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Alginate aerogel/glass and carbon fiber composite substitutes for balsa cores in wind turbine blades

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Alginate aerogel/glass and carbon fiber composite substitutes for balsa cores in wind turbine blades

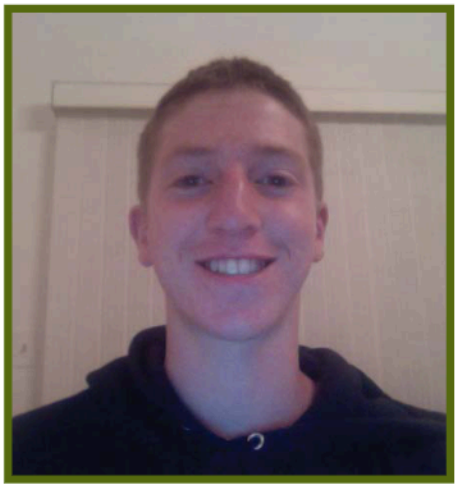
ABSTRACT

Aerogels are mesoporous solids composed of 90-95% air. Their remarkable properties include: high strength-to-weight ratios, low thermal conductivity, high absorptiveness, and tunable properties. In this experiment, five 5wt% (5 g of alginate for every 100 mL of deionized water) ice-templated alginate aerogels were prepared in a freeze-drying process. The samples were frozen either horizontally or vertically and then sandwiched between carbon fiber or glass fabric. The flexural moduli and specific flexural moduli were measured and will be compared to those of current wind turbine blade cores. Out of all of the samples prepared, and ignoring the samples with high uncertainty, the vertically frozen 1-0-1 aerogel structure reinforced with carbon fiber composite exhibited the highest flexural modulus (10.26 2.03 MPa) and the highest specific flexural modulus (3888 808.3 MPa/(g/mm^3)). This material may be able to serve as an environmentally-friendly substitute for balsa wood and synthetic foams in wind turbine blade cores.

INTRODUCTION

The global wind energy industry is growing and is set to make up a significant portion of the future electricity portfolio. A key area of wind turbine research and development focuses on blade materials. Until today, turbine blades were roughly the length of airplane wings and allowed for technology, computer software and material science to easily transfer from the aerospace industry to the wind industry. However, in the near future, newly manufactured blades will be much longer than airplane wings. This will cause aerospace technology to no longer be sufficient. This creates a high demand for new technology. More wind energy can be harnessed with longer blades; the power a turbine generates is proportional to the square of blade length. Longer blades, however, are heavier and experience more flap-wise and edgewise bending. . Blade weight is roughly the cube of blade length. This weight exerts more strain on the overall turbine structure. For these reasons, one of the most critical areas of wind energy innovation is in the manufacturing of high strength-to-weight ratio materials for turbine blades. Most blades today consist of an external fiberglass skin surrounding an internal layer, called the "core." The core is made of either PVC foam or balsa wood. The skin gives the blade flexural strength. The core reinforces the shell's flexural strength and provides shear and compressive strength. The material used in most turbine blade cores today is balsa wood. Balsa wood is a great material for the role because it has a high strength-to-weight ratio, is naturally available, and is biodegradable.

However, the global supply of balsa wood will not sufficiently satisfy orders for planned wind turbine development. This lack of supply creates a high demand in the wind-energy industry for new synthetic foams that can imitate the function of balsa wood in the blade cores. Leading foams include



Gideon Grossman

Gideon Grossman is a junior majoring in mechanical engineering at Princeton University. He is passionate about fighting climate change through clean renewable energy technologies and plans to work for a renewable energy company. In his free time he loves to rock out on the tenors in the Princeton University Band, swim, workout, and watch NOVA scienceNow videos.

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Table 1. Summary of samples prepared

Type	Fabric	Laminate Structure	Freezing Direction
A	None	0-0-0	Vertical
B	Carbon fiber	1-0-1	Vertical
C	Carbon fiber	1-0-1	Horizontal
D	Carbon Fiber	2-0-2	Vertical
E	Glass Fabric	1-0-1	Vertical
F	Glass Fabric	1-0-1	Horizontal
G	Glass Fabric*	2-0-2	Vertical

PVC G-foam and Corecell A-Foam. These foams have high strength-to-weight ratios, and are not in limited supply, but are petrochemical-based and their production processes release toxins. The latter traits make these materials violate the environmental ideals of wind energy. Alginate aerogels may serve as a new core material that, like balsa, are naturally available and biodegradable and, like the petrochemical-based foams, are in abundant supply.

