Sustainable Biocomposites for Construction

by

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Abstract

Typical construction materials and practices have a large ecological footprint. Many materials are energy-intensive to produce, and construction and demolition debris constitutes a large percentage of U.S. landfill volume. Biocomposites are structural materials made from renewable resources that biodegrade in an anaerobic environment after their useful service life to produce a fuel or feedstock to produce a biopolymer for a new generation of composites. These materials are being researched and developed to replace less eco-friendly structural and non-structural materials used in the construction industry. In this study, the mechanical behavior of biocomposites made from cellulose acetate and polyhydroxybutyrate matrices and hemp fiber (fabric) have been characterized experimentally. The data shows that these biocomposites have mechanical properties similar to structural wood. The biocomposites studied have the potential to be used for scaffolding, formwork, flooring, walls and for many other applications within buildings, as well as temporary construction.

Introduction

Most construction practices and materials used within the building industry leave a large ecological footprint. For example, roughly 40% of U.S. landfill volume results from construction and demolition (C&D) debris. (1) C&D debris is composed of 30-50% wood, drywall, and plastic. (2) These materials are recalcitrant in landfills and can potentially be replaced by biocomposite materials.

Biocomposites are manufactured from renewable materials that biodegrade in an anaerobic environment. The biocomposites studied here are composed of natural fiber fabrics and biopolymeric matrices and are intended for use in non-structural and structural applications.

Potential applications for biocomposites within buildings include framing, walls and wallboard, window frames, doors, flooring, decorative paneling, cubicle walls and ceiling panels. In construction, biocomposites could be used for formwork and scaffolding, for instance. The use of biocomposites for temporary and adjustable components of buildings would limit landfill waste when the interior designs within the building are changed or in seismic regions where non-structural damage may be significant after an earthquake.

Prior Biocomposite Research

Mohanty *et al.* (3) and Wool & Sun (4) provide a thorough review of recent research on biocomposites, natural fibers and biopolymers. Much of the research on biocomposites has focused on mechanical testing of short-fiber biocomposites, micromechanical studies such as fiber treatments for improved fiber-matrix interface properties, and modeling of biocomposite properties from fiber and matrix properties. (3)

Limited biocomposite research has extended to structural-scale studies. Where structural-scale testing has been conducted it has been primarily on partially bio-based composites using either synthetic matrices or synthetic fibers. Dweib *et al.* manufactured and tested foam-core roof-panels using a synthetic core. (5) The matrix was a comonomer of acrylated epoxidized soybean oil and styrene and the fibers were chicken feathers, corrugated paper and e-glass. (5) Lackey *et al.* pultruded natural fibers and a synthetic polymer for application within the automotive industry. (6) Burgueño *et al.* manufactured, tested and modeled cellular composites made from short hemp fibers and ortho-unsaturated polyester matrix. (7-8) Burgueño *et al.* also studied sandwich panels with short fiber composite cores and hemp, jute, and glass fabric skins. (9-10)

Mechanical Properties of Hemp Fabric Biocomposites

In this research, hemp/cellulose acetate and hemp/polyhydroxybutyrate (PHB) composites have been studied. Hemp fabric was chosen as the natural fiber for biocomposites because it has a high modulus of elasticity (42-70 GPa) relative to most other woven natural fibers such as flax (28-80 GPa) or jute (13-27 GPa). Cellulose acetate, which is produced from cotton or wood pulp, and PHB, which is produced by microbes, were chosen as a matrix materials based on preliminary studies indicating rapid anaerobic biodegradability. (11) Additionally, preliminary studies to produce PHB using methane, a greenhouse gas and a by-product of anaerobic degradation, as a feedstock show that PHB can be created from waste. (12)

To characterize the biocomposite material for use in construction-related applications such as formwork and scaffolding, Hemp/cellulose acetate (HCA) and hemp/PHB (HPHB) composites were manufactured by laminating bi-directional plain weave fabric. Eight-layer composite plies were tested according to ASTM standards in tension, compression, shear and flexure. An MTS 858 table top tester with a capacity of 13,500 N was used with the proper fixtures to conduct these experiments. Tensile, shear and flexure results are presented here.

