifetime. Thus, the most effective way to minimize environmental impact of an aircraft is to minimize the amount of power required to operate the aircraft.

With respect to an existing aircraft structure, the primary design choice for reduction of the operating power is a reduction in the weight of the aircraft by replacing materials with more weight-efficient alternatives. Thus, from an environmental perspective, new materials should be used in aircraft if they accomplish the same function as the part they are replacing with equivalent or less weight.

While the environmental impacts of sourcing raw materials, processing, and end-of-life are typically small relative to the energy/fuel usage of an aircraft, it is still important to quantify these impacts to better understand the opportunities and challenges for environmental stewardship. This is especially true because as battery-powered vehicle technology advances, the environmental impacts of the use phase are expected to decrease with improvements in battery efficiency and a cleaner electricity grid.

4.6.2 SUMAC LCA: Scope, Methodology and Assumptions

This LCA modeling effort focuses on comparing the environmental impact of a conventional fiber composite comprised of glass fibers and a phenolic thermoset polymer to a sustainably derived composite comprised of natural fibers and several naturally sourced resins for advanced air mobility applications. The sustainably derived panels include either hemp or flax fibers and either polylactic acid (PLA), polyhydroxybutarone (PHB), or polyamide 11 (PA11) as the resins.

4.6.2.1 Scope and Assumptions

The scope of this LCA is cradle-to-use phase for an electric powered advanced air mobility aircraft including raw materials, manufacturing, and use. Disposal is considered out-of-

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scope at this point in the project since end-of-life scenarios for advanced aircraft are currently speculative and likely to change. Flights of the same aircraft will be compared with the only difference being the composite panel used. Therefore, only the panel materials and their associated weight are in scope as the rest of the components of the aircraft are identical, so the environmental impacts are the same in comparison. The sustainably derived panels are still under development, so their specific materials properties are not fully characterized or optimized. The panels may have slightly different thicknesses to meet their functional requirements depending on the properties of the fibers and matrix materials. The panels are assumed to have similar mechanical and durability properties over their lifetime.

Aircraft composite panels are comprised of a core material, composite skins with fibers and a polymer matrix, flame retardants on the skins, and an outer decorative film. The flame retardants and decorative film for each composite panel are assumed to be the same for all cases and therefore are left out of scope.

Given that at the time of project completion neither the application area for the fiber composite system nor the fiber composites systems mechanical properties were fully defined, the LCA modelling effort will investigate the effect of both reducing and adding mass to the vehicle as a result of replacing the conventional composites with the sustainably derived composites. The sustainably derived composite will be modeled at the same mass as a conventional panel and at both 10% and 20% lower and higher mass. This range should account for a wide range of panel mechanical properties and final panel thicknesses and densities.

4.6.2.2 Functional Unit

The functional unit for this LCA is a generic interior panel for an advanced air mobility aircraft with dimensions of 48 inches by 60 inches operating for 10,000 flights at 30 minutes per flight. These results can be scaled to larger panel areas as appropriate.

4.6.3 Life Cycle Inventory (LCI)

The life cycle inventory details the key inputs and outputs which comprise the LCA models for each of the composite panels. This inventory is based on lab-scale experiments, company product specifications, research articles, scientific estimates, and LCA inventory databases such as EcoInvent as detailed in this section.

4.6.3.1 Raw Materials

The project investigated a number of promising naturally derived resin materials including Arkema PA11 which is produced from castor oil, Mango PHB which is produced by methanotroph bacteria using methane from landfills/wastewater treatment plants, and Pond Global PLA which is a biodegradable plant-derived thermoplastic resin.

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The mass inputs for the bio-based composite panels are based on lab-scale panels produced at NASA Glenn at a 12" x 12" scale. The composition of each fiber/resin combination is 50%/50% by mass. The conventional panel reference is taken from an LCA article on novel aircraft interior panels and it has a glass fiber-to-phenolic resin matrix ratio of 63%/37% and a panel skin-to-core ratio of 74%/26% [3]. The sustainably derived polyetherimide foam core from this article is assumed to be the core of our sustainably derived composite for the LCA model whereas the conventional panel has an aramid fiber paper honeycomb core. The sustainably derived composite skin-to-core ratio is also fixed from the LCA article at 86%/14%. Table 4.16 gives the mass of the panels using these benchmarks, the NASA sustainably derived composite compositions, and scaling everything up to the functional unit area of a 4' x 5' panel.

Table 4.16 Inventory masses for 4' x 5' panel.

Component	Material	Amount (kg) - baseline (equal panel masses)		
		Conventional Panel	Hemp/Biopolymer Panel	Flax/Biopolymer Panel
Core	Aramid Fiber Paper	0.76	---	---
Flax / biopolymer	Polyetherimide	---	0.40	0.40
Skin polymer matrix	Phenolic Resin	0.78	---	---
	PLA/PHB/PA11	---	1.25	1.25
Skin fiber reinforcement	Glass fiber	1.36	---	---
	Flax fiber	---	---	1.25
	Hemp fiber	---	1.25	---
Total mass		2.90	2.90	2.90

The LCI inventory is provided in Table 4.17 listing the design material, LCA material or proxy, specific LCI process and source. In some cases, the specific materials were not publicly available (n/a) for the LCA model at the end of this project so proxy inventory data was chosen when available using other materials with similar eco-profiles. The PHB and PA11 polymers do not have good LCI public data and data from the specific manufacturers has not yet been provided so the composites with these polymer matrices were not modeled and results are not yet available. The models, however, can be built using the methods and details in this report in the future when the actual inventory data are available.

The conventional panel core material was an aramid fiber paper from the aircraft interior panel LCA article [3]. The LCI data was not available for this polymer typically synthesized using aromatic acid-chloride solution polycondensation and solvent handling.

Polycarbonate is a common polymer with public LCI data which has a reasonably close combination of aromatic feedstocks and a chlorinated-reagent polymerization process and was used as a proxy for the aramid fiber paper in the model.

The biopolymer composite panel core was chosen as polyetherimide (PEI) from the same aircraft interior panel LCA article [3]. The LCI data was also not available for this polymer,

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but polysulfone is a good proxy and it has a similar synthesis and processing which require high temperature aromatic step-growth and is solvent-intensive.

Table 4.17 LCI panel material details for the LCA model.

Panel Material	LCA Material	LCI Process	LCI Source
Aramid Fiber Paper	Polycarbonate	Polycarbonate {RER} polycarbonate production Cut-off, U	EcoInvent 3
Polyetherimide	Polysulfone	Polysulfone {GLO} polysulfone production, for membrane filtration production Cut-off, U	EcoInvent 3
Phenolic Resin	Phenolic Resin	Phenolic resin {RER} market for phenolic resin Cut-off, U	EcoInvent 3
PLA	PLA	Poly(lactic acid, granulate {GLO}) market for poly(lactic acid, granulate Cut-off, U	EcoInvent 3
PHB	n/a	Waiting for company-specific (Mango) data	
PA11	n/a	Waiting for company-specific (Arkema) data	
Glass Fiber	Glass Fiber	Glass fibre {GLO} market for glass fibre Cut-off, U	EcoInvent 3
Flax Fiber	Flax Fiber	Fibre, flax {GLO} market for fibre, flax Cut-off, U	EcoInvent 3
Hemp Fiber	n/a	Hemp data available but not in fiber form	

Inventory masses were scaled up and down based on Table 4.16 to get biopolymer panels that were both 10% and 20% lighter and heavier. These alternative inventory mass scenarios keep the core-to-skin and matrix-to-fiber mass ratios the same and are shown in the Appendix of this LCA section. Changing panel thickness and hence weight is one way to affect mechanical properties. Another approach to optimizing mechanical properties would be to adjust the fiber/resin and skin/core ratios which were held constant for this modeling effort.

4.6.3.2 Fabrication Methods

The general manufacturing process and flow are shown in Figure 4.152. The process is similar for each polymer and natural fiber system. The process starts with PLA, PHB, or PA11 pellets which are pressed into sheets. Those sheets are combined with dried flax or hemp sheets to produce the composite panels. Current NASA lab-scale processing of these composites uses 390 °F, 380 °F, and 250 °F ramped to 410 °F, for PLA, PHB, and PA11 polymers, respectively. Since processing has not yet been optimized and energy use was for lab-scale manufacturing rather than industrial-scale manufacturing, detailed process energies have been left out of the LCA scope though some basic materials processing energy for molding and pressing polymer sheets (~2 kWh/kg) and panels has been estimated and included. More accurate and properly scaled energy usage can be added later as the process is refined. This decision is justified based on the general LCA knowledge that raw materials energy and impacts are typically at least an order of

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magnitude higher than processing energy and impacts. Moreover, the manufacturing of conventional panels by pressing glass fibers into a polymer matrix is estimated to be similar or more than for biofibers and biopolymers. Different manufacturers have different processes and it is noted that pressing temperatures for phenolic/glass fiber composites are typically in the 350 – 365 °F range.

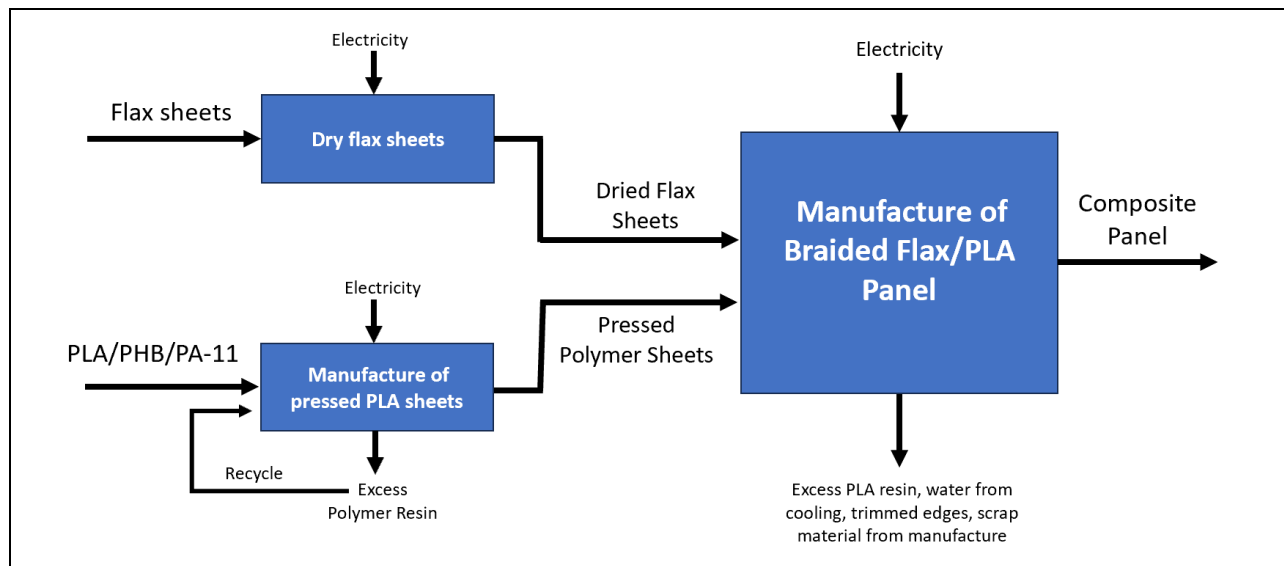


Figure 4.152 Manufacturing process flow for composite panel production with flax and a polymer matrix.

4.6.3.3 Use Phase

Publicly available estimates of the cruise, hover, and climb energy consumption [4] of an advanced air mobility vehicle were leveraged to establish estimates of the environmental impact of an advanced air mobility vehicle over the course of its service life. These and other key assumptions that governed the use phase model are summarized in Table 4.18.

Table 4.18 Estimates of key parameters used to determine the environmental impact of an advanced air mobility aircraft's use phase.

Parameter	Value
Cruise Consumption	98 kW
Hover/Climb Consumption	375 kW
Hover/Climb Share	0.25
Hours for Average Trip	0.5 hours
Power train & Battery Efficiency	0.75
Number of flights	10,000

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The mathematical expression that relates mass and power requirements for a given configuration of a propeller driven airplane operated at constant altitude and constant lift coefficient at $(\text{Lift/ Drag})_{\max}$ [5] is given in equation (4.19):

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{m_2}{m_1}\right)^{\frac{3}{2}} \quad (4.19)$$

$$E = P \cdot t = P_1 \cdot t \cdot \left(\frac{m_2}{m_1}\right)^{\frac{3}{2}} \quad (4.20)$$

where P_1 is the power required for the aircraft with mass m_1 and P_2 is the power required for the aircraft with weight m_2 . Equation (4.20) builds off equation (4.19) and considers the time in each of the different phases of flight to determine total energy requirements. Based on the Joby Aviation S4 production prototype aircraft specifications [6], the aircraft has an empty mass of 4,300 pounds and a 1,000 pound payload. Using this information, the electricity requirements for an average aircraft flight (based on our assumptions) are approximately 111.5 kWh/flight. Assuming the aircraft operates for 10,000 flights this amounts to a lifetime energy usage of 111,500 kWh.

The mass differences for the different composites (Table 4.16) allow the estimation of the electricity required to leverage those composites on the aircraft using equation (4.20). The mass of the aircraft with the conventional panel is 5,300 lb (2404 kg) while the weight with the other panels at both 10 and 20 % lighter and heavier is shown in Table 4.19. The corresponding energy requirements for these panels was calculated using equation (4.20).

Table 4.19 Mass and energy for panels with the same and different masses.

	Sustainable Composite Mass Relative to Conventional Panel				
	Equal Mass	10% Lighter	10% Heavier	20% Lighter	20% Heavier
Aircraft Mass (kg)	2,404	2,403.71	2,404.29	2,403.42	2,404.58
Aircraft Electricity (kWh)	111,500	111,480	111,520	111,460	111,540

A U.S. national average electricity grid is assumed to charge the batteries of the aircraft modelled in this study. The fuel source percentages are shown in Table 4.20 based on the EPA eGrid 2023 database [7]. For simplicity, typical energy production processes were chosen based on dominant subgrids rather than breaking down energy sources for each region of the electrical grid. This choice is expected to have a minor effect on the final results and could be adjusted to specific eGrid subregions as part of future modeling efforts. The fuel source breakdown in Table 4.20 is used to estimate the greenhouse gas (GHG) equivalents and other environmental impacts. The total for these source percentages is slightly above 100% due to rounding errors in the original data.

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Table 4.20 Assumed US grid fuel source breakdown used in this study.

Electricity Fuel Source	US eGrid Average 2023 Fuel Source (%)	LCI Process	LCI Source
Natural Gas	42.7	Electricity, natural gas, at power plant/US	USLCI
Coal	16.2	Electricity, bituminous coal, at power plant/US	USLCI
Oil	0.6	Electricity, residual fuel oil, at power plant/US	USLCI
Other Fossil	0.5	n/a	
Nuclear	18.6	Electricity, nuclear, at power plant/US	USLCI
Hydropower	5.9	Electricity, high voltage {US-WECC} electricity production, hydro, pumped storage Cut-off, S	EcoInvent 3
Biomass	1.1	Electricity, biomass, at power plant/US	USLCI
Wind	10.1	Electricity, high voltage {US-TRE} electricity production, wind, 1-3MW turbine, onshore Cut-off, S	EcoInvent 3
Solar	4.0	Electricity, low voltage {US-WECC} electricity production, photovoltaic, 570kWp open ground installation, multi-Si Cut-off, S	EcoInvent3
Geothermal	0.4	Electricity, high voltage {US-WECC} electricity production, deep geothermal Cut-off, U	EcoInvent3
Other	0.1	n/a	
Total	100.2		

4.6.3.4 End of Life

For this study, the aircraft panel end-of-life will be neglected due to uncertainty and the expectation of relatively low environmental impacts. Many LCA studies for the disposal of the low toxicity materials like present in this system find small contributions compared to the other life cycle phases. Conventional composites often end up in landfills because the panels are difficult to recycle given the bonding of the thermoset resins and the glass fibers. These materials breakdown very slowly and have few emissions. There are potential pros and cons for the end-of-life of the sustainably derived composite panels. These materials are designed with the intention to be composted with environmental benefits, but the logistics and infrastructure for these materials is still not robust. On the other hand, if these panels are disposed in landfills due to lack of composting options, the organic materials will decompose anaerobically to produce methane, a powerful greenhouse gas if not collected.