Discovered in 1931, aerogels are recognized for their record-breaking properties including low thermal conductivity, high strength-to-weight ratios and high absorbency. Aerogels are mesoporous materials consisting of 90-95% air. They are used in aerospace equipment, construction, and packaging . The motivation behind this experiment was to find an aerogel/fabric composite that could replace balsa wood and PVC foam in the core of wind turbine blades. To qualify as an effective replacement, the material would need to exhibit a compressive, shear, and flexural strength, comparable to that of materials used in the core of wind turbine blades. If these alginate aerogel/fabric sandwiches exhibit satisfactory strength, they will serve as excellent blade materials for several reasons. The raw materials, algea and water, are in abundant supply; balsa wood is sparse. Alginate - readily obtained from algae - is nontoxic and biodegradable, and the freeze-drying process is cleaner than PVC production. The only waste product of this process is water vapor. Finally, aerogel properties are tunable, unlike those of balsa wood.

Seven different samples of alginate aerogel were prepared and tested for flexural strength. Each sample had a different arrangement of carbon and glass fiber. These fabrics were chosen for this experiment because of their high tensile strength and porosity. As mentioned above, strength is necessary for structural integrity of wind turbine blades. Porosity was of interest because it was hypothesized that porosity would enhance adhesion to the aerogel matrix by allowing alginate polymer chains to seep through the fabric pores. These fabrics were also chosen because they are commonly used in wind turbine blades.

EXPERIMENTAL

Materials

Ammonium Alginate, deionized water prepared using a Barnstead RoPure low pressure reverse osmosis system, glass fiber fabric (E-glass; 2 oz; 3 mil thick; made with an untwisted yarn; Sweet Composites, Bethesda, MD), and Carbon fiber.

Sample Preparation

Seven aerogel/fabric composite samples were prepared. One sample was prepared as a control with no fabric and was vertically frozen, three samples were made with carbon fiber, and three samples were made with glass fiber. Each set of three consisted of one 1-0-1 and one 2-0-2 laminate arrangement that was frozen vertically, as well as one 1-0-1 laminate arrangement that was frozen horizontally. Table 1 summarizes the various samples that were prepared.

This terminology will be explained further on in this portion of the report. Each sample contained a 5wt% alginate aerogel. The alginate was mixed with the deionized water in a Waring model MC2 mini laboratory blender for approximately 15 seconds, yielding a green, viscous, and gelatinous mixture. The gel was poured into a frame (the materials and dimensions of the frames used are described further on). The surface of the gel was evened out by sliding a precut plastic leveler over the gel. The sample was then freeze-dried in a Virtis AdVantage Model EL-85 (lyophilizer). The freeze-drying process consisted of two stages. In the first stage, the sample was frozen at a shelf temperature of -70 °C. A 6" x 6" frame with ½"-thick, 1" tall polypropylene sides and a ¼" thick aluminum bottom was used for the two 1-0-1 vertically frozen samples and the unlaminated zero-fabric vertically frozen sample. Due to the relatively high thermal conductivity of aluminum, versus that of polypropylene, ice crystals originated on the aluminum surface and grew in columns stemming perpendicularly outward from the aluminum surface, penetrating up through the gel. As depicted in Figure 1, as the crystals grew, they

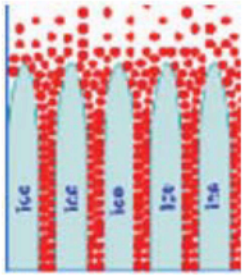

Figure 1. The blue portions denote ice. Reproduced with permission from Qian L. and Zhang, H.

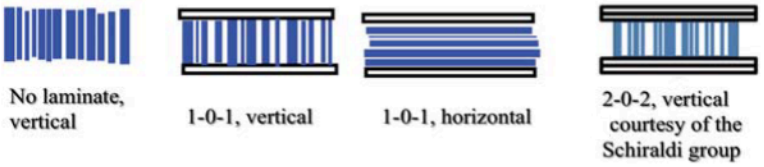

Figure 2: Laminate structures prepared

pushed the alginate polymer out of the way.

When an ice column encountered a chunk of alginate too thick to displace, the ice path skewed off to the side and connected to a neighboring ice column. This process arranged the polymer into a matrix formation, dubbed the "house of cards" structure.

In the second stage of the freeze-drying process, the lyophilizer was set to five microbars and room temperature (25°C). The sample was left in the lyophilizer at these conditions for three days until all of the ice had sublimed into water vapor. The final product was a strong, mesoporous material composed of connected columnar alginate fibers.

