

# Investigation of Cork as Filler for Fiber-reinforced Composite Material in Kayaks

by

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submitted to the Department of Mechanical Engineering in  
partial fulfillment of the requirements for the degree of

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at the  
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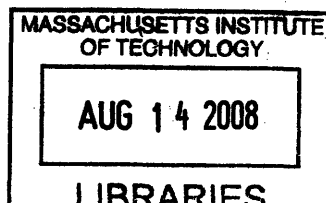
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## **ABSTRACT**

This project is a continuation in the investigation of ways in which cork can be incorporated into composite material for boats and kayaks without significant performance losses. Fiberglass lay-ups (cloth, mat, and epoxy) and cork-epoxy samples are prepared by vacuum bagging. Samples undergo a three-point bending test (ASTM D790) and a Charpy impact test (ASTM D6110) to investigate maximum flexural stress, effective elastic modulus, and impact resistance. Fiberglass-epoxy samples serve as the control for comparing the results of the cork composite samples.

The average flexural strength of the fiberglass ranged from 191-234 MPa with the different configurations of fiberglass cloth. The effective elastic modulus ranged from 8.4–10 MPa. These values fall in the lower range of other composites when compared to general Ashby charts. Its impact resistance, taken with respect to cross-sectional area to account for variations in the thickness from sample to sample in the formation process, ranged from 54.9 to 64.5 kJ/m<sup>2</sup>.

The cork composite samples were at least four times weaker than their fiberglass counterparts in all investigated respects. However, the cork samples were up to three times lighter and needed less than half of the epoxy the fiberglass samples required. The inclusion of fiberglass cloth helped increase its strength significantly without sacrifice to weight, indicating the likely need to incorporate chopped fiberglass strands in future testing.

Thesis Supervisor: David Wallace

Title: Associate Professor of Mechanical Engineering



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## **Introduction**

Composite materials used in boat and kayak hulls are both stiff and light because of the use of a low-density core material in combination with a high strength outer veneer.

A Portuguese cork company is looking for novel applications for its product, and is interested in the possible use for cork in kayaks and boats. There is the added benefit that cork is natural and more environmentally friendly to produce than typical materials such as fiberglass or carbon, and it can be recycled.

This project is a continuation in the investigation of ways in which cork can be incorporated into composite material for boats and kayaks without significant performance losses. Fiberglass lay-ups (cloth, mat, and epoxy) and cork-epoxy samples are prepared by vacuum bagging. Samples undergo a three-point bending test (ASTM D790)<sup>[1]</sup> and a Charpy impact test (ASTM D6110)<sup>[3]</sup> to investigate maximum flexural stress, effective elastic modulus, and impact resistance. Fiberglass-epoxy samples were made to serve as the control for comparison to the cork composite samples.