4.6.4 LCA Methodology

Several life cycle impact assessment (LCIA) methods were used to fully characterize the environmental impacts of this aircraft panel system.

The main method was the EPA Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [8]. This tool provides characterization factors to quantify the potential impacts that inventory items have on the following impact categories: acidification, climate change, ecotoxicity, eutrophication, human health impacts, ozone

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depletion, and smog formation. TRACI version 1.09 was used with the US 2008 normalization factors. The global warming calculations in TRACI use the International Panel for Climate Change (IPCC) 100-yr global warming potentials (GWPs). Cumulative Energy Demand (CED) is a method which sums all energy use across the processes and materials within the LCA boundaries. It is useful because energy amounts are typically more accurate and easier to explain and interpret across stakeholder knowledge levels. CED methods can also differentiate between different sources of energy (e.g. fossil, nuclear, renewable) which have different environmental impacts due to their significantly different inputs and outputs. In this work, CED version 1.12 [9] was also used to provide life cycle energy totals across the systems under study.

ReCiPe, one of the most widely used LCA impact methods, was also used to combine all quantitative environmental impacts into a single environmental score [10]. This option is not available using TRACI since the latter does not provide specific subjective weighting factors for the individual environmental impact categories. The ReCiPe method includes subjective weighting factors for three different cultural perspectives: individualist (I), hierarchist (H), and egalitarian (E). The individual perspective is categorized by short term timeframe and only proven scientific impact. The hierarchist perspective is the most commonly used because it is rooted in scientific consensus regarding impact and it uses a balance between short- and long-term timeframes. The egalitarian perspective is based on a very long timeframe and considers all potential environmental impacts. In this work, the ReCiPe 2016 Endpoint (H) V1.09 / World (2010) H/A method was used. The sensitivity of the LCA results to these different perspectives can be varied in future studies depending on the stakeholder preferences.

SimaPro v9.6 was used as the LCA modeling software and EcoInvent v3 was used for most of the inputs and outputs except as detailed in the sections above.

4.6.5 Results

Preliminary LCA model results have been completed for the conventional aircraft panel and the PLA/Flax sustainably derived composite at the same mass, 10% lighter/heavier, and 20% lighter/heavier. As mentioned above, the missing LCI inventory prevented the LCA analysis of sustainably derived composites with hemp as a fiber and PHB and PA11 as the polymer matrix. The LCA models can readily accommodate these material systems as the inventory data becomes available. Table 4.21 shows the global warming impact values in units of kg CO_{2,e} which refers to equivalent carbon dioxide mass since this value combines all greenhouse gases and scales their potential warming effect relative to carbon dioxide. It is seen that the aircraft electricity usage drives the global warming results compared to the aircraft composite panels. This matches the results in the literature for previous studies of this type with a variety of materials. It is the differences between the panel materials and masses that are more relevant for comparison. The differences between the lightest/heaviest panels and the baseline are on the order of 20 kg CO_{2,e} while the difference for the panel materials and processing is on the order of 3 - 4 kg CO_{2,e}. This again points to the importance of mass savings to minimize environmental impact.

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The electricity and materials contribution to global warming impact increases as the composites add mass and decrease as the composites lose mass. This result is partially due to the model assumptions that panel components stay in the same mass ratios as their total mass changes. This assumption may not hold with future research to optimize the properties of the panels in an attempt to reduce their overall mass which is seen to have the largest impact on the overall greenhouse gas emissions.

Table 4.21 Global warming values for panels using TRACI and IPCC GWPs.

Panel Type (relative mass)	Global Warming (kg CO _{2,e})					
	Conventional (baseline)	PLA/Flax (-20%)	PLA/Flax (-10%)	PLA/Flax (baseline)	PLA/Flax (+10%)	PLA/Flax (+20%)
Aircraft Electricity Usage	64,430	64,410	64,420	64,430	64,440	64,450
Materials & Manufacturing	14.9	13.9	15.7	17.4	19.1	20.9
Fiber	3.45	1.39	1.56	1.73	1.90	2.08
Polymer Matrix	3.51	1.02	1.15	1.27	1.40	1.53
Core	4.58	8.84	9.94	11.0	12.1	13.3

The bottom three rows of Table 4.21 breakdown the materials and manufacturing global warming into the panel components. Manufacturing electricity is not included as a separate row, but is included in the Materials & Manufacturing category as it's the least accurate of the model data. From this data, it is useful to note that the conventional panel has roughly equal global warming impacts for its fiber, polymer, and core. The result is quite different for sustainably derived composites as the core is almost a factor of 10 higher than the sustainably derived fibers and matrices and more than twice that of the conventional core.

This results is partially due to some model assumptions. This NASA composite work was focused only on the fiber and polymer composite for the skin of the panel and did not look at core materials and processing. To make this LCA more complete and realistic, the core materials and relative masses were added to the model based on a previous LCA study on aircraft composite materials. It is not known for certain but hypothesized that the polyetherimide core from that article was chosen for its low mass and high mechanical performance since it is a relatively high-performance polymer and has significantly higher global warming emissions per unit mass than the aramid fiber paper used for the core of the conventional panels. A logical step for the future would be to research sustainably derived novel core materials as well so that the entire composite panel could be sourced from more sustainable, lower embodied energy, and compostable materials.

Table 4.22 shows the Cumulative Energy Demand for the same panels. The differences in total aircraft electricity use are very small because of the modest weight of the interior panel relative to the overall aircraft. It is not surprising that they follow the same trend as the greenhouse gas emissions since a high percentage of the energy used over the life cycle of these panels comes from fossil sources. The energy breakdown for all panel cases is

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approximately 76% fossil fuels, 18% nuclear energy, and 6% renewable energy sources. This is driven primarily by the fuel mix in the model which was assumed to be the US national average for electricity. If the electricity came from a subregional grid with higher renewable energy percentages, the Cumulative Energy Demand would not change but the greenhouse gas emissions would drop significantly. This will be true if the overall US grid moves to more renewable and nuclear energy and less fossil fuels. If this occurs, the total global warming impacts for electric aircraft flight will drop significantly and be a less dominant contributor across the life cycle. This is one motivation for continued work in this area as materials will have a larger contribution to the system as the grid moves to more renewable energy.

Table 4.22 Cumulative Energy Demand (CED) results for the panels.

Panel Type (relative mass)	Cumulative Energy Demand (GJ)					
	Conventional (baseline)	PLA/Flax (-20%)	PLA/Flax (-10%)	PLA/Flax (baseline)	PLA/Flax (+10%)	PLA/Flax (+20%)
Aircraft Electricity Use	1354.9	1354.4	1354.7	1354.9	1355.2	1355.4
Panel Materials and Manufacturing	0.325	0.441	0.496	0.551	0.606	0.662

Figure 4.153Figure 4.154 show network diagrams from the ReCiPe impact assessment method for the panels at the same mass. Network diagrams are common LCA visual representations of the aggregated environmental impact factor in units of ecopoints (Pts) which include subjective weighting factors across the different impact categories. They allow direct comparison of the overall environmental impacts among products with the same functional unit. The network diagram shows a visual flow of environmental impacts from the system at the top down through the materials and processes below. Only the top two levels of the network diagrams are shown in the figures for the conventional and flax/PLA panel – there are many lower levels which include all of the inventory for all of the materials and processes which make up the panel components. Full network diagrams allow environmental impacts to be traced down through the whole life cycle inventory, but adding more levels gives a very large and complex diagram quickly. Note that the width of the red lines between the various unit process boxes in the network diagram is proportional to the weighted environmental impact for easier visual interpretation of the individual impact values which are also listed at the bottom of each materials or process box. Similar diagrams for the lighter and heavier panels are not shown as they would look nearly identical since the materials and processes are the same, but the magnitude of the impacts would scale up as the masses increase as was seen in the previous results. These diagrams show that the conventional panel has roughly equal contributions from the fibers, polymer, and core while the sustainably derived composite has a much stronger impact from the polysulfone core material. These results are largely consistent with the results presented in Table 4.21 for global warming impact, but these results include global warming impact and well as many other environmental factors.

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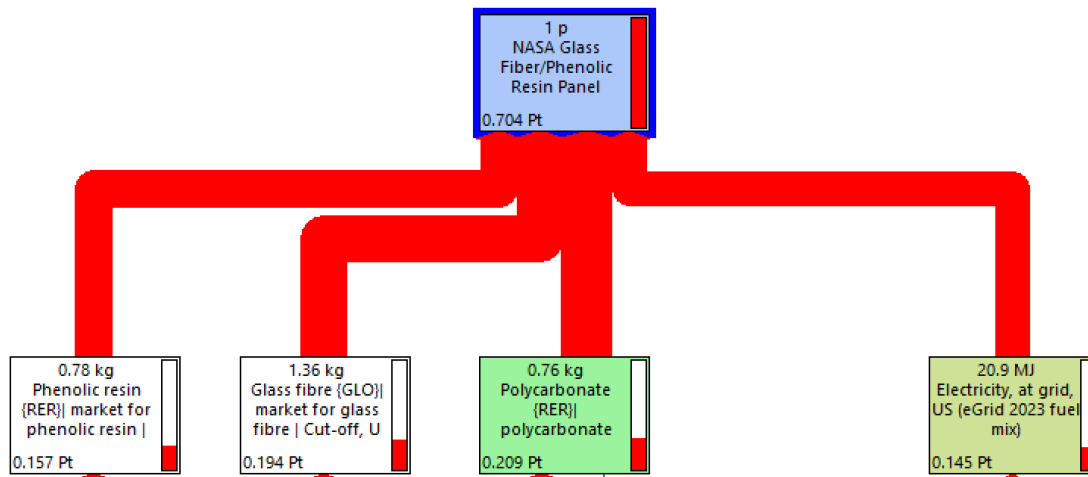


Figure 4.153 ReCiPe network diagram showing weighted total environmental impacts for the conventional panel.

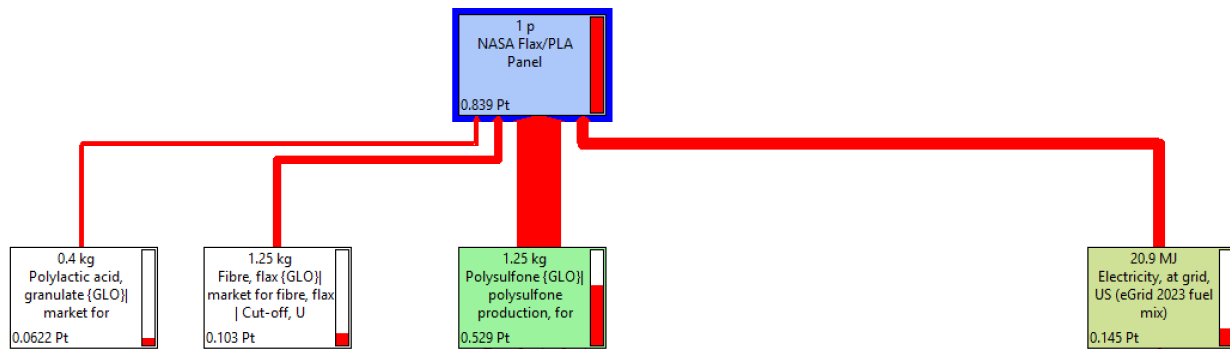


Figure 4.154 ReCiPe network diagram showing weighted total environmental impacts for the Flax/PLA panel.

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4.6.6 References

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4.6.7 Appendix

Table 4.23 10% lighter bio-sourced panels keeping core-to-skin and matrix-to-fiber ratios fixed.

Component	Material	Amount (kg) - baseline (equal panel masses)		
		Conventional Panel	Hemp/Biopolymer Panel	Flax/Biopolymer Panel
Core	Aramid Fiber Paper	0.76	---	---
	Polyetherimide	---	0.37	0.37
Skin Polymer matrix	Phenolic Resin	0.78	---	---
	PLA/PHB/PA11	---	1.12	1.12
Skin Fiber reinforcement	Glass fiber	1.36	---	---
	Flax fiber	---	---	1.12
	Hemp fiber	---	1.12	---
Total mass		2.90	2.61	2.61

Table 4.24 10% heavier bio-sourced panels keeping core-to-skin and matrix-to-fiber ratios fixed.

Component	Material	Amount (kg) - baseline (equal panel masses)		
		Conventional Panel	Hemp/Biopolymer Panel	Flax/Biopolymer Panel
Core	Aramid Fiber Paper	0.76	---	---
	Polyetherimide	---	0.45	0.45
Skin Polymer matrix	Phenolic Resin	0.78	---	---
	PLA/PHB/PA11	---	1.37	1.37
Skin Fiber reinforcement	Glass fiber	1.36	---	---
	Flax fiber	---	---	1.37
	Hemp fiber	---	1.37	---
Total mass		2.90	3.19	3.19

Table 4.25 20% lighter bio-sourced panels keeping core-to-skin and matrix-to-fiber ratios fixed.

Component	Material	Amount (kg) - baseline (equal panel masses)		
		Conventional Panel	Hemp/Biopolymer Panel	Flax/Biopolymer Panel
Core	Aramid Fiber Paper	0.76	---	---
	Polyetherimide	---	0.32	0.32
Skin Polymer matrix	Phenolic Resin	0.78	---	---
	PLA/PHB/PA11	---	1.00	1.00
Skin Fiber reinforcement	Glass fiber	1.36	---	---
	Flax fiber	---	---	1.00
	Hemp fiber	---	1.00	---
Total mass		2.90	2.32	2.32

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Table 4.26 20% heavier bio-sourced panels keeping core-to-skin and matrix-to-fiber ratios fixed.

Component	Material	Amount (kg) - baseline (equal panel masses)		
		Conventional Panel	Hemp/Biopolymer Panel	Flax/Biopolymer Panel
Core	Aramid Fiber Paper	0.76	---	---
	Polyetherimide	---	0.48	0.48
Skin Polymer matrix	Phenolic Resin	0.78	---	---
	PLA/PHB/PA11	---	1.50	1.50
Skin Fiber reinforcement	Glass fiber	1.36	---	---
	Flax fiber	---	---	1.50
	Hemp fiber	---	1.50	---
Total mass		2.90	3.48	3.48

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5. Conclusion and Future Work

The CAS SUMAC project has demonstrated the technical feasibility and strategic value of multifunctional natural fiber thermoplastic composites for aerospace applications. By combining hollow-core flax and hemp fibers with bio-sourced thermoplastic resins (PLA, PHB, and PA11), the SUMAC project advanced the frontier of lightweight, multifunctional, and recyclable composite systems. These sustainable materials provide distinct benefits over conventional carbon fiber composites, including weight savings, superior vibration damping, acoustic attenuation, interference-free communication, and recyclability. These characteristics are well aligned with the performance requirements of Advanced Air Mobility and the long-term vision for commercial airliners.

Extensive, rigorous characterization confirmed that natural fibers can deliver glass-fiber-equivalent mechanical properties, with braided flax and woven hemp twill showing the strongest potential for aerospace-grade applications, while flax-PA11 commingled fibers offered a combination of high strength and toughness. PA11 emerged as the most promising resin, balancing thermal stability, mechanical properties, and environmental durability, while PLA and PHB showed application-specific advantages but also durability challenges. Fabrication of representative aerospace components, including Joby Aviation propeller blade skins and seat brace prototypes, demonstrated the manufacturability of SUMAC composites. Integrated sensing research highlighted that the performance of natural fiber composites can be further enhanced through tailored sensing technologies, with ultrasonic, microwave, dielectric, and THz methods, enabling material state awareness and structural health monitoring for future aerospace systems. Computational materials research offered predictive modeling and design optimization tools for SUMAC composite system, accelerating natural fiber and resin down-selection, and guiding experimental validation. Life cycle analysis further confirmed the environmental advantage of SUMAC composites over conventional composite systems, based on the natural fibers and bio-sourced thermoplastic resins the SUMAC project selected.

The project's impact extended beyond material science. Close collaboration and partnership with Joby Aviation, Boeing, EnviroTextiles, the U.S. Army, and Oak Ridge National Laboratory facilitated industry engagement, provided direct application pathways, and strengthened the domestic hemp fiber supply chain. Outreach through the SUMAC Working Group and workforce development efforts engaged over 120 stakeholders and trained more than 25 interns, ensuring knowledge transfer and a strong pipeline of future engineers and scientists in sustainable aerospace composite technology.

