

BIOBASED BAMBOO COMPOSITE DEVELOPMENT

Tech Collaboration between Resource Fiber LLC and Manufacturing Demonstration Facility (MDF)ⁱ

Resource Fiber Phase I Summary Report

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David Knight, Lee Slaven – Resource Fiber LLC
Uday Vaidya, MDF ORNL and University of Tennessee



Resource Fiber LLC identified that bamboo fiber could be integrated with synthetic materials to create stronger, lighter weight and “greener” products. In this Phase I work, Resource Fiber collaborated with the Manufacturing Demonstration Facility of Oak Ridge National Laboratory and the University of Tennessee (MDF). The goal of the collaboration was to conduct proof of concept studies on bamboo fibers with thermoset and thermoplastic resins with a view to create commercial products.

Bamboo is one of the fastest growing plants in the world. It is rapidly renewable and widely used today in the manufacture of products. The global market for bamboo is estimated to be more than \$60 billion, and is rapidly growing. When coupled with additional products that could be manufactured using bamboo fiber, the scale of the industry becomes sizeable and, in time, is projected to be valued in the billions of dollars within the United States.

Studies have shown that the energy consumption to produce a bamboo-fiber mat (10 MJ/kg), including cultivation, harvesting, and fiber separation, amounts to approximately 17% of the energy to produce a glass-fiber mat (55 MJ/kg). The application areas are very broad ranging from truck trailer decking, railroad ties, beams, joists, low cost housing, filtration, additive material feedstock, biomedical products, security panels, furniture and many more.

Figure 1 provides a comparison of bamboo relative to conventional materials. It must be noted that bamboo interfaces with the wood and composites space effectively both in terms of performance and cost.

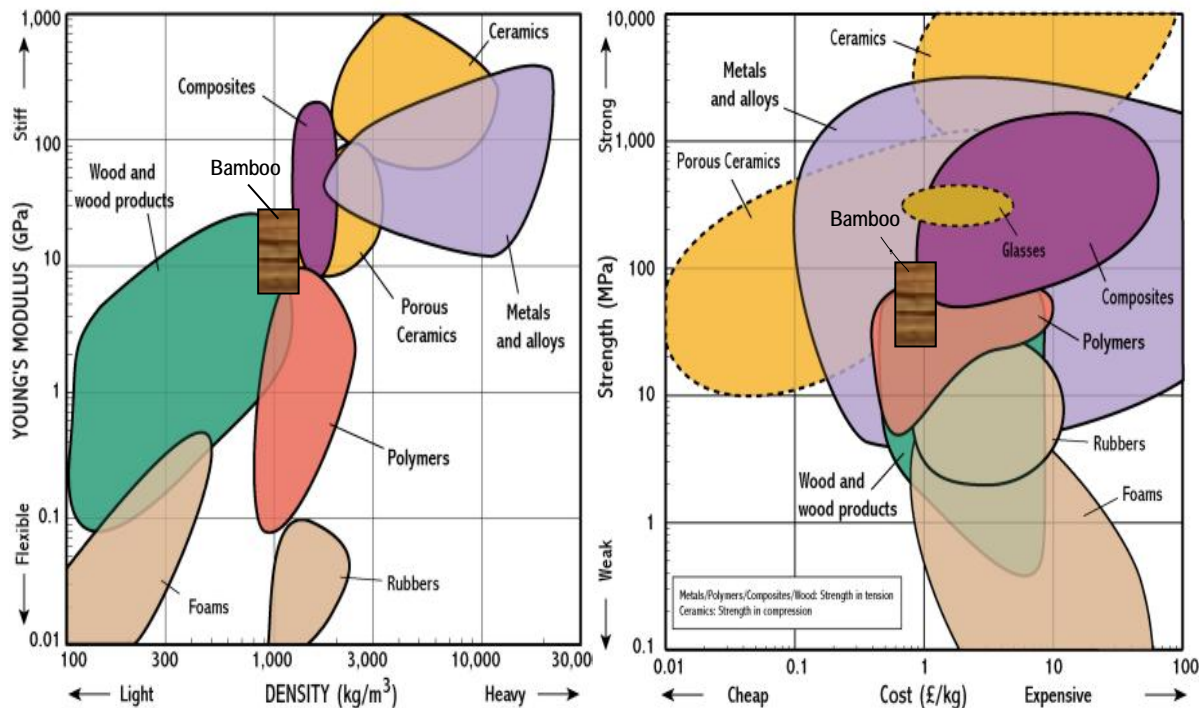


Figure 1. Comparison of bamboo to wood products and other engineered materials.