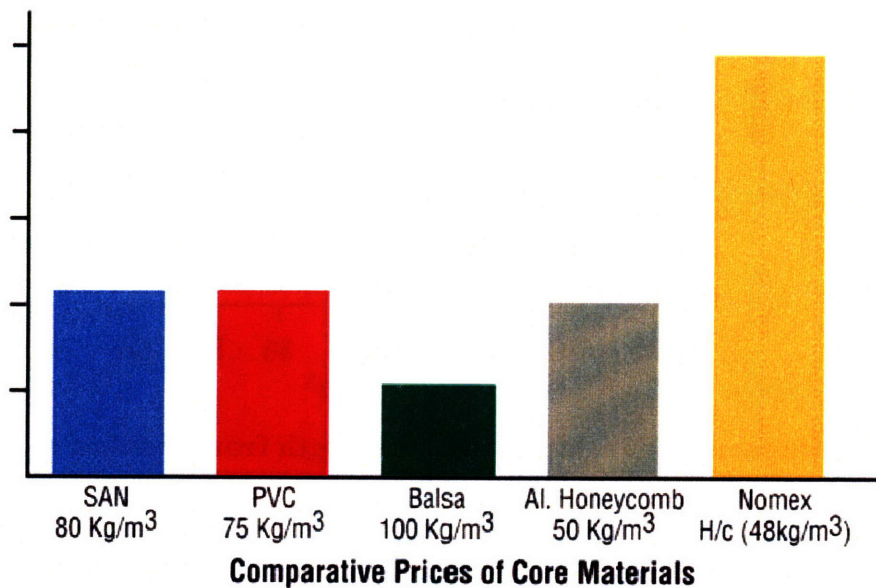


## Background

### *Composite Structures*

Composite structures are often preferred over homogenous materials for their increased strength and stiffness per weight. Honeycomb, foam, and wood are examples of light materials used in composite panels. Cork is being explored as a low-density natural alternative that is additionally less wasteful in manufacture and recyclable. In the context of boats and kayaks, possible beneficial properties include cork's buoyancy, flexibility, and dampening effects.

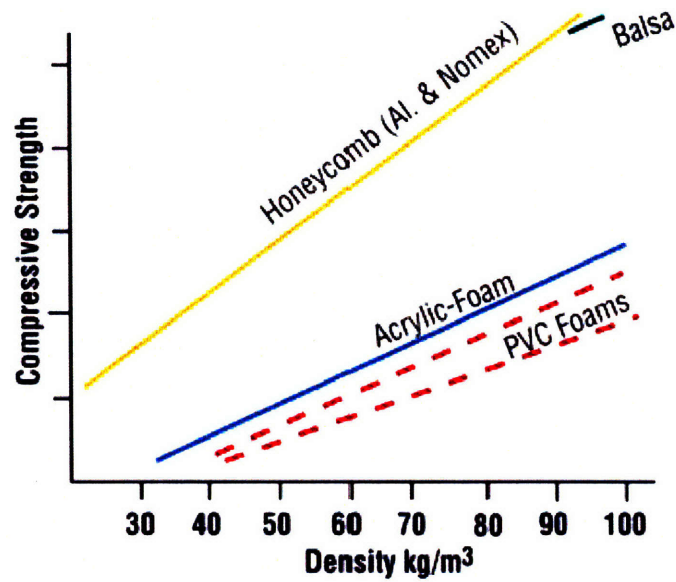
Possible incorporation of cork includes using its agglomerate form, granules bound together with pressure and adhesive binder, as the core itself and mixing loose granules with resin as filler, akin to how chopped fiberglass strands are added to increase strength. Shown below in Figures (1) through (3) are relative comparisons of competing materials done by SP Systems. Cork is under consideration as a competing filler material.



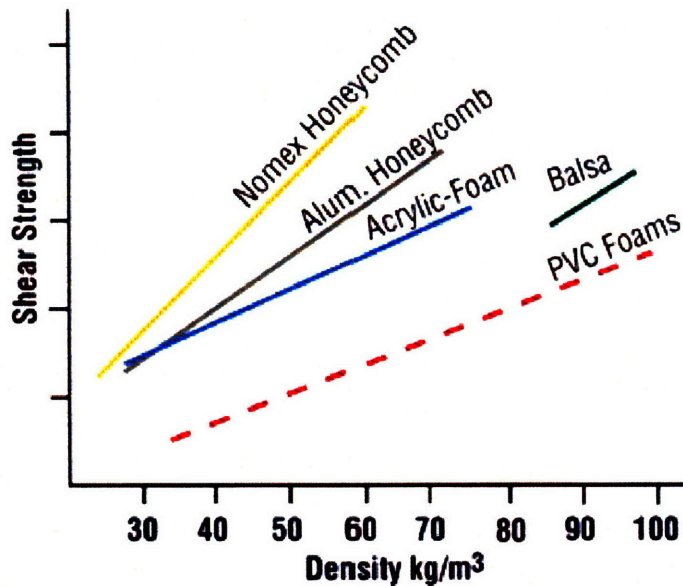
**Figure 1: Chart of relative prices of currently used core materials.<sup>1</sup>**

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<sup>1</sup> "Core Materials in Polymeric Composites." The A to Z of Materials.