Looking forward, several key areas of research and development remain, including:

- **Fiber and Resin Optimization:** Continued down-selection of natural fibers and bio-sourced thermoplastics, with emphasis on improving consistency, resin matrix affinity, surface treatment, and environmental durability including UV, moisture, and elevated temperature.

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- **Acoustic and Damping Characterization:** Comprehensive testing across temperature and amplitude ranges, with targeted frequency studies for AAM aircraft, rotorcraft, and commercial airliner applications.
- **Prototype Demonstrations:** Fabrication and testing of bulkhead panels, fuselage liners, and acoustic panels under representative flight conditions to validate damping, acoustic, and mechanical performance.
- **Sensing and Monitoring:** Further development and demonstration of frequency-selective surface (FSS) sensors and other embedded sensing technologies to enable in-service material state awareness.
- **Computational Design Integration:** Expansion of multiscale modeling, machine learning, and digital twin concepts to accelerate composite design, guide certification testing, and enable predictive maintenance.
- **Domestic Fiber Supply Chain:** Scale-up and standardization of U.S. hemp processing to ensure consistency, mechanical reliability, and competitive sourcing, compared to European flax markets.
- **Certification and Integration:** Engagement with FAA and aerospace OEMs to evaluate flame, smoke, and toxicity (FST) performance and define certification pathways for adoption of natural fiber-reinforced composites in aviation.
- **Cross-Sector Applications:** Advancement of cross-domain applications in space, aero, automotive, packaging, and renewable energy systems to accelerate transition of SUMAC composite technology and strengthen industrial demand.
- **Life Cycle Assessment (LCA):** Expand LCA studies of SUMAC composites to include end-of-life recycling pathways and comparison with next-generation carbon fiber-thermoplastic systems to quantify long-term environmental and economic benefits.

In conclusion, the SUMAC project has successfully laid the foundation for a new class of aerospace composites that advance NASA's vision for multifunctional lightweight composite technology and sustainable aviation, while offering broader societal and industrial benefits in strengthening U.S. leadership in the natural fiber market, enhancing domestic supply chain resilience, and supporting workforce development. By uniting performance with sustainability, SUMAC composite technologies are set to impact the design of next-generation aircraft and beyond, helping shape a more efficient and environmentally responsible future for aerospace and related industries.

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6. Appendix

6.1 SUMAC Project Execution Timeline and Resource Plan

Table 6.1 Execution timeline of CAS SUMAC project (planned).

Quarters in Execution	FY24				FY25			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
SUMAC				ID	P3			CO

ID – Investment Decision

P3 – Persevere, Pivot, Punt Decision Point

CO – Close out phase (1 quarter/3 months) at approved maximum Level of Effort (LOE)

Table 6.2 Execution resource plan of CAS SUMAC project.

Resource Summary				
	FY24	FY25	FY26	Total
Procurement (\$K)	\$ 356.59	\$ 570.38	\$ 483.91	\$ 1,410.88
AFRC	\$ -	\$ -	\$ -	\$ -
ARC	\$ 46.38	\$ 11.00	\$ 11.00	\$ 68.38
GRC	\$ 237.52	\$ 424.73	\$ 331.66	\$ 993.91
LaRC	\$ 72.70	\$ 134.65	\$ 141.25	\$ 348.60
FTEs / WYE	2.48 / 0.07	6.9 / 1.05	7 / 1.4	16.38 / 2.52
AFRC	0 / 0	0 / 0	0 / 0	0 / 0
ARC	0.19 / 0.03	1 / 0	1 / 0	2.19 / 0.03
GRC	0.86 / 0	2.3 / 0.65	2.5 / 0.75	5.66 / 1.4
LaRC	1.44 / 0.03	3.6 / 0.4	3.5 / 0.65	8.54 / 1.08
Travel (\$K)	\$ 11.66	\$ 30.00	\$ 30.00	\$ 71.66
Full Cost (\$K)	\$ 848.48	\$ 1,986.86	\$ 1,958.33	\$ 4,793.67

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6.2 P3 Execution Events Summary Table (Planned)

The following table provides a summary of the CAS P3 Execution events agreed upon between CAS PM and PI, typically 2-4 of these per year. More thorough description of these items is located in the Event Descriptions and Timeline section below. The final close out report is due to CAS PM at the end of the Close out Phase (4QFY26).

Event #	Due Date	Activity Event (P3 Decision Point or Highlight Event)	Barrier (s) being addressed (i.e., D and/or V and/or F)	Criteria (measurable approach or test to overcome Barrier)	Outcome Anticipated and Stakeholder (s) engaged
R1/R2	4QFY25 Completed (xx/xx/xx)	P3 Decision, Resin Down Select	Viability, Most Promising Material Properties	Thermal test results, rheology, microscopy	Best resin, PLA or PHA, for AAM applications
R3	4QFY26	Operational Environment Evaluation	Viability, determination of ability of resins to persist in operational environment	Mechanical test results, thermal test results, rheology, microscopy	Determined durability of resins in operational environment
R4	4QFY26	Crystallization Kinetics (Nice to Have)	Feasibility, influence of thermal processing on crystallization	Thermal test results, rheology, microscopy	Identification of ideal thermal processing conditions to maximize manufacturing rate and degree of crystallinity
R5	4QFY26	Isosorbide Research (Nice to Have)	Desirability, Lower TRL Material Research	Mechanical test results, thermal test results, rheology, microscopy	Determination of whether these materials can be utilized for AAM applications
F1	1QFY25	P3 Decision, Fiber Down Select	Viability, Most Promising Material Properties	Mechanical test results for natural fiber systems	Best fiber material, flax or hemp, for AAM applications
F2	4QFY25	Resin-Fiber Interaction Characterization	Feasibility, enabling best composite mechanical properties	Mechanical test results, microscopy, contact angle goniometry	Best resin/fiber combination and infusion process
F3	1QFY26	Fabric Characterization	Feasibility, determination of best weave patterns	Mechanical test results, microscopy	Best weave pattern for AAM applications

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Event #	Due Date	Activity Event (P3 Decision Point or Highlight Event)	Barrier (s) being addressed (i.e., D and/or V and/or F)	Criteria (measurable approach or test to overcome Barrier)	Outcome Anticipated and Stakeholder (s) engaged
F4	2QFY26	Environmental Stability Evaluation	Viability, determination of ability of fibers to persist in operational environment	Mechanical test results, microscopy, spectroscopy, contact angle goniometry	Determined durability of natural fiber systems in operational environment
F5	3QFY25	Material Property Variation Evaluation	Viability, batch to batch variability	Mechanical test properties, optical microscopy, spectroscopy	Determination of anticipated change in material properties from different fiber batches
M1/M2	1QFY26	P3, Composite Material System Down-select	Material availability, manufacturability, and composite properties	Composite panel manufacture and test to demonstrate (1) high quality laminate production and (2) acceptable mechanical properties	Report on the manufacturing process and mechanical test data for candidate materials.
M3	4QFY26	Sub-Element Fabrication and Assessment	Possible variation in mechanical property data, scale-up of the manufacturing process, and performance for use in an AAM application.	Manufacturing and joining of sub-elements. Low variability in sub-element test data. Reduced weight or similar performance to current state-of-the-art.	Report on the procedure to develop sub-element components, manufacturing assessment, and mechanical test data.
S1	3QFY25	Optimize Sensing Architecture	Viability, identifies viable sensing approaches for sustainable materials	Demonstrated sensitivity to material properties and key degradation mechanisms	Outlined sensing plan, initial models of sensing mechanisms
S2	4QFY26	Nondestructive Mechanical Property Assessment	Desirability, addresses potential for material property variation in sustainable composites.	Demonstrated in-situ measurement accuracy relative to mechanical testing	Demonstration of mechanical property measurement and tracking at vehicle-scale

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Event #	Due Date	Activity Event (P3 Decision Point or Highlight Event)	Barrier (s) being addressed (i.e., D and/or V and/or F)	Criteria (measurable approach or test to overcome Barrier)	Outcome Anticipated and Stakeholder (s) engaged
S3	3QFY26	P3, Report on Sensing Needs for AAM	Sustainable composite viability in operating environment. Feasibility of health monitoring for tracking material state (V, F)	Demonstration of in-situ moisture monitoring. Vehicle-scale demonstration of elastic property assessment.	Summary of viable sensing techniques and next steps for monitoring natural fiber composites in AAM aircraft.
S4	4QFY26	Evaluating Damage Tolerance	Desirability of sustainable materials via improved damage tolerance. Feasibility of wireless sensing for monitoring for damage events.	Quantified sensitivity to strain, impact, and vibration. Quantified strength retention in sustainable materials post-impact.	Report on damage tolerance metrics and sensor performance.
CM1	2QFY26	P3, Component and Composite Model Development	Feasibility of resolving composite microstructure and component-specific properties with modeling.	Mechanical validation with experiments. Numerical stability and scalability.	Model for each component and the composite. 3D weave tools adaptation to natural fiber 2D weaves.
CM2	1QFY26	Weave Pattern and Composite Layup	Desirability, efficiently screen weave patterns of natural fibers for composites.	Provide guidance for new weave pattern testing. Mechanical and structural experimental agreement.	Weave simulation and analysis. Influence on experimental weave design. Microstructural features and mechanical behavior correlations.
CM3	4QFY26	Composite Simulation and Microstructural Analysis	Viability, diagnose sustainable composite performance changes due to variation, non-uniformity and component changes.	Discern full composite performance sensitivity due to microstructure and components. Qualitative agreement with experimental mechanical tests.	Deformation simulations of idealized composite. Composite mechanical performance sensitivity to fiber-resin interaction.

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Event #	Due Date	Activity Event (P3 Decision Point or Highlight Event)	Barrier (s) being addressed (i.e., D and/or V and/or F)	Criteria (measurable approach or test to overcome Barrier)	Outcome Anticipated and Stakeholder (s) engaged
SA1	2QFY25	Compile and Review the Existing AAM Concept Vehicle Designs and Requirements	Material property data availability and intellectual property concerns of AAM vendors.	Testing completed as part of this CAS project will help inform material property data. Space Act Agreements and publicly available data will be sought as needed.	AAM target application identified.
SA2	4QFY26	Life Cycle Analysis	Material property data availability and intellectual property concerns of AAM vendors	Testing completed as part of this CAS project will help inform material property data. Space Act Agreements and publicly available data will be sought as needed.	Completed lifecycle analysis for component identified.

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6.3 Sub Topic Overview and Timeline (Planned)

6.3.1 Sustainably-derived Thermoplastic Resins

Overview

The goal of this focus area is to develop sustainably-derived thermoplastic resins for Advanced Air Mobility (AAM) applications in the SUMAC program. This will be achieved by selecting and formulating appropriate thermoplastic resins, characterizing their material properties, and evaluating their environmental performance for SUMAC composites. The SUMAC thermoplastic resins offer great mechanical properties, reduced waste, recyclability, and reusability in comparison to traditional thermosetting resins, making them a viable option for the SUMAC program. In this focus area, commercially available products and custom-formulated sustainable thermoplastic resins will be adopted for natural fiber reinforcement, sustainable composite manufacturing, sensor-based structural health monitoring, computational modeling, and life cycle analysis for efficient recycling and reusability. The timeline for the activities associated with this focus area is shown in Figure R1.

Task	Pre-Year		Year 1				Year 2			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
R1: Pond PLA										
Procure Pond PLA										
Rheological Characterization of Processing Conditions*										
Primary DSC Data Collection (Tg, Tm)*										
Fiber wetting study (Contact Angle Goniometry/Microscopy)*,**										
Dynamic Mechanical Analysis (Young's Modulus, Damping)***										
Spectroscopy (FTIR, Raman)										
R2: Mango Materials										
Initiate Mango Materials Partnership										
Receive Initial Custom Formulation										
Rheological Characterization of Processing Conditions* (First Formulation)										
Primary DSC Data Collection (Tg, Tm)* (First Formulation)										
Fiber wetting study (Contact Angle Goniometry/Microscopy)*,** (First Formulation)										
Dynamic Mechanical Analysis (Young's Modulus, Damping)*** (First Formulation)***										
Discuss Reformulation with Mango Materials										
Receive Second Custom Formulation										
Rheological Characterization of Processing Conditions* (Second Formulation)										
Primary DSC Data Collection (Tg, Tm)* (Second Formulation)										
Fiber wetting study (Contact Angle Goniometry/Microscopy)*,** (Second Formulation)										
Dynamic Mechanical Analysis (Young's Modulus, Damping)*** (Second Formulation)										
Spectroscopy (FTIR, Raman) (Second Formulation)										
Report Results and Down-Select Resin										
Determine whether a Third Mango Materials Formulation is Needed										
R3: Operational Environment Evaluation										
Prepare Mechanical Test Specimens										
Environmental Exposure (UV, thermal cycling, water absorption)										
Mechanical Testing and Microscopy Analysis										
Thermal stability testing (TGA, Rheology)										
Multi-cyclic Mechanical Test Specimen Generation and Testing										
Prepare Resin Coupons to Support Manufacturing and Test Team (e.g., Vibrational Analysis)										
R4: Crystallization Kinetics										
Crystallization kinetics study (Nice to have)										
Multi-batch Characterization for A or B Basis Allowables (Nice to have)										
Receive Third Custom Formulation (Potential)										
Rheological Characterization of Processing Conditions* (Third Formulation)										
Primary DSC Data Collection (Tg, Tm)* (Third Formulation)										
Fiber wetting study (Contact Angle Goniometry/Microscopy)*,** (Third Formulation)										
Dynamic Mechanical Analysis (Young's Modulus, Damping)*** (Third Formulation)										
Spectroscopy (FTIR, Raman) (Third Formulation)										
R5: Isosorbide Research										
Develop Funding Opportunity for Research Grant to Develop Isosorbide (Nice to Have)										
Award University Researchers										
Coordinate and Collaborate Activities with Academic Partner										
Report Results										

Figure R.1 Sustainably-derived thermoplastic resins activity timeline. Blue cells are active periods, orange cells are for report out events, yellow cells are “nice to have” activities, and stars indicate P3 events.

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Background

Thermoplastic resins derived from bio-based resources can maximize the sustainability of SUMAC composites. The bio-based thermoplastic resins can be categorized into three major groups: (1) natural bio-polymers such as polysaccharides and celluloses, (2) synthetic polymers from natural monomers such as poly-lactic acid (PLA) and isosorbide (ISB), and (3) bio-polymers from microbial fermentation such as polyhydroxyalkanoate (PHA). PLA, one of the promising bio-thermoplastic polymers, can be produced from various natural sources, including corn starch, potatoes, sugar beet and other agricultural byproducts. Bio-sourced isosorbide, instead of petrochemical monomers, can be used to make bio-derived synthetic polymers such as SUPERBIO-K or a ketone-type poly arylene ether (PAE), offering excellent thermal/mechanical properties, scalability, and sustainability that match those of petrochemical-based engineering thermoplastic resins. In addition, PHAs are bacterial polyesters known for their biodegradable properties and tailorable compositions including poly(3-hydroxybutyrate) (PHB) and varying PHA copolymers for improved mechanical properties.

R1: Pond PLA

Research Question/Event Purpose

Can polylactic acid (PLA) polymers from Pond,* be used to sustainably manufacture AAM components? By assessing PLA resins from Pond, this activity aims to investigate the molecular structure, material properties (thermal/mechanical/rheological), and interfacial affinity with natural fiber reinforcement for SUMAC composite manufacturing. Ultimately, this activity seeks to contribute to more sustainable manufacturing practices in the aviation industry, aligning with environmental sustainability goals of SUMAC program.

*Pond Global, <https://pond.global/>

Event Approach/Actions

The research approach involves a comprehensive evaluation of PLA polymers through in-house laboratory testing to assess their molecular structure and mechanical/thermal properties. Initial action items include sourcing PLA candidate resins from Pond and setting up protocols for standardized testing to compare them against traditional high-performance thermoplastic polymers for aircraft manufacturing. Technical collaboration with the resin supplier will ensure that the optimized PLA resins are formulated for SUMAC applications.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q3 of FY25.