Tension. The tensile specimens were tested according to ASTM D638, "Standard Test Method for Tensile Properties of Plastics." (13) Modulus of elasticity, maximum strength, percent elongation and poisson's ratio for the material were measured and calculated. The specimen geometry is shown in Figure 1(a). The specimen was gripped between flat mechanical wedge grips with a saw-tooth profile. Loading was displacement-controlled at 5 mm/min. The longitudinal strain was measured using an extensometer with a 50 mm gage length. Transverse strain was measured by a strain gage. The stress-strain behavior is shown in Figure 1(b). The average modulus of elasticity calculated from the initial slope of the stress-strain graph is 5400 ± 100 MPa for HCA and 5500 ± 200 MPa for HPHB. The average maximum stress is 54 ± 3 MPa for HCA and 56 ± 3 MPa for HPHB. The average strain at peak load is 4.0% ± 0.2% for HCA and 3.5% ± 0.1% for HPHB. The average poisson's ratio is 0.33 ± 0.02 for HCA and 0.30 ± 0.04 for HPHB.

Shear. Shear specimens were tested according to ASTM D3518, "Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate" (14) to determine the material's shear modulus and maximum shear strength. The specimen geometry is shown in Figure 2 (a). The fibers in the composite were aligned at 45° angles to the applied tensile loading. The specimens were tested at a constant rate of displacement of 1.27 mm/min. An extensometer with a gage length of 50mm measured the strain at the center of the specimen. The shear stress-strain behavior is shown in Figure 2(b). The response in Figure 2(b) is plotted up to strain of 5%. Above 5% strain the fibers were no longer aligned at 45° angles to the testing direction; therefore, the measurements and calculated strains no longer depicted the shear stress-strain behavior accurately. The average shear moduli calculated from the initial slope of the stress-strain graph are 1090 ± 50 MPa and 880 ± 50 MPa for HCA and HPHB respectively. The average maximum shear stresses are 12.3 ± 0.1 MPa and 9.85 ± 0.03 MPa for HCA and HPHB respectively.

Flexure. The flexural specimens were tested according to ASTM D790, "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials." (15) The specimen geometry is shown in Figure 3(a). The dashed lines represent the location of loading for 3-point bending. The span-to-thickness ratio for the specimens was 16:1. The stress-strain behavior at the outermost tensile fiber is shown in Figure 3(b). The average maximum flexural stress and stiffness calculated at the outermost tensile fiber was calculated for five specimens of each material type. The maximum stresses are 95 ± 3 MPa for HCA 65 ± 3 MPa for HPHB. The average moduli of elasticity calculated from the slope of the load-displacement response, the specimen geometry, and boundary conditions are 6560 ± 370 MPa and 5050 ± 440 MPa respectively for HCA and HPHB.

Discussion of Mechanical Properties

The mechanical properties of the HCA and HPHB composites are compared to wood-based materials and synthetic composites in Table 1. The strength of HCA and HPHB composites in flexure and shear is comparable to structural lumber and exceeds the strength of plywood. The flexural modulus is 45% to 73% of that for lumber and plywood (parallel to grain).

The mechanical properties of the biocomposites are lower than those of synthetic composites. This result is expected because the mechanical properties of the synthetic matrix and fibers exceed those of the biocomposite components. In addition, scanning electron microscope studies of the failure surfaces of the HCA composites have shown that the matrix does not penetrate to the center of the yarn. (16) Without a strong bond to the matrix, the hemp fibers can more easily slip rather than stretch thereby, reducing the possible stiffness. Poisson's ratios for the biocomposites are within the same range as those for the synthetic composites.