**Figure 2: Comparison of relative compressive strength from manufacturers' data sheets.<sup>2</sup>**



**Figure 3: Comparison of relative shear strength from manufacturers' data sheets.<sup>3</sup>**

Previous flexural testing has been done using cork agglomerate as the core in a sandwich composite<sup>4</sup>. However, the agglomerate core failed by shear stresses

<sup>2</sup> "Core Materials in Polymeric Composites." The A to Z of Materials.

<sup>3</sup> "Core Materials in Polymeric Composites." The A to Z of Materials.

<sup>4</sup> B. Soares, L. Reis, and A. Silva. 2008.

before the outer carbon fibers during the three-point bending test. This failure was attributed to the adhesive used in agglomerate manufacture.

The experiments in this thesis stray from using cork agglomerate and explore its form as filler additive to epoxy resin. Glass fiber cloth is used for the outer layer and the core is a mixture of cork granules with epoxy, also exploring the inclusion of chopped fiberglass strands. Since fiberglass and epoxy resin are often used in higher end kayaks, the control samples use fiberglass cloth and layers of chopped fiberglass mat wetted through with epoxy resin.

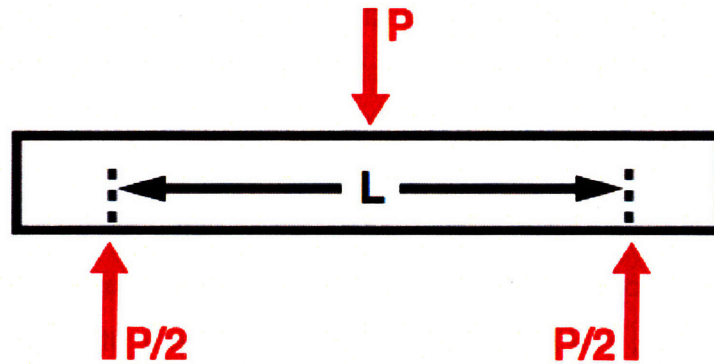
### ***Experimental Theory***

#### **Flexural stiffness measurement via three-point bend test**

The flexure equation for a composite beam incorporates the modulus of elasticity of the material being examined  $E$ , the moment  $M$  exerted on the beam, the distance  $y$  from the neutral axis, and an effective flexural stiffness,  $(EI)_{eff}$ ,

$$\sigma = \frac{EMy}{(EI)_{eff}}. \quad (1)$$

where  $I$  is the area moment of inertia. For a homogenous beam, the maximum stress occurs at the outer fibers at the center of the span.



**Figure 4: A beam undergoing a three-point bending load**

During a three-point bending load, shown in Figure 4, the moment varies along the span, designated here as the  $x$ -axis, according to

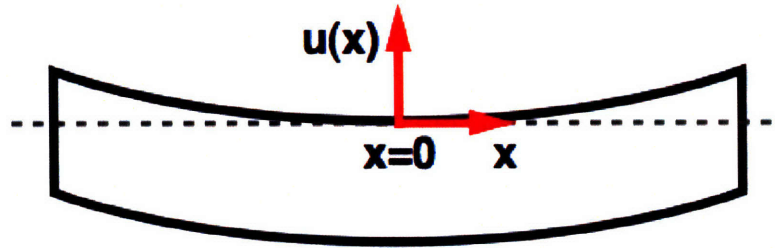
$$M(x) = \frac{P}{2} \left( \frac{L}{2} - x \right), \quad (2)$$

where  $x = 0$  at the center of the beam,  $P$  is the load, and  $L$  is the length of the support span. The moment is the greatest at the center of the span.

Load and displacement can be related to the flexural stiffness by using the moment-curvature relation for small deflections,  $u$ :

$$M = \frac{(EI)_{eff}}{\rho} \approx (EI)_{eff} \frac{\partial^2 u}{\partial x^2}, \quad (3)$$

where  $\rho$  is the radius of curvature of the beam.