The 1-0-1 horizontally-frozen samples were prepared in exactly the same way as the 1-0-1 vertically-frozen samples, but in a different frame. The frame for horizontal freezing had two opposing aluminum sides, two polypropylene sides, and a polypropylene bottom surface. The goal of using this mold was to induce horizontal crystal growth. This was not the outcome, as will be discussed in the results section of this report.

The 2-0-2 vertically frozen samples were prepared in ½ " x 3" cutouts embedded in a 7" x 7" x 1" frame with polypropylene sides and an aluminum bottom.

The "1-0-1" samples were prepared for freezing by first laying a sheet of fabric on the bottom of the frame, then covering the fabric layer with 1 centimeter of gel, and finally covering the gel with a second layer of fabric.

The process used to prepare the 2-0-2 samples was similar to that used to prepare the 1-0-1 samples. The sole difference was that the sample was frozen in three steps instead of just one. First, a fabric/1mm of gel/fabric sandwich was placed in the freezer; just before that material fully froze, the sample was removed from the freezer and an 8mm-thick layer of alginate gel was poured on, followed by a third sheet of fabric. The sample was placed in the freezer a second time. Before the sample fully froze, it was taken out once more and a final 1mm-thick layer of alginate gel and fabric layer were added. The sample was placed back in the freezer for a third time. The purpose of this layer-by-layer method was to ensure that the fabrics remained even and the appropriate distances apart.

After the samples had freeze-dried, a band saw was used to cut them into uniform rectangular specimens matching ASTM standards (a width of 0.5" and length of 1"). The 2-0-2 samples did not need to be cut because they were prepared in molds that already had the appropriate dimensions of 0.5" by 1".

Characterization

A three-point bending test was performed on the specimens to determine their flexural moduli. Testing was done according to the ASTM-790 standard, using an Instron universal test machine with a 1mm/min crosshead speed and a 50mm span distance (Figure 3).

The exact length, width, and thickness of each specimen were measured with a digital caliper. The mass of each specimen was measured with an analytical balance.

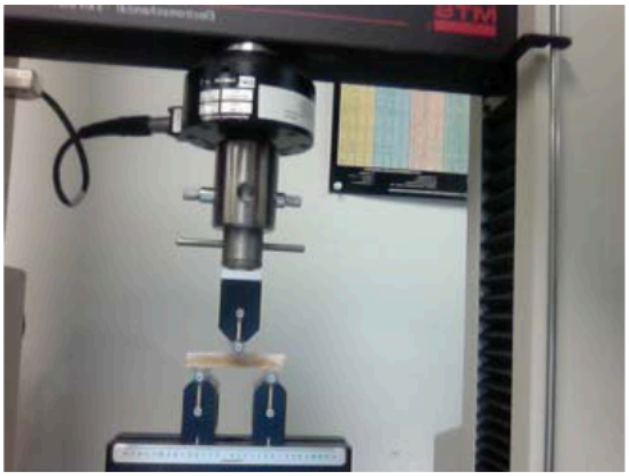

Figure 3. Instron Universal Test Machine set up for flexural testing

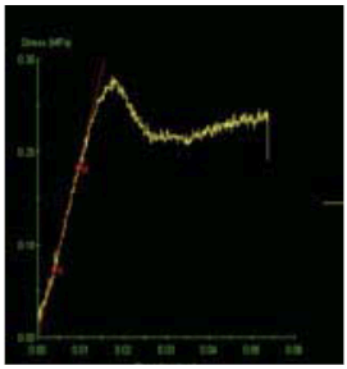

Figure 4: Stress-strain curve example (1-0-1 vertically-frozen, carbon fiber. Specimen #6)

Analysis

Load-displacement data from the testing machine was translated into a stress-strain curve and a flexural modulus was determined from the linear-elastic regime (Figure 4). The density of each specimen was calculated on Excel by dividing the mass by the volume. Volume was calculated by taking the product of the width, length, and thickness. Specific flexural moduli of each specimen were also calculated by dividing flexural modulus by density. For all samples, flexural modulus, density, and specific flexural modulus values of each specimen were averaged and standard deviations were calculated on Excel.