The stress-strain behavior of the HCA and HPHB composites is highly nonlinear, as shown in Figures 1(b) and 2(b), which is in contrast to the typically linear-elastic response of synthetic composites up to failure. The nonlinearity is attributed to the nonlinear behavior of the plastic matrix, a combined failure mode of fiber rupture, pull-out, and slip, and incomplete fiber/matrix bond. While micromechanical models can be used to understand the nonlinear stress-strain behavior, classical models for short-fiber and continuous-fiber composites are inapplicable because the yarns are composed of tightly packed short hemp fibers.

Potential Applications for Biocomposites

There are numerous potential applications for biocomposites within buildings (e.g. framing, flooring, decorative paneling) as well as in construction (e.g. form-

work, scaffolding). The low modulus of elasticity characteristic in the biocomposites suggests that their component design will be controlled primarily by deflection limits. To meet these limits, biocomposites can be shaped to have high geometric stiffness. In such optimizations it is desired to keep the stresses on the biocomposites within the linear-elastic range.

The use of biocomposites for formwork is briefly discussed here. Biocomposites could be manufactured to provide a surface with a smooth finish or a variety of textures. Although plywood forms typically can be used about five to ten times, with a polymer surface overlay to repel water and other chemicals, the number of reuses increases. (17) While it has not yet been thoroughly researched, there exists the potential for forms of biocomposite material to be coated by a hydrophobic biopolymer to increase the form's ability to be reused while not compromising its ability to biodegrade anaerobically.

For the design of plywood sheathing, deflection limits rather than strength limits are expected to control. Committee 347 of the American Concrete Institute addresses formwork for concrete and recommends the deflection limit for plywood used in formwork to be 1:360 (deflection: span) (18). To meet deflection limits required for plywood sheathing, biocomposites must achieve the same stiffness (EI, or Modulus of Elasticity x Moment of Inertia) as plywood. The modulus parallel to grain and an effective moment of inertia, which accounts for variation in ply orientation, are used to determine plywood deflections.

Given a pressure of 0.026 MPa, a width of 305 mm, and support spacing of 305 mm (typical for forming a concrete slab), the deflections of plywood and HCA and HPHB panels are calculated, assuming that the panels are continuous over 3 or more spans, using the following equation: $\Delta_{max} = Pwl^4/145EI$, where P is pressure, w is width, and l is span length. As shown in Table 2, both the HCA and HPHB panels meet the deflection limits with a slightly smaller thickness than plywood. The maximum stress experienced by the HCA and HPHB panels are 6.4 and 6.5 MPa which fall within the linear-elastic range of the stress-strain responses. The preceding example indicates that biocomposites have the potential to replace plywood within formwork, in this case for a slab form.

Conclusions

Mechanical testing of Hemp/Cellulose Acetate and Hemp/Polyhydroxybuterate composites were performed and demonstrated that these biocomposites have strength properties comparable to structural lumber and higher than plywood. The moduli of elasticity of the biocomposites are lower than that for lumber and plywood parallel to grain. Due to the low modulus of elasticity, deflection limits are expected to control the design of hemp biocomposite components. Biocomposite components can be shaped to have high geometric stiffness to meet deflection limits while minimizing material use. Finally, from preliminary analysis it appears that a 15.625 mm (5/8") plywood sheathing for formwork could be replaced by a similar thickness of biocomposite to meet deflection limits for formwork for slabs.