**Figure 5: Display of coordinate system on a beam**

Applying the moment from Equation (2) in Equation (3), the result can be integrated twice to find the relation between flexural stiffness, the load, and the deflection:

$$(EI)_{eff} = \frac{PL^3}{48u}. \quad (4)$$

This can be calculated from the load and displacement data recorded from a three-point bend test. To compare the modulus of elasticity of the lay-up as a whole, the effective moment of inertia can be that of a normal rectangular beam,

$$I = \frac{bh^3}{12}, \quad (5)$$

where  $b$  is the width of the beam and  $h$  is the thickness. Substituting Equation (5) into Equation (4), an  $E_{eff}$  can be found from the slope of the linear-elastic region of the load-displacement curve  $m$ ,

$$E_{eff} = \frac{L^3 m}{4bh^3}. \quad (6)$$

This makes the effective flexural stress  $\sigma_{FS}$  at the outer fiber:

$$\sigma_{FS} = \frac{3PL}{2bh^2}, \quad (7)$$

and the flexural strain  $\varepsilon_{FS}$ :

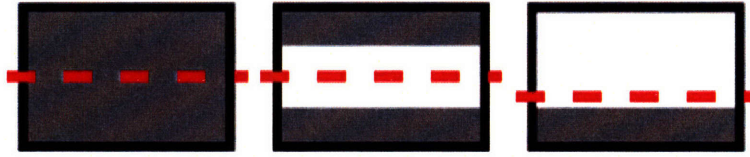
$$\varepsilon_{FS} = \frac{6Ph}{L^2}, \quad (8)$$

both of which can be used for a quick comparison between different materials.

For a more accurate calculation, the effective flexural stiffness  $(EI)_{eff}$  can be related to the elastic moduli and moments of inertia of its components:

$$(EI)_{eff} = E_{core}I_{core} + E_{skin}I_{skin}, \quad (9)$$

where the term skin refers to the outer layers of the lay-up, that will be fiberglass cloth in this case. As seen below in Figure (6), a homogeneous beam<sup>5</sup> and a two-sided composite have a neutral axis at the center. The  $I_{skin}$  is calculated by using the parallel-axis theorem. The one-sided composite lay-up is a little more complicated to calculate due to the shifted neutral axis.



**Figure 6: Neutral axis for a homogenous beam, a two-sided composite, and a one-sided composite. Relative thicknesses and dimensions are not to scale with those used in the experiments.**

The material properties of the core are of interest, because it is assumed to be weaker than the skin. To find the stresses within the core using Equation (1), the elastic modulus of the core can be found using Equation (6) by using test specimens of just the core.

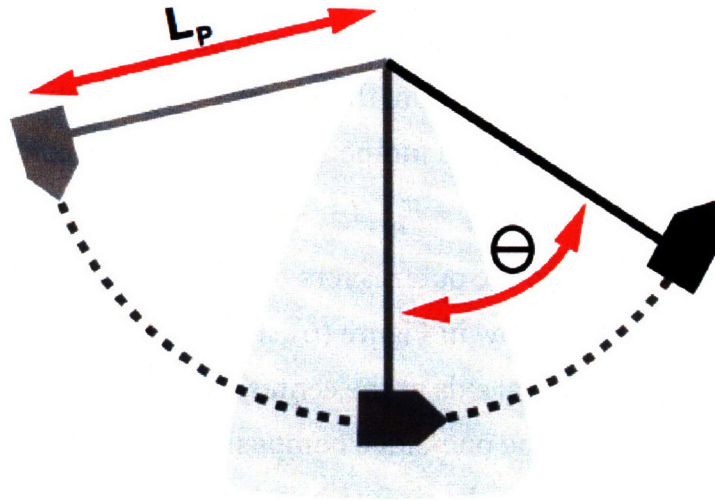
For the purpose of preliminary investigation, the incorporation of different moments of inertia has been omitted and an effective moment of inertia for a rectangular beam is used from Equation (5).