Anticipated Outcome/Hypothesis

The anticipated outcomes of this activity include validating PLA thermoplastics as viable, sustainable resins for SUMAC composites, confirming their material properties required for

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SUMAC composites, and verifying their suitability for sustainable manufacturing processes for AAM vehicles. In collaboration with the resin supplier, the chemical structure of PLA could be tailored to provide optimized mechanical and thermal properties and enhanced interfacial affinity with natural fiber reinforcement. This work will also establish protocols and best practices for integrating PLAs into existing aerospace manufacturing processes. Finally, successful implementation of the selected SUMAC resins in AAM, supported by robust mechanical and thermal data, could encourage broader use of sustainably-derived thermoplastics across various sectors.

Criteria

The viability of this activity will be measured by the ability of PLAs to meet or exceed the material performance (Table R.1), particularly in terms of mechanical properties, thermal stability, interfacial affinity with natural fiber reinforcement, and environmental durability in the intended application space.

Table R.1 Material Property Metrics for Commercial Bio-based Thermoplastic Resins from Pond.

PLA from Pond	Material Properties	Material Specifications
Melting temperature (T _m)	> 160°C	T _m = 165-170°C
Thermal stability (30°C or greater above T _m)	> 190°C	3 point bending DMA tests on natural fiber composites (about 50 wt% fiber loading) showed that about 70 % of the bending modulus is retained at 100°C.
Minimum viscosity at processing temperature	< 1000 Pa.s	The viscosity is tailorable within the specified range.
Fiber wetting	Excellent	
Tensile modulus	> 20 GPa	Bending modulus > 20 GPa

Barrier(s)

One potential barrier to the success of this activity is the limited application of PLA composites to certain AAM components, due to their restricted mechanical and thermal properties. Optimized formulation and natural fiber reinforcement can help overcome this problem. When transitioning from small-scale laboratory synthesis to industrial quantities can be challenging and costly. Another significant barrier could be the initial cost of bio-based resins, which might be higher than traditional materials, potentially hindering their acceptance by cost-sensitive sectors of the aerospace industry. Regulatory hurdles also pose a barrier, as obtaining approval for new materials in aviation applications involves rigorous testing and certification processes that are time-consuming and expensive.

Data Management Plan

The data management plan for this activity involves a systematic approach to collecting, storing, and analyzing data to ensure integrity, confidentiality, and accessibility. All experimental and testing data and standard protocols on material properties and

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performance in various environmental conditions will be securely stored in a centralized database, e.g., Sharepoint, with controlled access to protect sensitive information and intellectual property. Regular backups and data audits will be automatically conducted to maintain data quality and prevent data loss. Additionally, the data management plan includes selectively sharing findings through peer-reviewed publications and presentations, to foster transparency and encourage further investigation into sustainable materials and manufacturing across aviation industry.

Stakeholder(s)

The stakeholders in this activity include: aerospace/automotive manufacturers that design and produce components, interested in innovative, sustainable materials to enhance their products; environmental regulatory agencies who are responsible for aircraft operation and safety and/or enforcing environmental standards; material suppliers that focus on developing new materials for aviation and other related sectors; sustainability advocacy groups that promote environmental sustainability and support the adoption of greener materials in industry; end users (airlines and cargo carrier companies) that operate aircraft and could benefit from reduced maintenance costs and improved public image due to sustainability; investors and funding entities who invest in sustainable technologies and innovations with potential for high impact and profitability.

R2: Mango Materials

Research Question/Event Purpose

Bio-based PHA thermoplastic resins offered by Mango Materials* are biodegradable polymers produced naturally by microbial fermentation of natural resources, which make them an excellent choice for sustainable manufacturing processes. Can PHA thermoplastic resins from Mango Materials be used as a sustainable alternative to conventional engineering polymers in AAM vehicles? SUMAC composites are developed by reinforcing PHA resins with natural fibers by sustainable composite processing, seeking to reduce the environmental footprint of aerospace manufacturing. This activity will closely work with Mango Materials to select the optimized PHA candidate materials and evaluate their major material properties and environmental performance to determine their feasibility for use in AAM components. Ultimately, this program effort strives to enhance sustainability within the aerospace industry and material supply chain, aligning with broader environmental objectives and setting a precedent for the adoption of green materials in aviation manufacturing.

*Mango Materials, <https://www.mangomaterials.com/>

Event Approach/Actions

The research approach involves a comprehensive evaluation of PHAs through in-house laboratory testing to assess their mechanical/thermal properties and interfacial affinity with natural fiber reinforcement. Initial action items include sourcing PHA candidate resins from Mango Materials and setting up protocols for standardized testing to compare them

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against traditional high-performance thermoplastic polymers for aircraft manufacturing. Technical collaboration with the resin supplier will ensure that the optimized PHA resins are formulated and tailored best suited for SUMAC applications.

Timeline

This activity is planned to begin during Q1 of FY25 and go through Q4 of FY25. If additional reformulation and testing are required, the activity may be subject to extension until Q3 of FY26.

Anticipated Outcome/Hypothesis

The anticipated outcomes of this activity include validating PHA thermoplastics as viable, sustainable resins for SUMAC composites, confirming their material properties required for SUMAC composites, and verifying their suitability for sustainable manufacturing processes for AAM vehicles. The iterative collaboration with the resin supplier will help tailor the molecular structure of PHA polymers, offering the optimized mechanical and thermal properties, enhanced interfacial affinity with natural fiber reinforcement, and improved performance in harsh environmental conditions. Finally, successful implementation of the selected SUMAC resins in AAM, supported by robust mechanical and thermal data, could encourage broader use of sustainably-derived thermoplastics across various sectors.

Criteria

The success viability of this activity will be measured by the ability of PHAs to meet or exceed the material performance (Table R.2), particularly in terms of mechanical properties, thermal stability, interfacial affinity with natural fiber reinforcement, and environmental durability in the intended application space. Another critical success metric will be the degree to which PHAs can reduce the environmental impact of manufacturing processes, as evidenced by improved recycling/reuse capability and reductions in greenhouse gas emissions and waste.

Table R.2 Material Property Metrics for Commercial Bio-based Thermoplastic Resins from Mango Materials.

PHA from Mango Materials	Material Properties	Specifications
Melting temperature (T _m)	> 160°C	T _m = 160-180°C
Thermal stability (30°C or greater above T _m)	> 190°C	Not stable above T _m = 180°C
Minimum viscosity at processing temperature	< 1000 Pa.s	275 Pa.s at 160°C
Tensile modulus	> 1.2 GPa	1200-1700 MPa (ASTM D638)
Tensile Strength	> 29 MPa	29-31 MPa
% Elongation at break	> 5%	5-7 %
Flexural modulus	> 2000 Pa	2000-2200 Pa

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Barrier(s)

One potential barrier to the success of this activity is the limited application of PHA composites to certain AAM components, due to their restricted mechanical and thermal properties. Optimized formulation and natural fiber reinforcement can help overcome this problem. When transitioning from small-scale laboratory synthesis to industrial quantities can be challenging and costly. Another significant barrier could be the initial cost of bio-based resins, which might be higher than traditional materials, potentially hindering their acceptance by cost-sensitive sectors of the aerospace industry. Regulatory hurdles also pose a barrier, as obtaining approval for new materials in aviation applications involves rigorous testing and certification processes that are time-consuming and expensive.

Data Management Plan

The data management plan for this activity involves a systematic approach to collecting, storing, and analyzing data to ensure integrity, confidentiality, and accessibility. All experimental and testing data and standard protocols on PHA material properties and performance in various environmental conditions will be securely stored in a centralized database with controlled access to protect sensitive information and intellectual property. Regular backups and data audits will be automatically conducted to maintain data quality and prevent data loss. Additionally, the data management plan includes selectively sharing findings through peer-reviewed publications and presentations, to foster transparency and encourage further investigation into sustainable materials and manufacturing across aviation industry.

Stakeholder(s)

The stakeholders in this activity include: aerospace/automotive manufacturers that design and produce components, interested in innovative, sustainable materials to enhance their products; environmental regulatory agencies who are responsible for aircraft operation and safety and/or enforcing environmental standards; material suppliers that focus on developing new materials for aviation and other related sectors; sustainability advocacy groups that promote environmental sustainability and support the adoption of greener materials in industry; end users (airlines and cargo carrier companies) that operate aircraft and could benefit from reduced maintenance costs and improved public image due to sustainability; investors and funding entities who invest in sustainable technologies and innovations with potential for high impact and profitability.

R3: Operational Environment Evaluation

Research Question/Event Purpose

The adoption of sustainable thermoplastic resins in aviation industry is crucial, given the increasing focus on reducing the environmental impact of materials used in aerospace applications. Can sustainable thermoplastic resins, such as PLA and PHA, exhibit their mechanical and thermal stability under various environmental conditions for use in AAM

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vehicles? By conducting key tests including exposure to UV light, varying temperatures, and mechanical stresses, this activity seeks to ensure these materials have the basic material properties to meet the rigorous safety and performance standards set by regulatory agencies like the FAA. The goal of this activity is to evaluate SUMAC resins for operational environment tests and reliably replace conventional materials.

Event Approach/Actions

This activity involves preparing test samples of sustainably-derived thermoplastic resins for a series of standardized tests to assess their mechanical, thermal, and environmental durability for aviation safety. The testing protocols include mechanical testing for strength and fatigue, as well as thermal analysis to determine stability across a range of operational temperatures. Subsequent tests focus on environmental resistance testing, evaluating how these materials withstand harsh operational conditions such as UV exposure, moisture, and extreme weather scenarios. Data collected from these tests will be meticulously analyzed to determine the degradation trends, performance thresholds, and operational limitations of these materials. In addition, test results will be also shared with other SUMAC team members to facilitate the SUMAC composite manufacturing and other activities. Based on the findings, comprehensive reports will be compiled, aiming for certification that paves the way for their use in AAM vehicle production. The environmental evaluation tests can include:

- Mechanical stability testing: tensile and compressive strength, impact resistance, cyclic fatigue tests.
- Thermal stability testing: thermal degradation, glass transition and melting temperatures for the operational temperature limits, coefficient of thermal expansion.
- Environmental resistance testing: UV exposure resistance, moisture absorption, and thermal cycling.
- Flammability tests to understand the material behaviors of ignition, burning, and fire propagation.
- Vibration testing: Random and harmonic vibration tests to assesses the durability and integrity of the material under conditions that simulate real-life operational vibrations and shocks.

Timeline

This work is planned to begin during Q1 of FY26 and go through Q3 of FY26.

Anticipated Outcome/Hypothesis

The anticipated outcomes of this work include a detailed understanding of the mechanical and thermal stability of SUMAC thermoplastic resins and their performance under harsh environmental conditions. We expect to identify the conditions under which these materials maintain their integrity and performance, as well as their limitations in terms of environmental degradation and mechanical wear. The findings will highlight areas where bio-sourced thermoplastic resins can match or potentially exceed the performance of

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traditional thermosetting resins. Additionally, this investigation activity will emphasize any necessary modifications to the resin formulations for AAM applications. Collected data could lead to regulatory approval of these sustainable materials, marking a significant advancement in sustainable aviation technology. Ultimately, this investigation effort could facilitate a broader industry shift towards more sustainable manufacturing practices, potentially setting new benchmarks for material performance and environmental responsibility in the aviation sector.

Criteria

This work will be meticulously executed, with a focus on several key metrics to assess the performance and suitability of sustainable thermoplastic resins for AAM applications. The investigation will measure mechanical properties such as tensile and compressive resistance, evaluating if they align with those of conventional AAM parts. Thermal stability will also be critically assessed through thermal exposure in the AAM operation conditions. Environmental durability will be evaluated based on the material resistance to UV exposure, moisture, and cyclic environmental conditions, to ensure the selected sustainably-derived resins can endure the harsh conditions faced during AAM flight. In addition, successful completion of flammability tests and vibration/fatigue tests will be crucial to meet safety standards and confirm the durability and long-term performance of SUMAC thermoplastic resins in operational AAM scenarios.

Barrier(s)

Several potential barriers could impact this activity in the rapidly evolving field of AAM industry. One significant challenge is the variability in the properties of bio-sourced materials, which might result in performance inconsistencies under diverse operational conditions of AAM vehicles. The AAM industry itself is still under development, which means operational conditions and regulatory frameworks could change, complicating compliance and certification efforts. Additionally, the environmental durability of the sustainably-derived thermoplastic resins, particularly their sensitivity to UV radiation, moisture, micro-defects, and vibrations, might pose challenges in maintaining material integrity over prolonged exposure periods. The complexity of simulating AAM conditions accurately in laboratory settings can also limit the ability to predict actual operational performance. With an evolving regulatory landscape in AAM industry, the certification and qualification process might delay the integration of the SUMAC resins into mainstream AAM vehicle and commercial airline production. Lastly, there might be resistance to change within the aviation industry, as companies may be reluctant to alter their established manufacturing processes and supply chains to accommodate a new material like PLA and PHA.

Data Management Plan

The data management for this activity will prioritize the systematic collection, storage, and analysis of test data from a series of experimental tests on sustainable thermoplastic resins. All raw and processed data and analysis results will be securely stored on centralized

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servers with controlled access to ensure confidentiality and integrity. A standardized format for data entry will be implemented to facilitate easy collection and comparison across different test scenarios and conditions. Rigorous data integrity protocols will be implemented to maintain data accuracy and prevent loss or corruption, with regular backups and restricted access to authorized personnel. Additionally, findings will be regularly documented and carefully reviewed to guide ongoing research and support regulatory submissions.

Stakeholder(s)

This research activity involves a diverse range of stakeholders including: AAM manufacturers, end users (airlines and operators) operating AAM vehicles, material suppliers, regulatory agencies, and government agencies and environmental organizations interested in promoting sustainable practices in transportation and reducing carbon footprints.

R4: Crystallization Kinetics (Nice to Have)

Research Question/Event Purpose

This activity investigates the crystallization kinetics of sustainable thermoplastic resins for AAM applications. The degree of crystallinity in thermoplastic polymers is critical because it strongly influences their chemical and mechanical properties. Can the study of crystallization kinetics help optimize the mechanical and thermal properties of thermoplastics to meet the high-performance standards and enhance safety and sustainability in AAM vehicles? Understanding crystallization kinetics assists in optimizing the formulation of SUMAC thermoplastic polymers and composite manufacturing processes, potentially reducing energy consumption and production time. These are critical factors in the scalability, economic viability, and sustainability of AAM technologies. This research effort can extend the limits of bio-sourced polymers and establish new benchmarks for their use in the cutting-edge AAM industry.

Event Approach/Actions

The proposed investigation into the crystallization kinetics of sustainable thermoplastic resins aims to map out the crystallization behavior under various conditions by employing advanced analytical techniques, such as differential scanning calorimetry (DSC) and X-ray diffraction (XRD). The action items include developing a series of formulations with different monomers and additives to enhance thermal and mechanical properties, as well as environmental performance. This research activity will also help to determine composite processing parameters to optimize the crystallinity of SUMAC composites and their material properties, ensuring their suitability for AAM industry standards.

Timeline

This work is planned to begin during Q1 of FY26 and go through Q3 of FY26.

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Anticipated Outcome/Hypothesis

The anticipated outcomes of this work include the identification of optimal crystallization conditions that maximize the mechanical strength and thermal stability of sustainable thermoplastic resins for AAM applications. Through fine-tuning new formulations, we expect to achieve improved performance in terms of durability and resistance to harsh environmental stressors, such as temperature fluctuations, mechanical vibration and fatigue, and UV exposure. Additionally, the optimization of composite processing conditions is anticipated to lead to more efficient manufacturing processes, reducing both energy consumption and production times.

Criteria

In this activity, several key metrics and criteria will be used to evaluate the investigation into crystallization kinetics of sustainably-derived thermoplastic resins. Achieving a targeted increase in crystallinity percentage, quantified by DSC, will serve as a primary metric. Enhancements in mechanical and thermal properties, such as tensile strength, modulus, glass transition temperature, and thermal degradation temperature, will be meticulously analyzed through standardized tests to optimize the crystallinity of the thermoplastic resins. The environmental performance test results will be also key metrics for the thermoplastic polymers with the optimized crystallinity. Additionally, reductions in manufacturing cycle times and energy consumption will be critical efficiency metrics for this study on crystallization kinetics.