The objectives of the Phase 1 tech collaboration between Resource Fiber and MDF were to:

- Develop bio-based (bamboo) additive materials as feedstock for 3D printing.
- Develop and characterize intermediates such as bamboo-polymer mats, compounded pellets and continuous-discontinuous hybrids.
- Characterize the long-term durability such as freeze-thaw and environmental thermal-humidity behavior of bamboo products such as railroad ties.
- Utilize the composite and additive infrastructure at MDF to realize prototype products in energy, automotive and related applications.

Bamboo fiber for large-scale additive manufacturing: Resource Fiber’s proposed use of bamboo fiber as feedstock in combination with polymers used in additive manufacturing has several advantages such as - (a) lower energy consumption; (b) less heat buildup due to the insulating nature of bamboo fibers; (c) lower shrinkage and warpage in the part; (d) reduced carbon footprint among others. In this Phase 1 work, bamboo fibers were compounded with polylactic acid (PLA) with the Big Area Additive Manufacturing (BAAM) facility at MDF to produce printed structures. The Resource Fiber bamboo was used as a constituent in a [printed exhibit](#) featured as a large-scale structure, see Figure 1.



Figure 1

Additively manufactured (3D printed) bamboo-PLA exhibit at the entrance of the Design Miami Pavilion. About 1200 lbs. of Resource Fiber bamboo (out of 3000 lbs. of total bamboo) was used on this structure. The pavilion is assembled from modules printed at the ORNL MDF using compounded bamboo-PLA pellets via extrusion-deposition.

Bamboo mats intermediates: The team developed and characterized bamboo fiber intermediates produced with wet-laid mats. The material variants included - (a) 100% bamboo fibers, and (b) hybrids of carbon fiber-bamboo fiber-thermoplastic and thermoset resins. Discontinuous (short fibers) of bamboo have been used in developing a range of material forms that can be used in a range of applications that would emerge by incorporating bamboo fibers. Representative tensile and flexural modulus and strength are shown in Table 1 and 2 respectively, for material with 5% and 10% carbon fiber loaded bamboo mats in thermoset vinyl ester resin. To put this into context, if we consider 22 weight % glass fibers sheet

molding compound (SMC) as a comparable discontinuous fiber material– the comparison is provided in Tables 1 and 2 respectively. So even at a nominal 10% carbon loading with bamboo, the performance is comparable to much higher fiber loading with glass fibers in tensile strength and tensile modulus. In flexural loading the 22% glass loading has slightly higher properties than the bamboo-10% carbon. ***This further implies that if the bamboo carbon content was increased to 20% the performance would significantly exceed comparable materials like SMC and yet provide very lightweight solutions.*** Here we provide just a representative comparison, however numerous comparable materials would include glass-BMC, other SMCs and LFT materials.

Table 1. Tensile test result for both plates variations

CF Content	E(GPa)	SD(GPa)	S _{tu} (MPa)	SD(MPa)
5% CF	6.75	1.26	50.16	6.39
10% CF	10.61	1.20	61.01	7.43
SMC 22% glass thermoset				
22% glass content	10.98	-	51	-

Table 2. Average flex data comparison between the two variances of the plates

CF Content	Avg Strength (MPa)	SD (MPa)	Avg Flex Modulus (GPa)	SD (GPa)
5%	64.23	10.55	3.30	0.78
10%	93.27	5.80	5.27	0.63
SMC 22% glass thermoset				
22% glass content	140	-	10.60	-

Compounding of Bamboo Short Fiber/Polypropylene: Polypropylene (PP) and bamboo fiber with 5 to 20% loading were compounded in a twin screw to produce pellets. The bamboo/PP composite panel was characterized for tensile, flexure, Izod impact and short beam shear test properties. Table 3 provides a summary of the bamboo polypropylene compounded pellets with the different bamboo loadings. Performance may be further enhanced with bamboo long fibers.