RESULTS and DISCUSSIONS

Flexural moduli, densities, and specific flexural moduli are presented in Table 2 and Charts 1 and 2. The 1-0-1 layered, vertically frozen glass fiber sandwich exhibited the highest flexural modulus and specific flexural modulus, but the value of each specimen in the sample were so varied (i.e. the sample's average values had high standard deviations) that the data was not significant. The sample that exhibited the highest flexural modulus (13.1 +/- 6.6 MPa) and specific flexural modulus (1.1E5 +/- 0.6E5 MPa/(g/mm^3)) with meaningful significance was the 1-0-1 vertically frozen carbon fiber sandwich (type B). Flexural modulus data for balsa wood was difficult to find in existing literature, so future work will include ordering a sample of SB. 100 balsa wood (the leading type of balsa in turbine blades) and testing it for flexural modulus in the same manner that the aerogel samples were tested in this experiment.

Aside from flexural strength, a turbine blade must also have high compressive and shear strength. Previously, Dr. Schiraldi's lab has tested the compressive strength and specific compressive strength of alginate aerogels of varied weight percentages with and without clay filler (Table 3). To expand upon this previous research, compressive and specific compressive moduli were looked up for balsa wood and leading synthetic foams (Table 4). The 15wt% with clay alginate aerogel sample had a specific compressive strength of 5.6E5 MPa/(g/mm^3). This value is nearly as high as that of balsa wood (6.1E5). This promising finding warrants further experimentation with alginate aerogels. The strength and specific strength can be further increased with the addition of cross-linkers and fibers, such as PVOH. The results in Table 3 also show that the increase in strength does not level off at the highest weight percentages prepared (15wt%). For this reason, a 20wt% sample was prepared and will be tested for both compressive and flexural strength. It should be noted that the 20wt% gel was difficult to pour evenly into the mold because of its high viscosity.

Table 2. Summary of results. *Will be retested because these samples had a large range of values

Type	Modulus (MPa)	Density(g/mm^3)	Specific Modulus
A	Not yet tested		
B	13.1±6.6	$1.2\times10^{-4}\pm0.1\times10^{-4}$	$1.1\times10^{5}\pm0.6\times10^{5}$
C	7.6±4.4	$7.2\times10^{-5}\pm2.8\times10^{-5}$	$9.7\times10^{4}\pm6.1\times10^{5}$*
D	10±2	$1.3\times10^{-4}\pm0.2\times10^{-4}$	$7.9\times10^{4}\pm2.5\times10^{4}$
E	$2.8\times10^{2}\pm3.0\times10^{2}$*	$1.9\times10^{-4}\pm0.2\times10^{-4}$	$1.4\times10^{6}\pm1.5\times10^{6}$*
F	5.9±0.9	$1.0\times10^{-4}\pm0.1\times10^{-4}$	$5.7\times10^{4}\pm1.5\times10^{4}$
G	Collapsed in freeze-dryer		

Chart 1: Bending Moduli (excluding the 1-0-1 verti-caly frozen glass sample glass sample

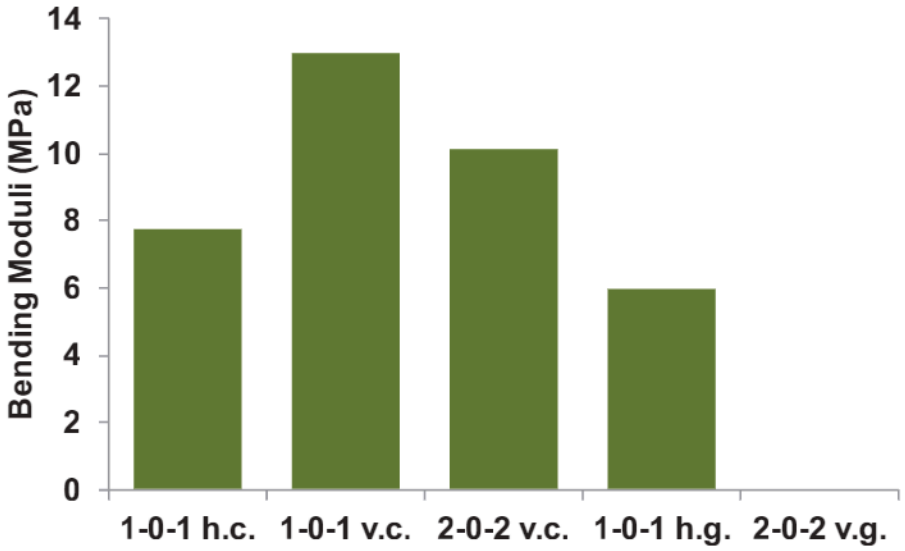

Chart 2: Specific Bend-ing Moduli (excluding the 1-0-1 vertically frozen glass sample)