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<sup>5</sup> In this case, the microscopically heterogeneous core is considered to act together like a homogenous material.

## Impact resistance measurement via Charpy V-notch test

A Charpy V-notch test<sup>[3]</sup> is run to calculate the impact resistance of the material to breakage by flexural shock. The testing apparatus consists of a simple pendulum.



**Figure 7: Dimensions marked out on the Charpy testing apparatus**

To convert from the angle reading  $\theta$  to energy, the following formula is used<sup>6</sup>:

$$E_{raw} = L_P W_P (1 - \cos \theta) \quad (10)$$

where  $L_P$  is the length of the pendulum arm,  $W_P$  is the weight of the pendulum head.

The machine is run without a sample to calibrate the results to a maximum value,  $E_{max}$ . The energy required to break the sample,  $E_{CVN}$ , is calculated by subtracting  $E_{raw}$  from  $E_{max}$ , thus eliminating the effects of friction and windage:

$$E_{CVN} = E_{max} - E_{raw} \quad (11)$$

The impact resistance is typically calculated per width of the specimen, however, due to the variance in thicknesses of the tested samples, a resistance over an area  $R_{impact}$  will be calculated:

$$R_{impact} = \frac{E_{CVN}}{bh} \quad (12)$$

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<sup>6</sup> Full derivation of this formula from the geometry of the striking pendulum can be found in ASTM procedure D6110.



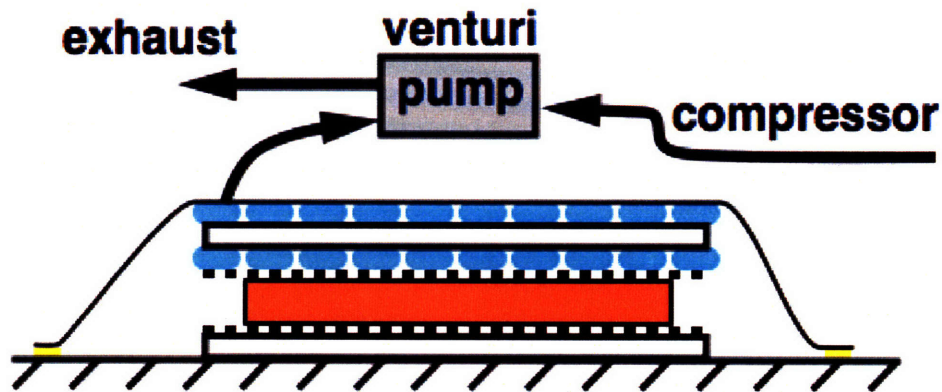
where  $b$  is the width of the sample and  $h$  is the thickness.



## Experimental Procedure

### *Composite Sample Making*

Flat composite samples were prepared in rough accordance with the ASTM D5687 procedure. Two pieces of plywood, covered in packaging tape to make them impermeable, were used for the flat mold. Shown in Figure (8) below is the setup. A layer of release fabric was placed over the bottom mold piece, followed by the lay-up, another layer of release fabric, breather material, the upper mold, and more breather material to reduce sharp edges under the bag.



**Figure 8: Cross-section diagram of the vacuum bag setup. Hollow rectangles are the flat mold pieces, dotted lines are release fabric, rounded dotted lines are breather material, and the shaded rectangle is the test specimen. Arrows indicate direction of airflow.**

The composite was cured under vacuum to provide an evenly distributed pressure over the specimen. A Venturi vacuum generator<sup>7</sup> was used in conjunction with a compressor yielding the pressure of 72 PSI. The apparatus was left on for 6 hours at a time then left alone to sit for a day to allow for full curing of the epoxy.

