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Mechanical behavior of fire-resistant biocomposite

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ABSTRACT

Biocomposites are typically formed by binding natural fibers derived from plants or cellulose using organic binders. The fibers that are used are normally industrial by-products and, hence, they are abundant and inexpensive. One such material is sawdust, and varieties of composite boards are being manufactured utilizing sawdust as filler material. Two major drawbacks of this system are their vulnerability to fire and very low bending strength. Both the matrix and the sawdust are flammable and this paper deals with using an inorganic matrix to improve the fire resistance. The inorganic matrix can resist temperatures up to 1000 °C and it provides protection to sawdust for short durations. The strength of these boards was increased by reinforcing with a very low percentage of high strength glass and carbon fibers. Since these fibers provide up to a fifteen-fold increase in strength, the cost increase is justifiable. Prisms were made using various proportions of sawdust ranging from about 11% to 38% by mass. The prisms were tested in compression and flexure to obtain the basic mechanical properties and determine the optimal sawdust content. Prisms with optimal sawdust content were also strengthened with glass or carbon fiber reinforcements to increase flexural capacity. The results indicate that it is possible to manufacture and engineer these types of composite beams to obtain a specified strength without using any specialized equipment, heat, or pressure, thus, producing an environmentally conscious biocomposite material.

1. Introduction

For many decades, the residential construction field has used timber as its main source of building material for the frames of modern American homes. The American timber industry produced a record 49.5 billion board feet of lumber in 1999, and another 48.0 billion board feet in 2002. At the same time that lumber production is peaking, the home ownership rate reached a record high of 69.2%, with over 977,000 homes being sold in 2002 [1]. Because residential construction accounts for one-third of the total softwood lumber use in the United States, there is an increasing demand for alternate materials. Use of sawdust not only provides an alternative but also increases the use of the by-product efficiently.

Wood plastic composites (WPC) is a relatively new category of materials that covers a broad range of composite materials utilizing an organic resin binder (matrix) and fillers composed of cellulose materials. The new and rapidly developing biocomposite materials are high technology products, which have one unique advantage – the wood filler can include sawdust and scrap wood products. Consequently, no additional wood resources are needed to manufacture biocomposites. Waste products that would traditionally cost money for proper disposal, now become a beneficial resource, allowing recycling to be both profitable and environmentally conscious. The use of biocomposites and WPC has increased rapidly all over the world, with the end users for these composites in the construction, motor vehicle, and furniture industries [1–4].

One of the primary problems related to the use of biocomposites is the flammability of the two main components (binder and filler). If a flame retardant were added, this would require the adhesion of the fiber and the matrix not to be disturbed by the retardant. The challenge is to develop a composite that will not burn and will maintain its level of mechanical performance [5,6]. In lieu of organic matrix compounds, inorganic matrices can be utilized to improve the fire resistance. Inorganic-based wood composites are those that consist of a mineral mix as the binder system. Such inorganic binder systems include gypsum and Portland cement, both of which are highly resistant to fire and insects [2]. The main disadvantage with these systems is the maximum amount of sawdust or fibers than can be incorporated is low [7,8]. One relatively new type of inorganic matrix is potassium aluminosilicate, an environmentally friendly compound made from naturally occurring materials. The Federal Aviation Administration has investigated the feasibility of using this matrix in commercial aircraft due to its ability to resist temperatures of up to 1000 °C without generating smoke, and its ability to enable carbon composites to withstand temperatures of 800 °C and maintain 63% of

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its original flexural strength [9]. Potassium aluminosilicate matrices are compatible with many common building material including clay brick, masonry, concrete, steel, titanium, balsa, oak, pine, and particleboard [10–19].

The primary objective of the research reported in this paper was to fabricate a biocomposite particleboard by combining the aforementioned potassium aluminosilicate matrix with waste sawdust. The effect of varying the proportion of constituents on the biocomposite was measured using compressive strength specimens. Small beams of this biocomposite were reinforced with glass and carbon fibers to obtain higher flexural strengths since the boards are relatively weak in flexure. Fire tests recently conducted at the Federal Aviation Administration (FAA) Technical Center show that the beams satisfy the stringent FAA fire requirements [20].