Barrier(s)

One potential barrier to the success of this work is the inherent variability in bio-based materials. Natural variations in the source materials can lead to inconsistencies in the resin properties, complicating standardization and reproducibility of results. Another challenge in this work on crystallization kinetics is the reinforcement with natural fibers in the following phase of composite fabrication. Natural fibers may introduce complexities due to their hygroscopic nature and potentially poor interfacial bonding with the resin matrix. The scale-up from laboratory synthesis to industrial scales often presents technical challenges, particularly in maintaining the desired consistency of crystallinity during large-scale manufacturing.

Data Management Plan

The data management plan for this investigation will ensure systematic collection, storage, and analysis of data to maintain integrity and accessibility. Experimental data and analysis results from a series of experimental investigation will be digitally recorded and stored in a secure, centralized server with regular backups to prevent data loss. Access to this database will be restricted to authorized personnel. Regular backups and strict access controls will be implemented to protect against data loss and unauthorized access.

Stakeholder(s)

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This research activity involves a diverse range of stakeholders including: AAM manufacturers, end users (airlines and operators) operating AAM vehicles, material suppliers, regulatory agencies, and government agencies and environmental organizations interested in promoting sustainable practices in transportation and reducing carbon footprints.

R5: Isosorbide Research (Nice to Have)

Research Question/Event Purpose

The purpose of this activity is to harness the potential of poly arylene ether (PAE), a sustainable thermoplastic resin synthesized from bio-based isosorbide (ISB), to innovate sustainable manufacturing of AAM. By collaborating with academic partners that have successfully synthesized PAEs or specifically SUPERBIO-K from bio ISB, * can we develop high-performance bio-thermoplastic resins that have excellent mechanical and thermal properties? This collaboration will enable us to leverage cutting-edge R&D capabilities and explore sustainable PAEs and their material properties, to determine their suitability for AAM applications.

* Park, Seul-A., Hyeonyeol Jeon, Hyungjun Kim, Sung-Ho Shin, Seunghwan Choy, Dong Soo Hwang, Jun Mo Koo et al. "Sustainable and recyclable super engineering thermoplastic from biorenewable monomer." Nature communications 10, no. 1 (2019): 2601.

Event Approach/Actions

This collaborative activity seeks to engage academic institutions with proven expertise in the synthesis of PAEs from bio-derived cyclic monomer (ISB), to co-develop an innovative, sustainable thermoplastic resin, like SUPERBIO-K, for application in AAM manufacturing. The initial step involves a comprehensive review of existing research and technologies in the synthesis of ISB-based PAE polymers, gauging their potential in AAM applications. We will then engage in experimental synthesis, structural analysis, and property characterization, focusing on optimizing the molecular structure and chemical formulations to improve their thermal and mechanical properties to meet the required ones for AAM components. Key action items include establishing research partnerships with academic partners, awarding funding to academic partners, establishing mutual agreement for responsibilities and intellectual property rights, allocating tasks such as material synthesis, property characterizations, and environmental performance tests specifically for AAM applications. In addition, all the experimental data and analysis results will be documented, and key findings will be published to contribute valuable insights to the scientific community and benefit future sustainable material innovations in the aviation sector.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q4 of FY26.

Anticipated Outcome/Hypothesis

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In this activity, we anticipate developing bio-derived high-performance PAE thermoplastic resins capable of withstanding the rigorous demands of AAM vehicles. Particularly through collaborative efforts with academic partners, we aim to further optimize the chemical structure and formulations of SUPERBIO-K derivatives to achieve superior mechanical strength, thermal stability, and environmental sustainability, suitable for the SUMAC program. Additional anticipated outcomes include the development of phase-transfer catalysis for high-molecular-weight biopolymer synthesis, securing intellectual property rights in materials and manufacturing techniques, and exploring extensive spin-off opportunities in other industry like biomedical. Another outcome will be the publication of our technical achievements, which will contribute to the public understanding of sustainable material innovations in aerospace. This not only establishes academic credibility but also promotes further R&D in the research communities.

Criteria

For this investigation activity, success metrics and criteria are carefully determined to ensure the project meets its goals effectively. The first metric is the achievement of specific thermal and mechanical properties in the SUPERBIO-K derivatives, such as a minimum glass transition temperature of 212°C and tensile strength exceeding 78 MPa. Secondly, the synthesis scale-up is considered successful if high-molecular-weight biopolymers (> 100 kg/mol) are reliably produced at an industry scale higher than 1 kg, while maintaining consistent quality and properties. Thirdly, the filing and granting of patents for new techniques and manufacturing processes will serve as a critical indicator of our capability to secure and protect intellectual property, thereby enhancing commercial potential. Additionally, the establishment of multiple partnerships with academic institutions for collaborative research will be considered a significant milestone, accelerating further innovation and development for the sustainable manufacturing. Lastly, successful publication of research discoveries in peer-reviewed journals will validate the technical merits and impacts of this work, promoting wider acceptance and recognition within the aerospace and material supply communities.

Barrier(s)

Several potential challenges can be anticipated in this collaborative effort. A primary technical challenge is achieving the increased molecular weight of PAE thermoplastics and ensuring they meet the strict mechanical and thermal properties required for AAM applications, such as high glass transition temperatures and tensile strength, comparable to traditional synthetic resins. Improvements in environmental test results under the demanding conditions of AAM operations and safety could also be significant challenges in this work. The scale-up synthesis of bio-derived thermoplastics from laboratory to industrial production without losing performance quality may be additional technical challenges.

In collaborations with external partners, complexities associated with intellectual property rights, particularly concerning the ownership of breakthrough technologies, may

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significantly delay research progress. Especially when engaging with foreign partners further complications may be involved in this collaborative work, due to additional regulations associated with international exchange of technology.

Data Management Plan

The data management plan ensures meticulous handling and preservation of experimental data to support the integrity and reproducibility of team achievements. All data generated during the activity, including experimental results, synthesis techniques, property analyses, and composite manufacturing processes, will be systematically documented and stored in a secure, centralized database accessible to all team members. Special protocols will be in place for managing sensitive intellectual property data to track data usage and access by authorized personnel only. Additionally, before sharing any experimental data or analysis results with technical communities, we will carefully review all data to ensure no sensitive IP is disclosed, thereby maintaining proprietary rights while still promoting transparency and collaboration in this work.

Stakeholder(s)

This activity about bio-derived PAE thermoplastics for AAM applications involves various stakeholders including: academic institutions, aerospace manufacturers, automotive industry, regulatory entities, government agencies for environment conservation, environmental advocacy groups, material supply chain vendors, and end users (AAM operators).

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6.3.2 Natural Fibers

Overview

The goal of the natural fibers focus area is to determine the most suitable fiber for manufacturing high-quality composite parts for AAM aircraft in the SUMAC Program. It will require thread and fabric characterization of mechanical properties with a focus on sustainability, availability, and environmental impact. Commercially available fabrics will initially be used for composite fabrication, but there will also be an option for exploring different weaves. The optimum plant growing conditions will also be determined for selecting fabrics with the most desirable mechanical properties. The timeline for activities associated with this focus area is shown in Figure F.1.

Task	Pre-Year		FY25				FY26			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
F1: Mechanical Property Characterization of Thread										
Procure thread/fabric										
Identify and procure test fixtures for mechanical testing										
Characterize thread properties: density, twist angle, fiber count, free volume/packing										
Complete tensile testing										
F2: Resin-Fiber Interaction Characterization										
Fiber pull out testing: microscopy of fracture surface										
Fiber functionalization to improve wetting (sizing)										
Fiber volume fraction										
Fiber alignment										
F3: Fabric Characterization (changes in over/unders, thread orientation, etc.)										
Design custom weave pattern										
Procure custom weave fabrics										
Mechanical property characterization										
Resin-fiber interaction studies										
F4: Environmental Stability Evaluation										
Thermal exposure										
UV exposure										
Solvent soak??										
Hygrothermal aging										
F5: Material Property Variation Evaluation (Nice to have)										
Procure fiber samples from different crops/locations/seasons/etc.										
Microscopic and spectroscopic characterization										
Mechanical property characterization										

Figure F.1 Natural fibers activity timeline. Blue cells are active periods, orange cells are for report out events, yellow cells are “nice to have” activities, and stars indicate P3 events.

Background

From fiber to fabric, there are several factors that will affect the performance and suitability of SUMAC composites. The physical and mechanical characteristics can vary from one supplier to another. These factors must be considered in establishing a sustainable, environmentally friendly product for AAM products. Fibers traditionally have been harvested from a variety of plants. Flax and hemp textiles have a long history leading to the modern high-quality textile products available today. Natural fiber composites have been used in the early days of flight as wing skins for small aircraft. Henry Ford’s Kestrel, a car made from Hemp composite was known to have very high resistance to impact damage and was designed to be environmentally friendly and sustainable. It is these qualities that

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can once again be realized with SUMAC. The proposed approach to make the first steps toward this future is described in detail below.

F1: Mechanical Property Characterization of Thread

Research Question/Event Purpose

The use of natural fiber composites in AAM aircraft will have environmental advantages over glass or carbon fiber composites, but the mechanical properties must meet requirements for safety, longevity, and functionality. Both thread strength and the physical characteristics when manufactured into thread will have a major impact on the mechanical properties of the fabric and the resulting composites. This activity will answer the question, which fiber system, flax or hemp, should we move forward with based on results from mechanical properties determination and physical characteristics of threads?

Event Approach/Actions

This activity will require procurement of currently available threads and fabrics with different fiber composition, density, fiber count, and twist angle. Procurement of test fixtures will also be required for mechanical characterization of threads. The tensile testing output data will indicate thread properties most desirable in textiles and for use in stitching. Other mechanical test methods may be investigated as warranted based on the results from tensile testing.

Timeline

This work is planned to begin during Q3 of FY24 and go through Q1 of FY25.

Anticipated Outcome/Hypothesis

Upon completing this work, we will have an understanding of the types of thread and mechanical and physical characteristics of threads used in textiles targeted for aerospace composite applications. This work will influence selection of the best fabrics for manufacturing composite parts. The optimal fabric density, weave, and thread count can be chosen for the most durable composite.

Criteria

This work will determine the criteria necessary for desirable and suitable fabrics for AAM composites. Tensile and physical characteristics of thread will be analyzed to determine the most important factors in textile production. The strain characteristics may also influence the fabrication process by determining the need for pre-stressed fabrics for dimensional stability of composites.

Barrier(s)

Barriers to this work are anticipated, considering the relatively recent developments in sustainable composite materials for AAM applications. Differences in thread manufacture

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and fiber growing conditions may pose a problem in product consistency or performance. Environmental conditions, such as weather and pests, could also pose a threat to sustainable fiber production. Lastly, competition from conventional synthetic fibers will require obvious benefits from natural fibers to tilt the scale in favor of sustainable composites derived from natural fibers.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Characterization of natural fiber thread will be of major interest in the textile industry and may lead to unexplored composite applications for textiles. Other stakeholders include packaging industries, aerospace composites, military shielding product suppliers, automobile manufacturers and construction product suppliers.

F2: Resin-Fiber Interaction Characterization

Research Question/Event Purpose

It is critical for there to be significant, continuous interaction between the resin matrix and the fibers in a composite system to maximize the material properties. The purpose of this event is to answer the question, is there sufficient interaction between the resin and fibers, as indicated by fiber wetting, to enable generation of composite parts with maximized mechanical properties?

Event Approach/Actions

There are three activities that will be utilized to address the extent of resin/fiber interaction.

- Optical microscopy will provide significant information regarding the nature of the interaction between the resin and the fibers. Observation of large voids, discontinuity of resin along the fiber length, or other evidence of dewetting of the natural fibers would all be indicative of insufficient fiber wetting.
- Contact angle goniometry will also be utilized to determine surface tension and surface energy of the resin and fiber materials, respectively. This information can be utilized to generate wetting envelopes which provide a broader perspective on what range of surface tension/energy values would be most likely to exhibit advantageous interactions.
- Fiber pull-out mechanical testing will be implemented to evaluate the adhesion strength of each resin/fiber system.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q4 of FY25.

Anticipated Outcome/Hypothesis

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Completion of the proposed work will provide critical insight into how well the natural fiber surfaces are wetted by the intended thermoplastic resin systems. This will provide clear direction regarding which combinations of materials would be most likely to provide the greatest materials properties and ultimately the most robust flight components. Experimental conditions that improve wettability will also provide insights into processing conditions for the manufacturing events described below.

Criteria

Results from these efforts will directly address the viability and feasibility of utilizing the tested resin/fiber combinations for generation of composite articles. With sufficient wetting of the fibers by the resin, the mechanical properties of the resultant composite will be maximized yielding the broadest application space. Additionally, infiltration of large amounts of water or other potential contaminating fluids will be mitigated with well wetted fiber beds which could lead to longer operational lifetimes and greater reliability.

Barrier(s)

Quantitative determination of the degree of fiber wetting can be challenging, especially with respect to natural fiber systems where the surface chemical composition of the fibers is likely to be less consistent, relative to carbon fiber systems. Utilization of several characterization techniques will enable greater insight into the fiber wetting characteristics. Differentiation between surface wetting and resin penetration within fiber bundles can all be challenging; however, there is significant precedent for characterizing resin-fiber interactions in carbon fiber composite systems using microscopy of cross-sectional surfaces. This technique will be utilized in the proposed work. Finally, it is possible that the mechanical testing of adhesion strength may be difficult due to the fiber breaking before being pulled out of the resin matrix. If this is observed, then the adhesion strength will be assumed to be greater than the fiber strength which should be sufficient for the level of development of these systems.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

F3: Fabric Characterization

Research Question/Event Purpose

The purpose of this event is to answer the question, what weave pattern will provide the greatest composite mechanical properties for the intended AAM application? The physical characteristics of fabrics can vary widely, impacting the mechanical characteristics and processing of a composite. This activity will require design and fabrication of fabrics with

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different weave patterns and areal weights. Two previously selected fibers, flax and hemp, will initially be used for this activity based on mechanical properties, physical properties, and existing utilization and commercialization. Mechanical property characterization of the fabrics is also included in this activity to determine the use and functional limits when used in composite parts for AAM vehicles. Tensile testing and impact testing will be the most important of the mechanical properties for AAM applications.

Event Approach/Actions

This activity requires procurement of both custom weave and existing commercial weave of flax and hemp fabrics. Mechanical characterization of the fabrics will include tensile testing and impact testing. Resin fiber interaction in different fabrics will determine the level of crosslinking at the interface and the wetting ability in different weaves for optimizing composite fabrication processes.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q1 of FY26.

Anticipated Outcome/Hypothesis

Completing this work will determine the most desirable or necessary weave patterns and areal weights in fabrics used for AAM composites. A combination of different weaves and fabric fiber orientations are expected to produce composites tailored for some of the most challenging parts. Natural fiber composites typically can endure large deformations before failure leading to superior impact strength, an important characteristic for the lower altitudes expected to be in the AAM vehicle altitude spectrum.

Criteria

Necessary characteristics for natural fiber fabrics will be determined. The fabrics having a mechanical strength and physical characteristics to make a viable AAM composite part will be determined. There will likely be various criteria for meeting the needs of each AAM part. Depending on the required part geometry and expected loading during AAM operation, various fabric weave patterns and aerial weights may be chosen. Impact damage and absorption characteristics of fabrics with the matrix resin and water will be determined. These characteristics will determine the viability of the AAM part, the ease of fabrication, and the suitability in the operating environment.

Barrier(s)

Difficulty in comparing mechanical properties from different fiber systems and fabrics will undoubtedly be a barrier to this activity. By documenting the properties and determining the factors that affect mechanical properties, this barrier can be made an asset: a means to quickly determine fabrics with desirable mechanical properties. This will also manage the difficulty in discovering mechanical properties that are lower than desired for intended applications. Another barrier may be in changing established textile production from linen

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and garment production to composites. Fibers used today may have undesirable additives (softeners, etc.) for retail appeal. This barrier may be minimized by maintaining a sustainable domestic source of fiber with nearby processing facilities. Political and economic barriers are also a possibility but can also be minimized by maintaining a domestic capability.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Commercial and government stakeholders will benefit from this research activity: growers and fiber manufacturers, textile industry and product suppliers, composite manufacturers (including for AAM composites), the automobile industry, housing and construction industries, furniture and consumer product retailers. The military could also benefit from the impact shielding and drone manufacturing advantages of sustainable composites.