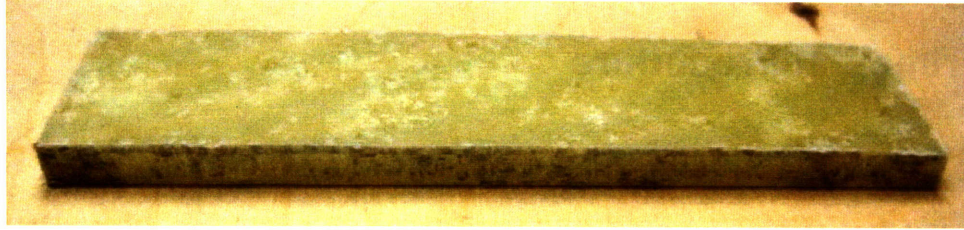
The control samples consist of one layer of medium-weight fiberglass cloth and ten layers of chopped strand fiberglass mat (0.75 oz/ft<sup>2</sup>), wet through with West System #105 epoxy resin and #205 fast hardener<sup>8</sup>.

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<sup>7</sup>West System Venturi Vacuum Generator. <<http://www.westsystem.com/>>

<sup>8</sup> West System 105 Epoxy Resin and 205 Hardener.

<<http://www.westsystem.com/>>



**Figure 9: Fiberglass bending sample.**

The cork samples have the same first layer of fiberglass cloth as the control samples, and the core is composed of cork granules of various sizes (1-3 mm) mixed with epoxy resin at a 1:2 ratio of cork to epoxy by mass, making it a 50% matrix content composite.



**Figure 10: Two one-sided cork samples laid up in half the flat mold.**



**Figure 11: One-sided cork sample, after curing and before machining.**



**Figure 12: Cross-section of mixed cork sample.**

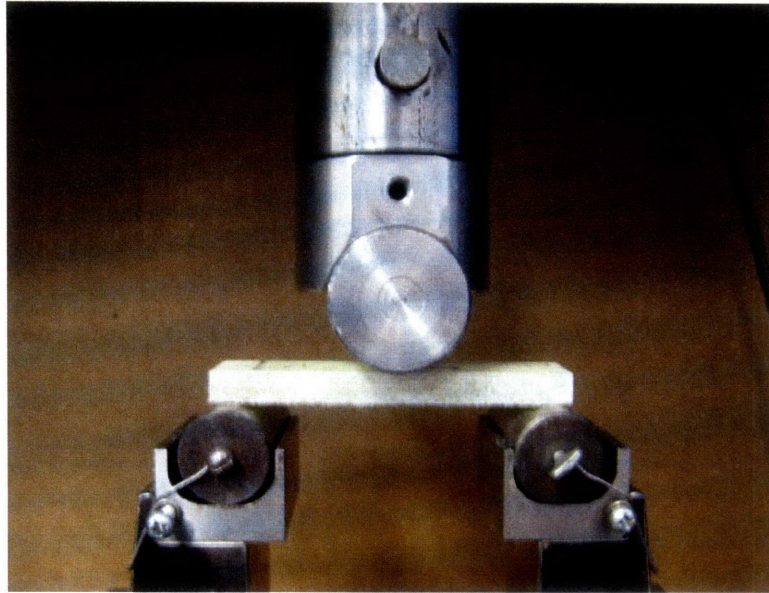


**Figure 13: Cork samples machined for the bending test (above) and the Charpy test (below)**

## ***Testing***

### **Three-point bend test**

Testing protocol was based off of the ASTM D790 procedure for determining flexural properties of plastics.