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Figures:
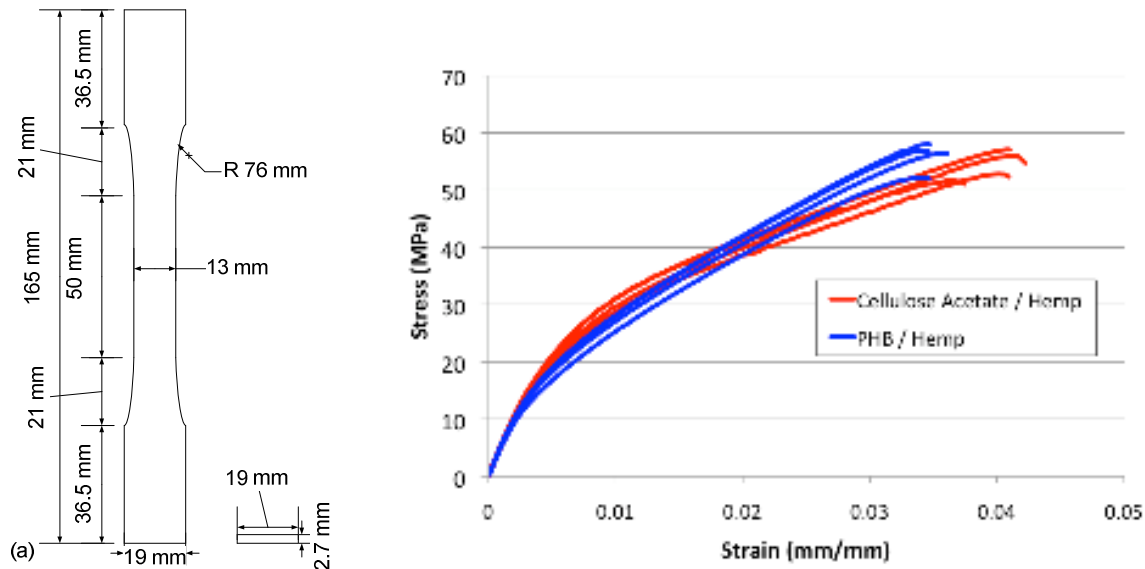
Figure 1: (a) Tensile specimen geometry; (b) Tensile stress-strain behavior of Hemp/Cellulose Acetate and Hemp/PHB composites
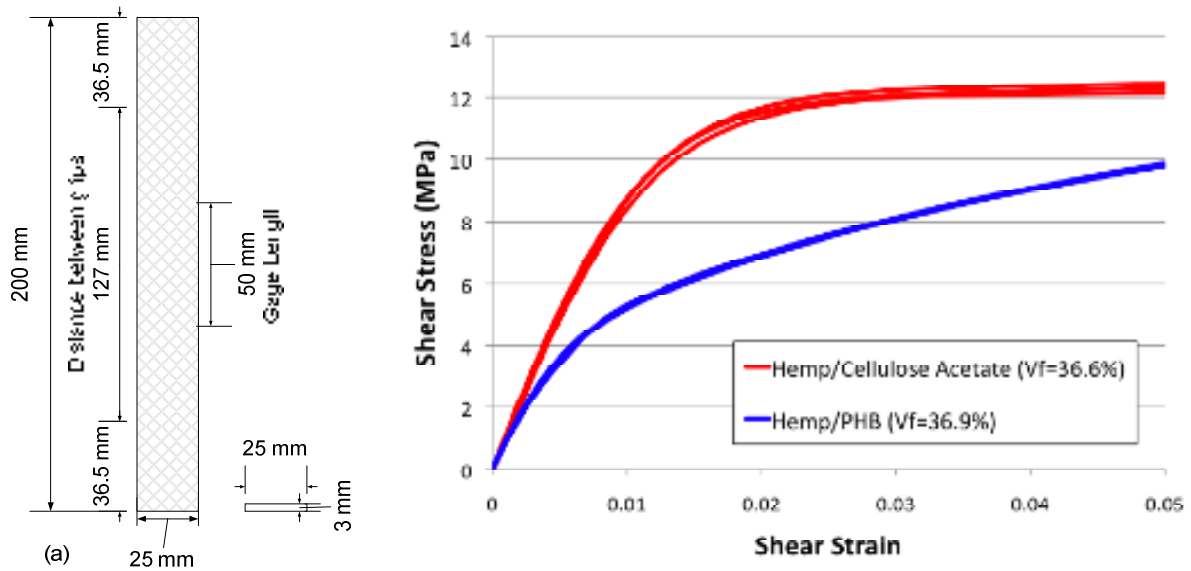
Figure 2: (a) Shear specimen geometry; (b) Shear stress-strain behavior of three specimens of Hemp/Cellulose Acetate and Hemp/PHB composites
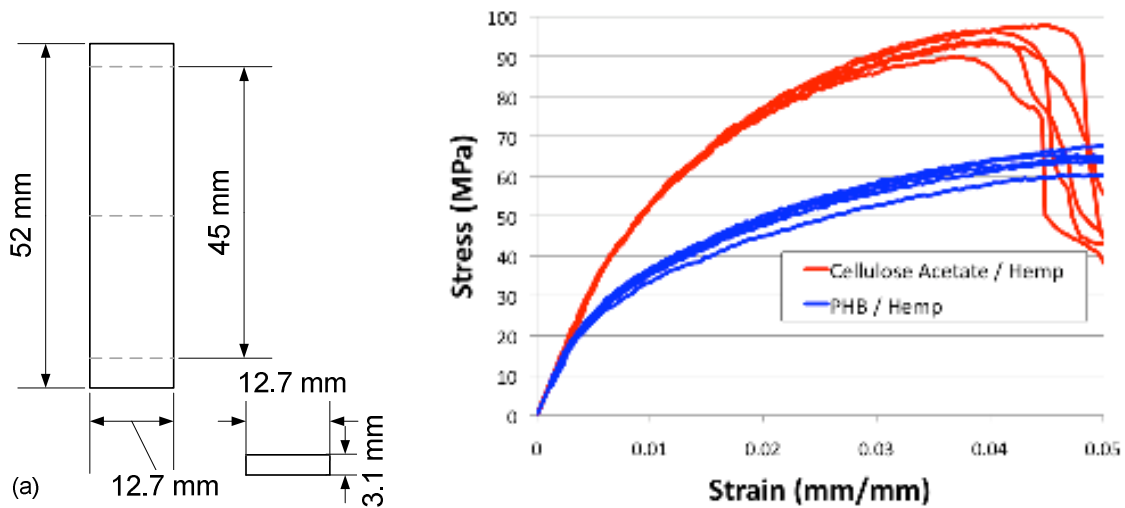