F4: Environmental Stability Evaluation

Research Question/Event Purpose

The operational environment of an advanced air mobility vehicle involves exposure to a range of thermal conditions, UV exposure, and changes in humidity. The purpose of this event is to address the question, how do the materials properties of the selected natural fiber systems change because of environmental exposure?

Event Approach/Actions

A series of exposure experiments will be performed on natural fiber samples followed by microscopy, thermal evaluation, and mechanical testing to assess how the materials properties changed. The exposure experiments will include: thermal cycling in a temperature/humidity chamber, accelerated UV weathering in a UV weathering chamber, and hygrothermal aging. All of these experiments will be performed according to procedures that are currently in use by materials supplies for aircraft manufacturers. Characterization of the exposed fiber materials will be consistent with the methods described in F3.

Timeline

This work is planned to begin during Q3 of FY25 and go through Q2 of FY26.

Anticipated Outcome/Hypothesis

Completion of these exposure experiments and subsequent characterization will provide insight into materials property retention capabilities of the selected fiber systems. This information will be critical to assess the operational lifetime of the fibers in an operational environment and will be utilized to provide greater insight into the response of composite

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samples exposed to similar conditions. The integration of stabilization additives, protective coatings, and additional sensing capabilities will be considered based on the change in materials properties.

Criteria

The outcome of this event will directly influence the feasibility of the selected natural fiber systems to be utilized for advanced air mobility applications since the operational environment will require sustained material performance under certain environmental conditions. Further, the viability of these fiber systems to be utilized broadly on an advanced air mobility platform will be determined. The fibers will need to show significant retention of the relevant material properties, i.e., modulus, toughness, etc., under a range of environmental conditions to be considered for exterior applications. If the fibers do not demonstrate these properties, their implementation could be limited to in-cabin applications.

Barrier(s)

Access to the environmental control chambers could be challenging as some of them are used for several projects. This will be mitigated by working with the other users to schedule either dedicated time for testing of these materials or, if the test conditions are identical, coordinated testing of materials from multiple projects. For all of the environmental control chambers and test conditions, there is no risk of contamination from one material to another. Due to limited information in the literature regarding the degradation lifetime of these natural fiber systems, there is a risk that the degradation kinetics will result in changes to material properties that fall outside the targeted exposure timelines. This will be mitigated by evaluating material properties at intervals during the full exposure timeline which will enable identification of degradation properties that are occurring too quickly to justify running the entire experiment. If nominal changes in material properties are observed, then decisions can be made to extend the exposure timeline.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

F5: Material Property Variation Evaluation

Research Question/Event Purpose

The natural fibers to be utilized in this work can exhibit variability in materials properties due to the fact that they are naturally-derived materials systems. As such, the exact genome of the seed material used to grow the parent plant the fibers are derived from can

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influence the ultimate material properties. The same is true for growing conditions, harvesting procedures, and material processing to generate the fibers. Therefore, a question that needs to be addressed is: How do the material properties of threads of natural fiber vary from batch to batch?

Event Approach/Actions

Tensile testing, as described in F1, will be utilized in this action. Microscopy and spectroscopy will also be utilized to characterize the physical properties of the threads from multiple batches of material. Depending on the results from these initial evaluation methods, more in-depth analysis may be performed to follow how differences in thread properties from multiple batches influence other aspects of composite materials fabrication, such as fiber wetting, pull-out strength, etc.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q4 of FY25.

Anticipated Outcome/Hypothesis

The results from these experiments will provide insight into the anticipated degree of variability of materials properties for these natural fiber systems. This is critical to enable certification of sustainably-derived thermoplastic composites for flight applications.

Criteria

The outcome of these events will directly impact the feasibility of naturally-derived fibers for flight applications. FAA certification for materials systems in flight applications requires a concise understanding of the degree of reliability of material properties for a specific material system in a specific flight application. Collection of the data proposed in this event will provide a foundation from which the variation of composite material properties can be derived.

Barrier(s)

Barriers for this effort include challenges accessing different batches of fiber materials that have been processed in a similar way. This will be critical since it will impact how comparable the results from each batch will be. The team will work closely with vendors to either acquire different batches of fiber materials over an extended period or collect fiber material from several farm sources to mitigate this risk. Additionally, the variation in materials properties may be small or convolute with other, intractable differences in the materials which will complicate the evaluation of materials properties relative to batch variation. This will be mitigated by performing a quantitative analysis of the results which will enable determination of whether or not the differences in results are statistically significant or not.

Data Management Plan

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Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

6.3.3 Manufacturing and Testing

Overview

The goal of the manufacturing and test task is to support SUMAC's goal of advancing sustainable materials for aerospace applications, specifically AAMs. SUMAC's manufacturing task will meet this goal through composite process development, part fabrication, and mechanical tests at the coupon and sub-element level. This will be accomplished with significant coordination with the resin and fiber tasks, which will direct material selection, and the sensors task with respect to incorporation of materials for structural health monitoring. The timeline for activities associated with this focus area is shown in Figure M.1.

Task	Pre-Year		FY25				FY26			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Select an Application for the Sustainable Composites										
Identify Center Responsible for Fabrication										
Procure Materials										
M1: Material Matrix Coupon Fabrication										
Procure Tooling to Fabricate Interlaminar Tension Coupons										
Manufacture Flat Panels for Tension and Compression Tests										
Manufacture Flat Panels for Short Beam Shear and Interlaminar Tension Tests										
M2: Mechanical Property Assessment										
Panel Inspection, Void Content, Fiber Volume Fraction										
Establish Process Parameters for Ultrasonic Welding										
Test Interlaminar Tension Coupons										
Coupon-level Mechanical Tests										
Report Data and Down-select a Material System										
Manufacture and Test Single Lap Shear Coupons by Ultrasonic Welding										
Manufacture and Test Vibration Damping and Fatigue Coupons										
M3: Sub-Element Fabrication and Assessment										
Design and Manufacture Tooling to Manufacture Sub-Element Parts										
Manufacture Sub-Element Parts										
Test Sub-Element Parts										
Report Data										

Figure M.1 Manufacturing and testing activity timeline. Blue cells are active periods, orange cells are for report out events, and stars indicate P3 events.

Background

Natural fiber polymer composites can be fabricated using traditional manufacturing techniques developed for conventional fiber-reinforced polymer composites and thermoplastics. These techniques include resin transfer molding (RTM), vacuum infusion, compression molding, direct extrusion, compounding and injection molding. These techniques and processes are well established with demonstrated success in producing composites with controllable quality. A considerable amount of manufacturing has

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demonstrated the suitability of these processes to natural fibers and sustainable resins. However, technical challenges do exist. For example, several material and manufacturing considerations that need to be addressed include fiber sizing optimization, uniformity of fiber distribution, uniformity of fiber bundle shape, resin wettability, and water absorption.

M1: Material Matrix Coupon Fabrication

Research Question/Event Purpose

The development of sustainable composites suitable for aviation is a novel effort and challenging task. A significant test campaign is required to screen candidate materials, optimize processing parameters, and characterize material properties. This information will help identify the most promising material candidate for sub-element assembly. A task in and of itself, significant process development is necessary to fabricate dense and defect-free coupons as the first step towards utilizing sustainable composites in aviation applications.

Event Approach/Actions

Preliminary decisions will be made in consultation with Joby and other external partners to select a specific application for this project. Tests that are relevant to the target application but also broadly applicable to sustainable composites for Urban Air Mobility vehicles will be selected. A manufacturing approach will be based on part geometry and the process requirements of each material. Manufacturing equipment is available at both GRC and LaRC. During this task the manufacturing will be split between the two centers.

A building block approach, Figure M.2, will be utilized to screen candidate materials from the coupon to the subcomponent level, with the first stage focusing on coupon fabrication. This approach enables the exploration of subcomponent manufacturing complexity in later stages, and the versatility to shift applications based on coupon data.

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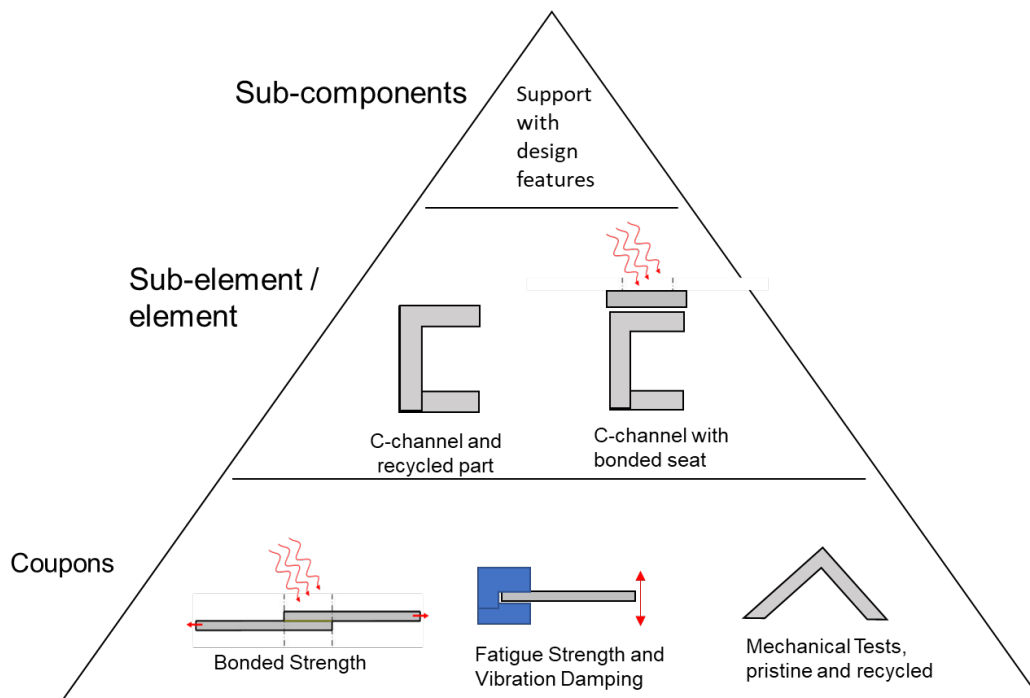


Figure M.2 Building block approach for material fabrication and testing.

The manufacturing task will coordinate with both the resin and fiber tasks to facilitate coupon fabrication. Necessary information includes:

- Resin task: rheology and differential scanning calorimetry data is required to inform processing cycles.
- Fiber task: coordination of fiber architecture, fiber type, and areal weight will enable comparison between the candidate fibers. In addition, fiber characteristics such as moisture uptake, resin wettability, and fiber/resin bond strength will guide requirements for pretreating the fibers prior to resin infusion.

If budget and schedule allow, we will evaluate Elium matrix composites in addition to matrix materials specified by the resins task. Elium is not a bio-based thermoplastic, but it is recyclable through full depolymerization followed by repolymerization for reuse. Addition of this material allows evaluation of material sustainability through recycling.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q4 of FY25.

Anticipated Outcome/Hypothesis

Completed coupon fabrication for initial material screening through tension, compression, short beam shear, and interlaminar tension testing under room temperature dry and either elevated temperature wet or room temperature wet (depending on the material properties). Interlaminar tension coupons are of interest because they add complexity

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through forming required and serve as an intermediary between flat panel and sub-element manufacturing. During this manufacturing stage a minimum and maximum fiber volume fraction will be established. This will include requirements for fiber or resin pretreatments, fiber volume fraction achieved, and reproducibility of panel quality (based on visual inspection, photo-microscopy, and nondestructive evaluation). Critical tests for SUMAC's AAM application and barriers to scale-up of the manufacturing processes will be identified.

Criteria

Viability success criteria will include the manufacturing of natural fiber-reinforced composites, with sustainable resin matrix, suitable for mechanical testing.

Barrier(s)

Barriers with this effort include process development to manufacture dense and defect-free coupons. Fiber pretreatment may be required to optimize the fiber/resin interface. Optimization of this pretreatment process may require considerable research.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

M2: Joining and Mechanical Property Assessment

Research Question/Event Purpose

Material properties of sustainable composites must be characterized to identify the most promising material candidate for down-selection. Mechanical testing will provide valuable data on the performance of composites under compression, tension, short beam shear, and interlaminar tension, equivalent to conditions experienced by components on an aircraft. Additional investigation of ultrasonic welding and single lap shear test coupons will provide insight to this manufacturing method and its potential for the joining of natural fiber-reinforced sustainable resin matrix composites. Vibration damping and fatigue testing will help identify the effectiveness of these methods toward the development of a sub-element assembly.

Event Approach/Actions

Mechanical testing will be conducted with coupons fabricated in M1: Material Matrix Coupon Fabrication. This testing will leverage lab-based test facilities and contribute to the development of a database of properties relevant to conditions experienced by components within an aircraft. Properties will be assessed, and a down-selection of material candidates made. An additional investigation into process development for ultrasonic welding of

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natural fiber-reinforced sustainable resin matrix composites will be conducted to evaluate the potential for joining sub-element components. Single lap shear coupons will be manufactured to measure bond strength. Thermoplastic joining/ fusion bonding is an environmentally friendly, low energy method of replace bolts in composite structures. Ultrasonic welding is especially useful for spot welding, and it is what we propose to use for this work as the equipment is available at GRC. Joined coupons will be tested in single lap shear additional, application specific mechanical tests. Vibration damping and fatigue testing will be conducted to identify the effectiveness of joints for aircraft relevant conditions.

Timeline

This work is planned to begin during Q2 of FY25 and go through Q3 of FY26.

Anticipated Outcome/Hypothesis

The first-year deliverable of the manufacturing task is coupon level data from candidate fiber/resin variations. This test data will be assessed and used to down-select to a system for subcomponent fabrication. Down-selection will be a coordinated effort between manufacturing, resin, and fiber tasks. Additionally, test data from ultrasonic bonding will provide insight on the joining of composite materials for sub-element assembly. Barriers for use in a UAM will be identified.

Criteria

Viability success criteria will include low variability in data for each mechanical test and composite system, and the demonstrated resilient joining of parts. A threshold goal will have the manufacturing process equal or improve upon state-of-the-art composite manufacturing with respect to environmental impact. A stretch goal will have the manufacturing process demonstrate a reduced environmental impact with respect to the state-of- the-art.

Barrier(s)

Barriers with this effort include possible large variation in mechanical property data. If this is the case, additional data or refinement of processing procedure could be necessary.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

M3: Sub-element Fabrication and Assessment

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Research Question/Event Purpose

Material development at the coupon level must be scaled to the sub-element level and leverage joining methodologies to enable the fabrication of complex components. Identifying manufacturing procedures and mechanical properties of these structures is critical to understanding the element's performance in operating conditions on an aircraft and the demonstrated potential for eventual certification.

Event Approach/Actions

Knowledge gained from prior manufacturing and testing will inform the procedure for fabrication and joining of sub-element components. The approach will leverage both processing and joining methodologies, as well as custom tooling. The sub-element will be tested under conditions representative of those experienced in an aircraft, for example crush and impact tests. A final report will be compiled with an assessment of the test data, and manufacturing process.

Timeline

This work is planned to begin during Q4 of FY25 and go through Q4 of FY26.

Anticipated Outcome/Hypothesis

A procedure for the development of sub-element components will be developed based on knowledge gained. Custom tooling and joining technologies will be leveraged to achieve necessary part geometries. A manufacturing assessment of subcomponent parts will be conducted, mechanical test data from subcomponent parts obtained, and a final report delivered.

Criteria

Viability success criteria will include successful manufacturing and joining of sub-elements along with low variability in data from sub-element testing. A threshold goal would be to demonstrate a combination of reduced weight or similar performance to current state-of-the-art.

Barrier(s)

Barriers with this effort include possible large variation in mechanical property data, scale-up of the manufacturing process, and performance for use in an AAM application. If this is the case, additional data or refinement of processing procedure could be necessary. This activity will help determine if the sub-element has potential to replace current state-of-the-art aircraft components and achieve FAA certification.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

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Stakeholders include the research community, aircraft OEMs, and material developers.