Table 3. Mechanical Properties of 5, 10, 15 and 20% bamboo-PP composites

Sample	Tensile Test				Flexure Test				Short Beam Shear Test		Impact Test	
	Strength MPa		Modulus GPa		Strength MPa		Modulus GPa		Strength MPa		Resistance Energy KJ/m ²	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
5%	26.02	1.1	1.81	0.07	59.82	1.47	1.26	0.03	5.56	0.25	3.66	1.44
10%	24.45	0.45	1.98	0.10	54.89	3.11	1.31	0.08	6.79	0.39	2.73	1.09
15%	23.77	1.49	2.11	0.09	50.20	5.17	1.54	0.08	7.72	0.25	2.30	0.78
20%	21.92	0.68	2.31	0.15	38.74	1.79	1.27	0.10	6.48	0.16	1.42	0.32

The property comparison from unidirectional continuous bamboo from Resource Fiber bamboo stems, compounded bamboo-PP and the neat polymers, and sheet molding compound (SMC) are shown in Table 4.

Table 4. Comparison of bamboo with traditional polymers and sheet molding compound.

Comparison		Bamboo*		PP	Composite (Bamboo/PP)**				HDPE	PU	Nylon 6	SMC
		Rubro	Moso	neat	5%	10%	15%	20%	neat	neat	neat	20% glass
Tensile	Strength, Mpa	191.87	150.42	23.71	26.02	24.45	23.77	21.92	30.49	69	76	50
	Modulus, Gpa	17.33	12.26	1.25	1.81	1.98	2.11	2.31	1.55	1.79	2.75	12

*Data from continuous stem of Resource Fiber bamboo

**Twin screw compounded pellets

The results summarized in Tables 1-4 are positive and are expected to allow Resource Fiber to advance to Phase 2.

Long term durability such as freeze-thaw and environmental thermal-humidity behavior of bamboo products such as railroad ties, beams etc.: Accelerated environmental testing has been conducted on bamboo railroad ties and on planks and beams of various widths and lengths produced by Resource Fiber’s manufacturing process. The purpose of these experiments was to evaluate the durability and stability of the bamboo products against conventional woods and comparable products.

Accelerated tests were conducted with the environmental cycle tailored to represent 1 day equivalent to 1 year of hygrothermal exposure under hot-wet and freeze-thaw conditions. The testing lasted for 327 days equating to 327 years. The Resource Fiber bamboo products showed very little expansion/contraction or degradation. Conservatively, when these products are used in their intended applications should last more than 100 years.

Early prototype products with bamboo: The work focused on the use of bamboo intermediates such as the mats and compounded pellets to produce products. Panels with bamboo-composite intermediates were considered in applications for the physical security market. Customers are continually seeking “green” offerings in this market due to the ever-growing demand. Bamboo intermediates were evaluated in mat form for a range of thicknesses and areal densities. The materials were tested for different threat levels and the bamboo configurations aided by composite configurations provided promising ballistic performance. This work is being advanced significantly in Phase 2 of this effort.

Value Proposition for Bamboo: The energy required to produce bamboo offers attractive potential to replacing polymers. Even small content of polymer replacement with bamboo has significant energy savings. Table 5 compares the energy of production of bamboo compared to the representative thermoplastic polymers and thermoset sheet molding compound (SMC). These materials would typically be used currently, where small amounts of bamboo can enable significant energy savings without compromising performance.

Table 5. Energy to convert bamboo fibers compared to polymers and SMC

Comparison	Bamboo	PP	HDPE	PU	Nylon	SMC
Energy to convert (MJ/kg)	10	64	103	73	250	90

Next Steps:

The work produced in Phase 1 provides the direction to pursue Phase 2 work with bamboo intermediates for ballistic panels, furniture and biomedical products. The collective technology of additive manufacturing, long and short fiber bamboo, production of pellets and intermediate mats, tooling and production of bamboo composites will be advanced. Resource Fiber’s Oneida, TN facility and the MDF/UT will continue to collaborate in Phase 2.

Note: A detailed, confidential, non-public report is available for review.

ⁱ The U.S. Department of Energy’s first [Manufacturing Demonstration Facility](#), established at Oak Ridge National Laboratories, helps industry adopt new manufacturing technologies to reduce life-cycle energy and greenhouse gas emissions, lower production costs, and create new products and opportunities for high-paying jobs.