Figure 3: (a) Flexure specimen geometry; (b) Force-displacement of five specimens of Hemp/Cellulose Acetate and Hemp/PHB composites

Tables:

Table 1: Mechanical Properties of biocomposites and other materials

	HCA Composite	HPHB Composite	Lumber (Western Hemlock) (19)	Plywood (B-B Class 1) (18)	E-Glass/Epoxy Composite (20)	Carbon/Epoxy Composite (20)
Tensile Modulus (GPa)	5.4 ± 0.1	5.5 ± 0.2	--	--	39	142 - 294
Tensile Strength (MPa)	54 ± 3	56 ± 3	45.5 - 77.9	27	1080	590 - 2860
Strain at Failure in Tension (%)	4.0 ± 0.2	3.5 ± 0.1	--	--	2.8	0.3 - 1.7
Poisson's Ratio (in tension)	0.30 ± 0.03	0.30 ± 0.05	--	--	0.28	0.23 - 0.27
Shear Modulus (GPa)	1.09 ± 0.05	0.88 ± 0.01	--	--	3.8	4.9 - 7.4
Shear Strength (MPa)	12.3 ± 0.1	9.85 ± 0.03	5.93 - 8.89	1.0	89	49 - 83
Flexural Modulus (GPa)	6.56 ± 0.37	5.05 ± 0.44	9.03 - 11.2	10.3*	--	130
Flexural Strength (MPa)	95 ± 3	65 ± 3	45.5 - 77.9	27	--	1700

* Parallel to grain (35 times the modulus perpendicular to grain)

Table 2: Properties for Formwork Sheathing Design Example

	Thickness (mm)	E (MPa)	I* (mm⁴)	EI (N-mm²)	Maximum Deflection (mm)	Span/Deflection
Plywood	15.875	10342	53694	555281470	0.85	360
PHB Composite	14.900	6600	84022	554544570	0.85	360
HCA Composite	14.980	6500	85383	554986621	0.85	360

*For plywood, I is the effective moment of inertia