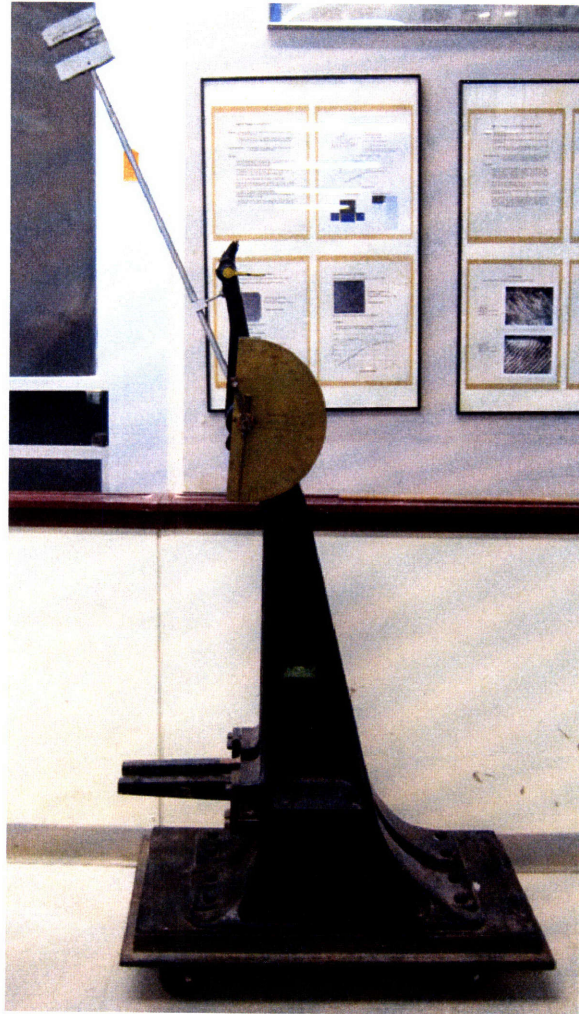


**Figure 14: Three-point bend test apparatus.**

The Instron 1125, modified by ADMET to include load control, was the test machine with a 20kN loading cell. The appropriate strain rate is calculated according to ASTM D790. The support span was 90mm, yielding a span-to-thickness ratio greater than 16:1. The radii of the supports were 12.7 mm and that of the loading nose was 19 mm, differing from the 5mm radii called for by the protocol.

### **Charpy V-Notch test**

The simple pendulum impact machine is as shown in Figure (15). A milled 45° notch is made to the side of the samples to produce a stress concentration that encourages brittle fracture. The angle to energy conversion is calculated through Equation (10).