6.3.4 Integrated Sensing

Overview

The goal of the integrated sensing focus area is to explore in-situ measurement approaches aimed at overcoming some of the biggest challenges for long-term use of natural-fiber composites in aircraft: moisture uptake and material property degradation. The effort will test electromagnetic and acoustic sensing approaches tailored to the unique properties and specific needs of natural-fiber composites. In addition, maintenance inspection approaches and dynamic load monitoring approaches will be explored in support of manufacturing quality control and material damage tolerance assessment. The effort will culminate in a report on the needs and viable approaches to integrated sensing for natural fiber composites in AAM aircraft applications. The timeline for activities associated with this focus area is shown in Figure S.1.

Task	Pre-Year		FY25				FY26			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Initiate Joby Partnership										
Purchase sensors and equipment										
Procure/fabricate representative sustainable composites										
Set up instruments and user interfaces for sensing										
Characterize baseline properties in representative composites										
Report on sensing needs for AAM										
S1: Optimize sensing architecture										
Characterize acoustic and electrical/dielectric properties										
Develop models of sensing response										
Conduct baseline tests to evaluate sensing capability										
S2: Nondestructive Mechanical Property Assessment										
Ultrasonic modeling of composites										
Lab based evaluation of material properties										
In situ measurement of material properties using surface-mounted sensors										
On-aircraft demonstration via Joby collaboration										
S3: In Situ Moisture Monitoring										
Ground truth characterization of effects of moisture on properties										
Sensor integration on moisture testing coupons										
Moisture mapping study										
S4: Evaluating Damage Tolerance										
Instrumentation of coupons with advanced and COTS sensors										
Impact testing to verify sensor sensitivity and damage dissipation										
Implementation of model inversion for full-field deformation										
Mechanical testing to verify residual strength										

Figure S.1 Integrated sensing activity timeline. Blue cells are active periods, orange cells are for report out events, yellow cells are “nice to have” activities, and stars indicate P3 events.

Background

Mechanical property variation and moisture absorption pose unique challenges for long-term application of natural fiber composites. Both degradation mechanisms can be detected

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nondestructively by leveraging changes in the material's response to energy input. For example, acoustic excitation of the material can be used to characterize the elastic constants due to the dependency of the mechanical properties on wave propagation characteristics (e.g., wave speed). For moisture absorption, electrical stimuli across electrodes on the surface or embedded within the material can be used to assess changes in the material's electric/dielectric properties due to water content in the microstructure. These basic sensing mechanisms will be tailored and optimized in the Integrated Sensing task to identify approaches with potential for long-term health monitoring in sustainable composites.

S1: Optimize Sensing Architecture

Research Question/Event Purpose

Material properties in sustainable composites are different than those of state-of-the-art composites. As such, the sensing approaches applied to conventional aerospace materials may not be applicable to natural fiber composites or may need to be adapted and optimized based on their unique attributes.

The purpose of this effort is to identify viable health monitoring architecture for these materials by characterizing the properties that dictate sensor interactions, establishing models of sensor interaction, and conducting baseline testing to establish sensitivities and noise levels.

Event Approach/Actions

This work will leverage lab-based ultrasonic and electrical test facilities to build up a database of the properties relevant to sensor interactions. These properties will feed into simplified physics-based models (both closed form and computational) that can estimate sensor responses. Models will be used to optimize sensing parameters including sensor geometries, frequencies, and arrangement on the specimen surface.

The processes of characterization and optimization will leverage commercial materials as a starting point and will be repeated as necessary to support sensing for sustainable composites developed under other tasks.

Specific actions that will be completed for each material system:

- Characterize acoustic properties and electrical/dielectric properties
- Develop simple models of sensing that can be used to identify viable approaches
- Perform baseline sensing to verify that approaches of interest work well in these material systems
- Document protocols for sensing

Timeline

This work is planned to begin during Q1 of FY25 and go through Q3 of FY25

Anticipated Outcome/Hypothesis

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The following outcomes are anticipated:

- Tabulated properties for sustainable composite materials
- Documented sensing protocols
- Baseline models that can be further utilized or expanded for detailed data analysis in later efforts

Criteria

Viability success criteria will be determined based on characterized material properties and consultation with internal subject matter experts for each sensing mode of interest. Feasibility success criteria will be based on sensitivities, noise levels, and repeatability found during initial testing.

Barrier(s)

Barriers addressed by this effort include known (and unknown) issues with material degradation. These are further addressed in sensing tasks related to Nondestructive Mechanical Property Assessment (S2), In-Situ Moisture Monitoring (S3), and Evaluating Damage Tolerance (S3).

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders for the advanced sensing technologies being developed under SUMAC include the academic and government research communities, sensor manufacturers, material suppliers, AAM vehicle OEMs, government regulatory bodies. Examples of specific stakeholders that have expressed interest in this work include Prof. Fu-Kuo Chang, who operates the Structures and Composites Laboratory at Stanford University and founded Acellent Technologies, which provides custom structural health monitoring sensors for aircraft OEMs across the world. Joby Aviation has also expressed interest from a vehicle OEM perspective, and a Space Act Agreement is being pursued to solidify their collaboration.

S2: Nondestructive Mechanical Property Assessment

Research Question/Event Purpose

Mechanical properties in natural fiber composites can change over time from a variety of factors including moisture uptake, extended UV exposure, and damage. For load-bearing applications, it is important to know that properties are within an acceptable range. Nondestructive assessment of properties is therefore a key enabler to broader application of these materials as replacements for state-of-the-art composites.

The purpose of this event is to develop and demonstrate ultrasonic nondestructive approaches for assessing elastic properties in natural fiber composite structures. This work will produce tools that will be utilized for the remainder of the program for assessing

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property changes due to moisture uptake (S3) and damage (S4) and will culminate in an on-aircraft in-situ demonstration of the techniques in collaboration with a vehicle OEM.

Event Approach/Actions

This work will begin with elastodynamic modeling and lab-based measurement of acoustic responses in composite layups, leveraging established capabilities within Langley's Nondestructive Evaluation Sciences Branch. This capability will then be transitioned to surface-mounted sensors suitable for in-situ property assessment in preparation for on-aircraft demonstration.

Processes and models developed during this event will be applied broadly to support manufacturing tasks and sensing tasks for the remainder of the CAS program.

Specific actions that will be completed for each material system:

- Model implementation for solving the elastodynamic governing equations for natural fiber composite layups
- Lab based ultrasonic data collection for fitting model parameters (i.e., elastic properties)
- Coupon-level experiments using surface-mounted sensors to verify property prediction capability
- Sensor installation on commercial AAM aircraft during manufacturing, with property assessment before and after certification testing

Timeline

This work is planned to begin during Q2 of FY25 and go through Q4 of FY26.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- Established models, experimental processes, and workflows for nondestructively measuring elastic constants that will be feed into other tasks
- Performance evaluation and feasibility assessment of elastic property measurement using surface-mounted piezoelectric sensors
- On-aircraft demonstration to demonstrate viability and feasibility of ultrasonic sensing for tracking vehicle health during certification testing

Criteria

Feasibility success criteria will be based on comparisons between elastic properties measured using mechanical testing and those measured using ultrasonic techniques.

Barrier(s)

This work addresses the barrier of material property variation in sustainable composites and the inability to assess current properties without destructive testing.

Data Management Plan

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Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

S3: In-Situ Moisture Monitoring

Research Question/Event Purpose

Natural fiber composites can absorb moisture in humid environments, leading to increased weight, fiber swelling, and changes in both stiffness and strength. Replacing materials that have unacceptable levels of moisture absorption is necessary to avoid losses in aircraft efficiency (due to weight gain) and structural performance (due to changes in mechanical properties).

AAM aircraft are expected to operate in a wide range of environments, making it difficult to apply a common schedule-based replacement schedule for natural fiber structures without incurring high operating costs. Techniques for monitoring moisture uptake can improve the cost-effectiveness of natural fiber composites by providing data needed to inform condition-based, data-driven maintenance and repair actions. The purpose of this work is to advance techniques for both remote and in-situ monitoring of moisture uptake.

Event Approach/Actions

This event will proceed in two stages. The initial stage will produce reference data for understanding the effects of moisture uptake on sensing responses and mechanical properties through standardized degradation protocols and lab-based property assessments. The second stage will assess the feasibility of combined dielectric and ultrasonic sensing approaches predicting moisture state using calibrations derived from reference specimens.

Specific actions that will be completed for each material system:

- Coupon-level humidity exposure tests leading to moisture uptake
- Characterization of moisture-dependent dielectric constants, weight, volume, and elastic properties
- Sensor response monitoring over the range of observed properties for calibration
- Demonstration of multi-modal (ultrasonic and capacitive) moisture prediction, with ground truth data provided through THz-based inspection

Timeline

This work is planned to begin during Q4 of FY25 and go through Q3 of FY26.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- Documented moisture responses at the material (as opposed to constituent) scale

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- Calibration data for understanding sensor response as a function of moisture in a controlled environment
- Demonstration of lab-based THz approaches for quantifying moisture and in-situ approaches for predicting moisture distribution

Criteria

Viability success criteria will be determined based on measured property changes and model responses over relevant moisture levels. Feasibility success criteria will be based on demonstration accuracy.

Barrier(s)

Barriers addressed by this effort include issues with moisture absorption that limit long-term and external use of natural fiber composites.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders for the advanced sensing technologies being developed under SUMAC include the academic and government research communities, sensor manufacturers, material suppliers, AAM vehicle OEMs, government regulatory bodies. Examples of specific stakeholders that have expressed interest in this work include Prof. Fu-Kuo Chang, who operates the Structures and Composites Laboratory at Stanford University and founded Acellent Technologies, which provides custom structural health monitoring sensors for aircraft OEMs across the world. Joby Aviation has also expressed interest from a vehicle OEM perspective, and a Space Act Agreement is being pursued to solidify their collaboration.

S4: Evaluating Damage Tolerance

Research Question/Event Purpose

Natural fiber composites have multi-scale irregularity that may improve their ability to dissipate energy. This characteristic is hypothesized to lead to improved damage tolerance in comparison to metallic and carbon-fiber composite counterparts. This damage tolerance can be leveraged to extend the operational lifetime of natural fiber composite components if sensing data can show that damage effects are (a) localized and not affecting global properties and (b) not growing.

This study will evaluate the ability for sustainable composites to dissipate impact damage and to maintain load bearing capability in the presence of damage using both conventional and advanced wireless sensors. This will simultaneously demonstrate the performance of the optimized natural fiber composites and will demonstrate various sensing techniques that could benefit future structural applications of these materials.

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Event Approach/Actions

This event will characterize the energy dissipation properties in natural fiber composites using controlled impact tests. In addition to characterizing the impact performance of these material systems, this test event will also be used to evaluate the capability of novel wireless conformal sensing technologies suitable for long-term monitoring in natural fiber composite structures.

Specific actions that will be completed for each material system:

- Instrument coupons with conventional sensors (strain gauges and accelerometers) and advanced wireless conformal sensors (surface acoustic wave and spoof plasmon polariton sensors)
- Conduct impact tests to verify sensor performance and material energy dissipation
- Implement inverse finite element modeling (iFEM) for full-field dynamic deformation analysis from sparse sensor data
- Conduct mechanical testing to assess post-impact load bearing capability

Timeline

This work is planned to begin during Q4 of FY25 and go through Q4 of FY25.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- Evaluation of damage tolerance in sustainable natural fiber composite layups
- Demonstration of novel sensing technologies that may support future applications of natural fiber structures

Criteria

Viability of natural fiber composites for applications requiring damage tolerance will be assessed based on resistance to impact damage and load bearing capability following impact. Feasibility of advanced sensing capabilities for monitoring damage state will be based on comparison to conventional sensing technologies.

Barrier(s)

This work addresses the barrier of cost effectiveness. By demonstrating damage tolerance, operational lifetimes in natural fiber structures may be able to be extended beyond the nominal lifetime established for state-of-the-art materials.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders for the advanced sensing technologies being developed under SUMAC include the academic and government research communities, sensor manufacturers, material suppliers, AAM vehicle OEMs, government regulatory bodies. Examples of specific

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stakeholders that have expressed interest in this work include Prof. Fu-Kuo Chang, who operates the Structures and Composites Laboratory at Stanford University and founded Acellent Technologies, which provides custom structural health monitoring sensors for aircraft OEMs across the world. Joby Aviation has also expressed interest from a vehicle OEM perspective, and a Space Act Agreement is being pursued to solidify their collaboration.

6.3.5 Computational Materials

Overview

The computational materials task will leverage advanced materials modeling techniques to guide the design of sustainable composites for aerospace applications, specifically AAMs, as pursued by SUMAC. The materials models will enable predictive analysis of different composite designs complementary to experimental efforts to inform SUMAC's composite materials development. Toward this objective, work under the task will include development of computational materials models for the composite components (i.e., fibers and resins), prediction of composite mechanical properties, and analysis of the material microstructure during mechanical deformation. The materials models can resolve the influence of each component in the full composite. Explicit representation of each component and the resulting resolution of the material's microstructure distinguish it from analysis methods in the other tasks. Work will be coordinated closely with the manufacturing, resin, and fibers tasks, including direct sharing of material properties, mechanical testing data, and simulation analysis. The timeline for activities associated with this focus area is shown in Figure CM.1.

Task	Pre-Year		FY25				FY26			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
CM1: Component and Composite Model Development										
Develop dry fiber model										
Develop resin model										
Develop composite model with fiber-resin interactions										
CM2: Dry Weave Pattern Assessment										
Generate plain weave configuration										
Generate non-plain weave configurations										
Simulate dry weave tensile and flexural deformation										
Disseminate results on the role of weave pattern										
CM3: Composite Simulation and Microstructural Analysis										
Simulate composite tensile and flexural deformation										
Analyze microstructural contact and stress behavior during deformation										
Simulate deformation in interlaminar configuration										
Vary resin and fiber composite properties and simulate deformation										

Figure CM.1 Computational materials activity timeline. Blue cells are active periods, orange cells are for report out events, yellow cells are “nice to have” activities, and stars indicate P3 events.

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Background

Fiber-polymer composites can be modeled as a single isotropic material. Single-material models are excellent for supporting part design and augmenting experimental design scope, as is being done by the manufacturing, integrated sensing, and systems analysis tasks. However, models that capture the influence of microstructure and micro-scale behavior are critical to understanding the intricacies of composite performance, particularly given the novelty, chemical diversity, and manufacturing variability of the sustainable composites of interest within SUMAC. Factors like inherent material variability (e.g., fiber chemical composition or yarn uniformity) and fiber microstructure influences on resin infusion greatly influence the composite properties and performance.

CM1: Component and Composite Model Development

Research Question/Event Purpose

Characterizing the performance of each component is central for composite design. Yet, component properties are likely insufficient to predict the full composite performance. Predicting and understanding the combined effects require more careful analysis using higher fidelity models, especially for less-characterized, sustainable composites. For example, the composite's Young's modulus is not simply the volume-average of resin and fiber Young's modulus. Microstructural and chemical factors, such as infusion quality, yarn contact structure, and resin-fiber interfacial strength, affect composite performance, and can cause anomalous behavior.

The purpose of this effort is to develop models for the composite resin, fiber, and resin-fiber interaction capable of capturing microstructural features, including weave pattern and resin infusion features.

Event Approach/Actions

This work will leverage material modeling capabilities for resins and fibers initially developed for thermal protection materials under the Entry Systems Modeling project (STMD's Game Changing Development program). Capabilities will be adapted and further advanced to develop high-fidelity models for the SUMAC materials of interest. Experimental mechanical and structural data from the literature and corresponding resin, fiber, and manufacturing tasks will be used to parameterize and verify models.

A fiber yarn model with twist and a coarse, isotropic network resin model is visualized in Figure CM.2. Mechanical testing will be applied to facilitate pure component mechanical parameterization. Fiber-fiber and fiber-resin interactions will be parameterized with the resin-fiber wetting properties. Material models will be developed in the Lagrangian, bonded-particle method* (implemented in Sandia National Lab's open-source LAMMPS software), which has no restraints on each component's relative strain, and the finite

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volume method** (implemented in NASA's open-source PuMA software), which can access larger system sizes.