2. Experimental design

The biocomposite material under investigation in this study consisted of the potassium aluminosilicate matrix mixed with waste sawdust obtained from commercial home improvement stores. While traditional particleboard typically requires both pressure and heat to bond the constituents [4], the authors opted for a much simpler and economical manufacturing system by casting the biocomposite by hand under standard laboratory conditions. For the first part of the experimental program, several formulations were mixed to examine the effect of varying the relative proportions of sawdust and resin. The proportion of sawdust for the eight formulations ranged from approximately 11–38% by mass and the primary response variables were workability, density, and compressive strength of the particleboard. The prismatic-shaped specimens were 100 mm long with a cross-section of 25 mm × 25 mm. The details of each of these specimens (C1 through C8) are presented in Table 1.

In the second phase of experimental work, the particleboards were evaluated for flexural loading using beams 500 mm long, 50 mm wide, and 25 mm thick. Based on the test results of workability and compressive strength, these prisms were fabricated using 29% sawdust by mass. Some of the specimens were also strengthened with either glass or carbon fiber reinforcement on both the tension and compression faces of the beam using the inorganic matrix to impregnate the fibers. The primary variables for the reinforcement were the amount and type of reinforcement.

- woven carbon and glass fabric with 3k carbon tows in the warp direction (“3k Woven C&G”); reinforcements were 3k carbon tows (3000 filaments) of 234 GPa modulus with area of 0.748 mm^2/cm;
- 3k unidirectional carbon tape (“3k Uni C tape”); reinforcements were 3k carbon tows (3000 filaments) and area of fibers was 0.985 mm^2/cm, while the modulus of elasticity was 230 GPa;
- 12k high-modulus carbon tows (“12k HMC tow”) consisting of 12,000 filaments per tow with a total reinforcement area of 1.14 mm^2 and a modulus of 640 GPa;
- 2k alkali-resistant glass roving (“2k AR-glass roving”) consisting of 1566 filaments with a total reinforcement area of 0.444 mm^2 and a modulus of 72 GPa;
- 4k standard glass roving (“4k E-glass roving”) consisting of 4000 filaments with a total reinforcement area of 0.262 mm^2 and a modulus of 72 GPa.

For each of the nine configurations, two identical specimens (“A” and “B”) were fabricated and tested, resulting in 18 beams, Table 2.

Table 1
Details of compressive strength specimens.

Specimen ID	Mass fraction of sawdust (%)	Density (g/cm^3)	Compressive strength (MPa)	Compressive modulus (GPa)	Strain at failure (%)
C1	10.9	1.741	39.6	2.52	2.4
C2	12.5	1.642	23.3	1.27	2.8
C3	14.0	1.636	18.0	1.01	5.0
C4	16.9	1.633	20.2	1.43	8.5
C5	29.0	1.254	6.8	0.64	8.0
C6	33.8	1.092	2.8	0.39	6.0
C7	35.5	1.067	4.3	0.40	7.8
C8	38.0	0.929	2.1	0.18	6.8

Table 2
Details of flexural specimens.

Specimen ID	Core beam density (g/cm^3)	”Total reinf. ratio” (%)	Reinforcement on each face			Average maximum moment (N m)	Deflection at peak load (mm)	Flexural stiffness, EI (N m^2)
			# Layers	Type	Area (mm^2)			
1A	1.017	0.00	0	None (control)	N/A	9.32	3.30	59
1B	0.997	0.00	0	None (control)	N/A			
2A	1.028	0.58	1	3 k Woven C&G	3.600	121.16	16.16	179
2B	1.009	0.58	1	3 k Woven C&G	3.600			
3A	1.027	1.15	2	3 k Woven C&G	7.200	140.80	12.26	389
3B	1.012	1.15	2	3 k Woven C&G	7.200			
4A	0.995	0.18	1	12 k HMC tow	1.140	34.02	2.56	259
4B	0.998	0.18	1	12 k HMC tow	1.140			
5A	1.017	0.55	3	12 k HMC tow	3.420	85.48	3.90	461
5B	1.012	0.55	3	12 k HMC tow	3.420			
6A	1.014	0.07	1	2 k AR-glass roving	0.445	21.25	2.58	156
6B	1.021	0.07	1	2 k AR-glass roving	0.445			
7A	1.024	0.14	2	2 k AR-glass roving	0.890	27.62	2.65	209
7B	1.036	0.14	2	2 k AR-glass roving	0.890			
8A	1.008	0.77	1	3 k Uni C tape	4.800	119.75	9.26	379
8B	1.002	0.77	1	3 k Uni C tape	4.800			
9A	1.033	0.14	1	4 k E-glass roving	0.844	22.52	3.08	161
9B	1.017	0.14	1	4 k E-glass roving	0.844			