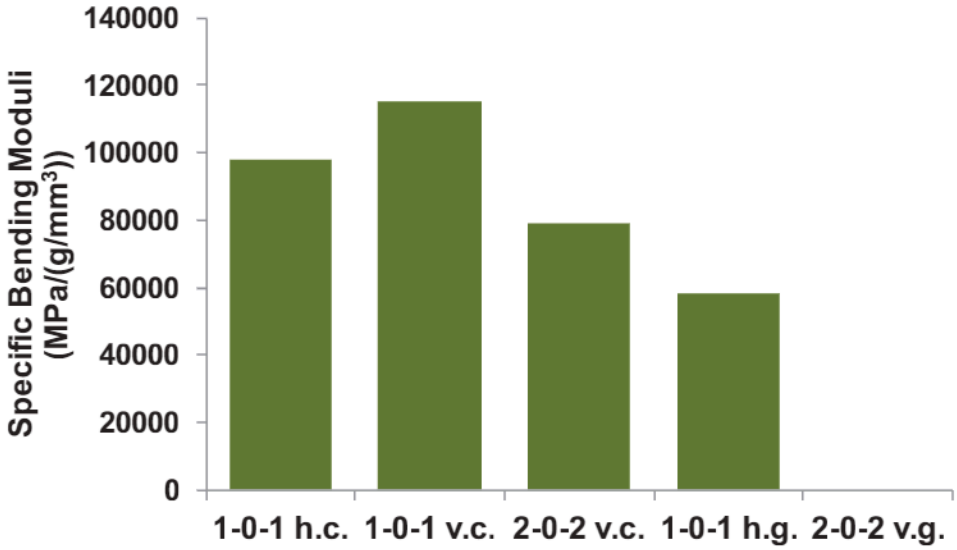

Table 3: Compressive Modulus, density and specific compressive modulus of alginate aerogels of varied weight percentages with and without clay. Reproduced with permission from Hongbing Chen. Modulus in MPa, Density in g/cm^3, Specific Modulus (M/d) in MPa- cm^3/g.

Alginate	Property	A5(5%)	A7.5(7.5%)	A10(10%)	A12.5(12.5%)	A15(15%)
No clay	modulus	0.99±0.06	3.2±0.2	9.4±1.4	20±2	46±9
	density	0.047±<0.001	0.066±<0.001	0.085±<0.001	0.108±<0.001	0.131±0.002
	M/d	21±2	49±3	110±17	185±16	350±64
C5 (5% clay)	modulus	5.8±0.7	21±3	42±5	70±7	97±11
	density	0.085±<0.001	0.108±0.002	0.130±0.002	0.152±0.002	0.174±0.002
	M/D	68±8	196±27	324±36	458±48	557±65

Table 4: Compression data for balsa wood and two leading synthetic cores. Balsa wood data source: Bech, A; Valsgaard P.. Foam data are from Gurit.

Material	Balsa Wood	PVCell G-Foam	Gorecell A-Foam
Compressive Modulus (Mpa)	460±71	65-300	41-217
Density (g/mm^3)	7.5×10^{-4}	6×10^{-5} to 2×10^{-4}	6.9×10^{-5} to 2.1×10^{-4}
M/d	6.1×10^{5}	1.5×10^{6}	1.0×10^{-6}

Another key observation was that the fabric layers on the top of the aerogel samples adhered to the aerogel well, while the fabric layer on the bottom did not adhere well. The supposed reason for this is that, while the gel was able to seep through the pores in the top fabric, it could not seep through the pores in the lower fabric because there was no room between the lower fabric and the frame's surface. In future experiments, this problem could be addressed by including a thin film of gel beneath the first layer of fabric.

Figure 5: The actual freezing direction of the 1-0-1 horizontally frozen samples.

Finally, a note about the directional freezing process: the samples that were supposed to freeze horizontally actually froze diagonally as depicted in Figure 5. The reason for this is believed to be that the distance from side to side of the mold is long enough to make it more likely for the ice crystals to encounter chunks of polymer, too thick to penetrate and cease growth in the horizontal direction.

Conclusions

With increased alginate weight percentages, and/or the incorporation of clay, fibers or cross linkers, alginate aerogels may be able to serve as a biodegradable and environmentally-sound substitute for balsa wood in turbine blade cores. The compressive strength of alginate aerogels with 15wt% and clay incorporation is nearly that of balsa wood and after the flexural strength of balsa wood is measured, a flexural strength comparison can be made as well. The results of this experiment warrant further research and may have profound implications for the developing wind energy industry.

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