*Y. Wang and X. Sun, Comp. Sci. Technol. **61**, 311 (2001).

F. Semeraro, et al. Comput. Mater. Sci. **178, 109631 (2020).

Specific actions that will be completed for each material system:

- Develop explicit-component models for dry yarns, resin, and their composite
- Parameterize models using data from literature and the experimental tasks
- Verify models with single yarn and resin tensile deformation simulations
- Report simulation inputs, model parameters, and verification simulation scripts

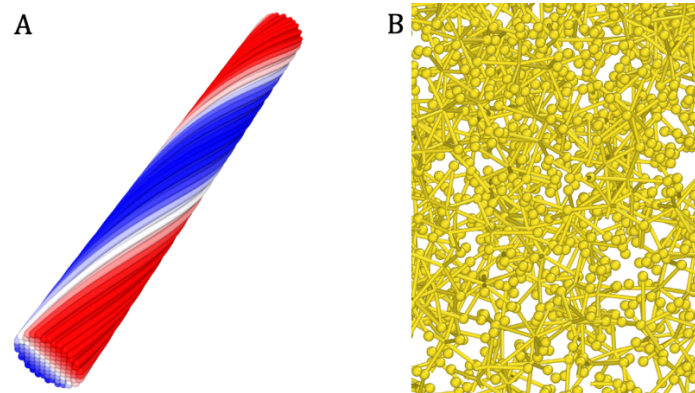


Figure CM.2 Visualization of potential (A) fiber and (B) resin models. Particles are bonded together, and bonds are modeled based on the material - natural fibers and bio-based polymeric resins.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q2 of FY26.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- A computationally viable model for each component and the composite
- Model parameterization iteration to improve validity
- Adaptation of tools developed for 3D weaves to natural fiber 2D weaves
- Models scaled up on NAS supercomputing resources

Criteria(s)

Feasibility success criteria will be determined based on validation of the material model and availability of parameterization data. Furthermore, the model stability and scalability at the weave unit scale using NAS supercomputing resources, must be satisfied.

Barrier(s)

This event addresses the feasibility of resolving composite microstructure and component-specific properties with modeling. The fiber-resin mechanical interaction can be difficult to isolate experimentally and may provide barriers for model parameterization. This barrier

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will be mitigated with surface energies from wetting experiments and composite coupon mechanical testing. Barriers to modeling due to material length- and time-scales will be mitigated using a multi-scale modeling approach by applying the bonded-particle model at smaller length-scales and the finite volume model to larger length-scales. FY26 findings from other tasks may require additional model refinement iterations without major delays.

Data Management Plan

Data generated will be stored on researcher and NAS computers. Final data, simulation inputs and scripts will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the bonded particle and fiber modeling research community, the composites materials community, and NASA's Entry Systems Modeling project.

CM2: Dry Weave Pattern Assessment

Research Question/Event Purpose

Natural fiber systems benefit from a multi-directional design space. Source material, chemical composition, yarn spin, and weave pattern are all areas that can be optimized for sustainable composites for aircraft. Weave-scale design – pattern, density and layer-to-layer angle – impacts mechanical and infusion behavior. Plain, twill, and unidirectional weave patterns each have benefits for strength and forming specific parts. For example, plain weaves, compared to twill weaves, are stiffer but have a more tortuous void space for resin infusion.

Event Approach/Actions

The dry fiber model developed in the first task will be applied to plain and twill weave configurations, as demonstrated in Figure CM.3. This work will leverage tools developed for thermal protection materials (Entry Systems Modeling project) for generating and deforming models of yarns and weaves. Experimental data from the corresponding fiber and sensing tasks will be used to verify fiber model and weave microstructure. Tensile and flexural mechanical moduli will be calculated with deformation simulations.

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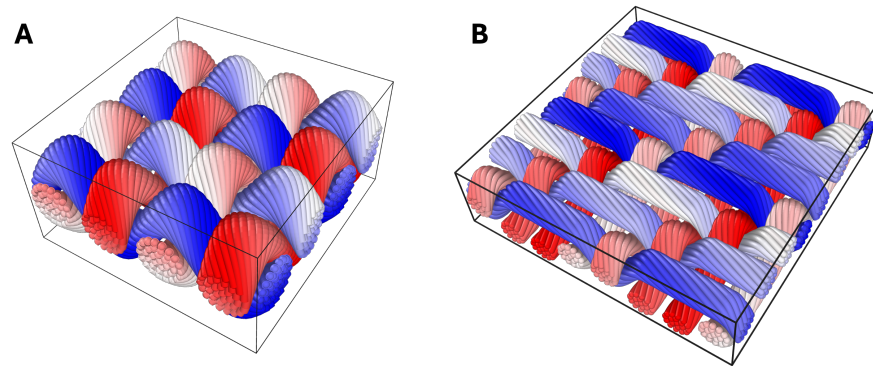


Figure CM.3 Visualization of (A) plain and (B) twill weave bonded-particle models. These weave configurations can be adapted easily in the models to inform weave design.

Specific actions that will be completed for each material system:

- Generate plain, twill, and unidirectional weave model configurations
- Simulate tensile and flexural deformation, and calculate stress-strain curves
- Verify with fiber task data, and support weave pattern down-selection
- Refine model based on simulation and verification performance
- Analyze different weave pattern microstructural properties during deformation

Timeline

This work is planned to begin during Q2 of FY25 and go through Q1 of FY26.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- Simulated weave performance and analysis to inform experimental weave design
- Correlations between microstructural weave features and mechanical behavior

Criteria

Desirability success criteria will be based on the ability to guide new weave pattern testing. Feasibility success criteria will be based on comparison with mechanical and structural data from tasks F1 and S2.

Barrier(s)

This event addresses desirability. Composites are partially so desirable for their ability to mix materials with distinct properties. For sustainable composites to be competitive, computational screening, including fibrous microstructure design (weave pattern), will help ensure sustainable composites are competitive.

Data Management Plan

Data generated will be stored on researcher and NAS computers. Final data and documented test protocols will be uploaded to the program shared drive.

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Stakeholder(s)

Stakeholders include the bonded particle and fiber modeling communities, textile industry and researchers, and the NASA Entry Systems Modeling project.

CM3: Composite Simulation and Microstructural Analysis

Research Question/Event Purpose

Applications for sustainable composites in aviation are broadened by the novel combinations of various bio-based resins and fibers. Manufacturing can lead to composite structural property changes, such as weave density, infusion void fraction and bonding quality, and thus affects the performance of promising candidates. Isolating the role of structural property changes on performance can be experimentally challenging from composite-scale testing. Component-specific models can isolate each component's contribution to mechanical properties and control for microstructural properties.

Event Approach/Actions

This approach will use simulations to remove the effect of non-uniformity, weave, resin infusion and bonding defects by modeling the idealized composite unit cell. The approach will infuse weaves tested in CM.2 with the resin model developed in CM.1, an example of which is visualized in Figure CM.4. Deformation simulations will calculate the tensile and flexural moduli of the idealized composite to provide a baseline for performance. Analysis of the microstructure will be applied to inform any differences with results from the corresponding manufacturing task. Sensing task data will help inform the scale of deviation from the idealized case.

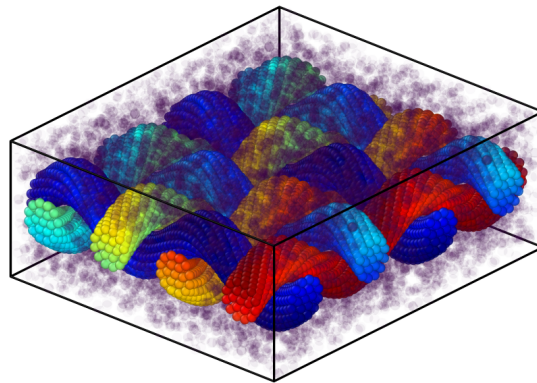


Figure CM.4 Simulation cell of 2x2 plain weave bonded-particle model of natural-fiber yarns (opaque) and bio-based resin network (transparent and purple).

Specific actions that will be completed for each material system:

- Infuse weave configurations with resin model

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- Simulate tensile and flexural deformation, and calculate stress-strain curves
- Verify mechanical properties with M.1 task data
- Analyze microstructural changes of each component during deformation

The direction of additional modeling with composite models will be based on progress in the other tasks and areas identified as most impactful by the SUMAC team, and resource and time availability. Anticipated directions include assessing composite properties with the weave patterns screened in CM2 or with new resin and fiber constituents, as well as deformation simulations of interlaminar configurations.

Timeline

This work is planned to begin during Q1 of FY26 and go through Q4 of FY26.

Anticipated Outcome/Hypothesis

The following outcomes are anticipated:

- Deformation simulations to establish an idealized model of the composite
- Composite mechanical performance sensitive to the fiber-resin interactions
- Correlations between microstructural weave features and mechanical behavior

Criteria

Viability success criteria will be determined based on qualitative agreement with experimental mechanical tests. Feasibility success criteria will be based on the system size and simulation time needed to capture composite behavior, considering CM.1 and CM.2 simulation requirements. If the mismatch is large-scale, non-destructive evaluation task work will inform more realistic model configurations to bridge the mismatch.

Barrier(s)

This event addresses viability. Improving and diagnosing sustainable composite performance due changes due to variation, non-uniformity and component changes will bring great value and confidence. Mismatch between the idealized composite and experimental tests may pose a barrier for this effort.

Data Management Plan

Data generated will be stored on researcher and NAS computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the bonded particle, textile, and composite communities, and the NASA Entry Systems Modeling project.

6.3.6 Systems Analysis

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Overview/Background

The goal of the systems analysis focus area is to study the potential uses of sustainably derived thermoplastic composites in the aviation industry. Weight reduction achieved with lightweight composites leads to improved fuel efficiency, reduced greenhouse gas emissions, and enhanced aircraft performance. The durability and high strength-to-weight ratios of these composites result in longer service life and reduced maintenance requirements. Furthermore, the research efforts for sustainable composites and manufacturing processes help to reduce environmental impact, build robust supply chains, and support the circular economy. To assess the various potential applications of sustainably derived thermoplastic composites in the aviation industry, a systems-level analysis is to be conducted. The timeline for activities associated with this focus area is shown in Figure SA.1.

Task	Pre-Year		FY25				FY26			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
SA1: Systems Analysis of Potential Applications for Sustainably Derived Thermoplastic Composites in AAM Applications										
Compile and review the existing AAM concept vehicle designs and requirements										
Evaluate AAM components for functional material property requirements and constraints										
Investigate AAM components/requirement for potential SUMAC material application										
SA2: Life Cycle Analysis										
Develop Funding Opportunity for Research Grant to Perform Life Cycle Analysis										
Award University Researchers										
Coordinate and Collaborate Activities with Academic Partner										

Figure SA.1 Systems analysis activity timeline. Blue cells are active periods, orange cells are for report out events, yellow cells are “nice to have” activities.

6.3.6.1 SA1: Identification of Part

Research Question/Event Purpose

This analysis will compile and review the existing AAM concept vehicle designs created by NASA and industry, develop an understanding of the respective state-of-the-art composite materials, and analyze the performance trade-offs between the multiple materials. These results will inform the CAS SUMAC activity on how to proceed and ensure a proper direction for the future for these technologies.

Event Approach/Actions

This work will include performing a top-level systems analysis of existing AAM vehicle concepts to inform trade studies on the feasibility and viability of using sustainably derived thermoplastic composites in such vehicles. This trade study shall decompose common AAM architectures into subsystems and components and evaluate those components for functional material property requirements and constraints. The requirements and constraints may regard such parameters as density, shear and tensile strength, impact resistance, thermal conductivity, stiffness, fatigue limits, and manufacturability. Additional levels of assessment are recommended to inform decisions such as component lifecycle; that is, high replacement wear items have a larger sustainability impact than what may be immediately obvious. Lastly, each of these components are to be investigated for the

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potential application of suitable sustainably derived thermoplastic composites and the resulting impact on the sustainability of the system.

Timeline

This work is planned to begin during Q3 of FY24 and go through Q2 of FY25.

Anticipated Outcome/Hypothesis

From this systems analysis, a list of components on an AAM vehicle for which suitable SUMAC materials exist is to be produced. This list shall include relevant material characteristics and be quantitatively prioritized by the sustainable impact of utilizing sustainable materials in lieu of conventional aviation materials.

Criteria

Desirability and viability will be ascertained through determination of the extent that sustainably-derived thermoplastic composite materials can be utilized as replacements for state-of-the-art carbon fiber composites or metallic components. Feasibility will be established through analysis of how much technological advancement will be required to extend the range of possible components that could be replaced by sustainably-derived thermoplastic composite materials.

Barrier(s)

Two major barriers could exist that would make advancing this research objective difficult. The first barrier is a lack of detailed information regarding the components of a prototype advanced air mobility platform. Without this information, it will be very challenging to adequately assess which components could be replaced by sustainably derived thermoplastic composite materials. This will be overcome by working with OEMs, e.g., Joby, Wisp, etc., to get access to this information. The second barrier is a lack of specific information on the anticipated material properties of the sustainably-derived thermoplastic composites. This would inhibit accurate assessment of the potential application space for these materials. This will be overcome by working with the resin, fiber, and manufacturing teams within SUMAC to make a conservative estimate of the potential material properties. Once this is completed, the systems analysis could proceed.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.

6.3.6.2 SA2: Life Cycle Analysis

Research Question/Event Purpose

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Characterizing the sustainability of a component requires quantifying measures of environmental consequence throughout the entire lifecycle of that component. The lifecycle of a component starts with the raw materials and any processing required to get the raw materials into a form for manufacturing. The manufacturing process itself must be considered including factors like the amount of scrap typical for various manufacturing processes. Then, the use phase of the component must be considered. For a AAM application, how the component contributes to the relative weight of the vehicle will be especially important because added weight requires more energy to power, and if the life of the AAM vehicle is long, the energy required to power the vehicle will quickly dominate environmental considerations. Finally, end of life factors for the component must be considered. These include whether the component can be reused, recycled or will have to be scrapped.

The life cycle analysis will work collaboratively with the systems analysis team to identify opportunities to infuse natural fiber composite systems into existing AAM applications to produce more sustainable AAM systems.

Event Approach/Actions

The lifecycle analysis for the SUMAC project will initially be used to help guide the selection of a AAM component where the use of sustainably derived composites will result in a more sustainable net product. Once the fabrication processes and physical properties of the sustainably derived composite that SUMAC moves forward with are better defined, a detailed lifecycle analysis will be completed. This analysis will provide a quantitative assessment of the environmental impact of the proposed composite system and compare it to the conventional material system in use today.

Timeline

This work is planned to begin during Q1 of FY25 and go through Q4 of FY26.

Anticipated Outcome/Hypothesis

The life cycle analysis will support the systems analysis in helping to identify AAM components that would benefit from being replaced with natural fiber composite materials. These components will be quantitatively prioritized by the sustainable impact of utilizing natural fiber composite materials in lieu of conventional aviation materials.

Criteria

Desirability and viability will be determined by characterizing the extent that sustainably-derived thermoplastic composite materials can be utilized as replacements for state-of-the-art carbon fiber composites or metallic components with a net environmental benefit. Feasibility will be established through analysis of how much technological advancement

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will be required to extend the range of possible components that could be replaced by sustainably-derived thermoplastic composite materials.

Barrier(s)

Two barriers exist to advance this research objective. The first barrier is a lack of detailed information regarding the components of a typical AAM platform. Without this information, it will be very challenging to quantify inputs for the lifecycle analysis. This will be overcome by working with OEMs, e.g., Joby, Wisp, etc., to get access to this information. The second barrier is a lack of specific information on the anticipated material properties of the sustainably-derived thermoplastic composites. This lack of information will inhibit accurate assessment of the design implications of leveraging these materials. This will be overcome by working with the resin, fiber, and manufacturing teams within SUMAC to make a conservative estimate of the potential material properties. Once this is completed, the lifecycle analysis can proceed.

Data Management Plan

Data generated will be stored on researcher computers. Final data and documented test protocols will be uploaded to the program shared drive.

Stakeholder(s)

Stakeholders include the research community, aircraft OEMs, and material developers.