**Figure 15: Charpy test apparatus.**

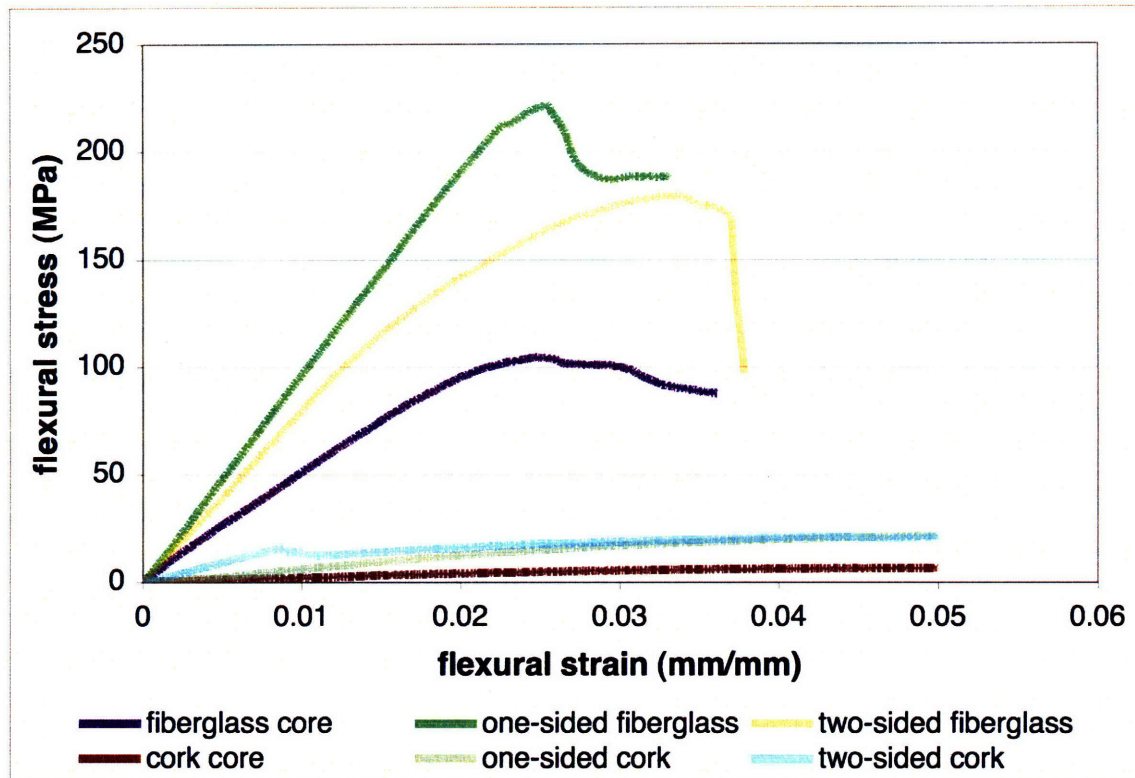




## Results and Discussion

### *Bending Test Results*

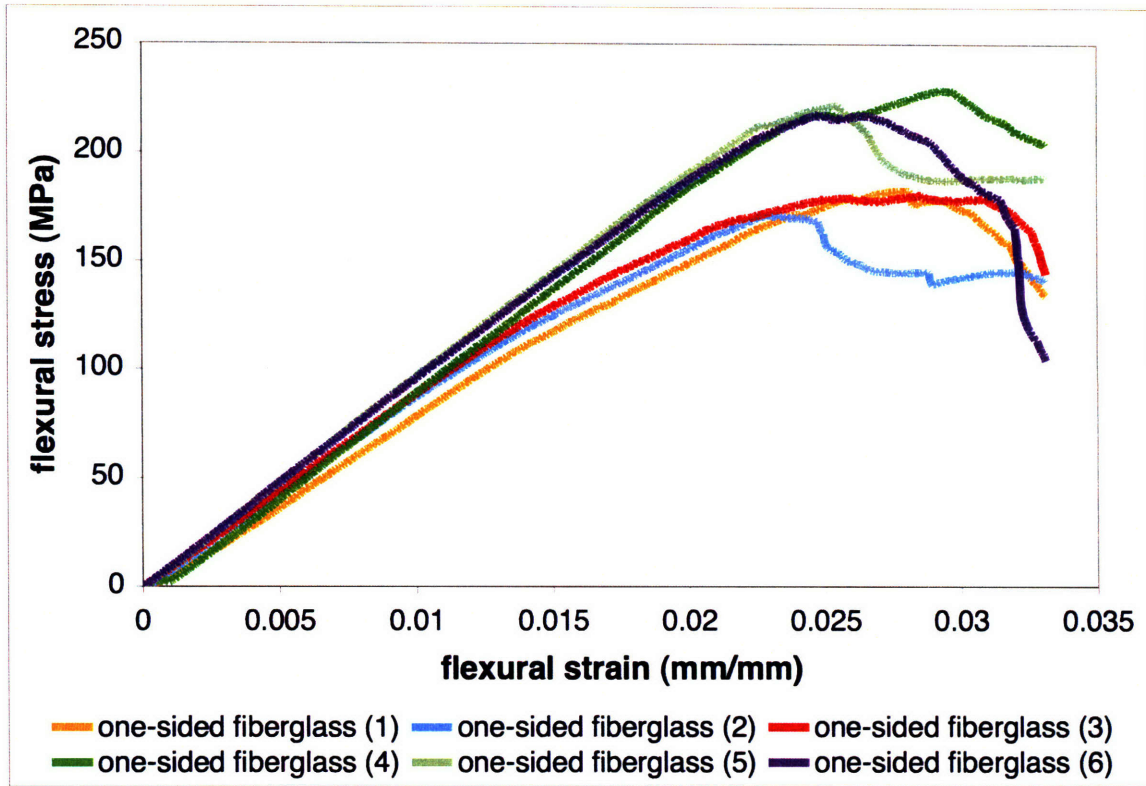
The fiberglass core composites were over an order of magnitude stronger than the cork composite samples. Shown below in Figure (17) are representative stress-strain curves from testing.



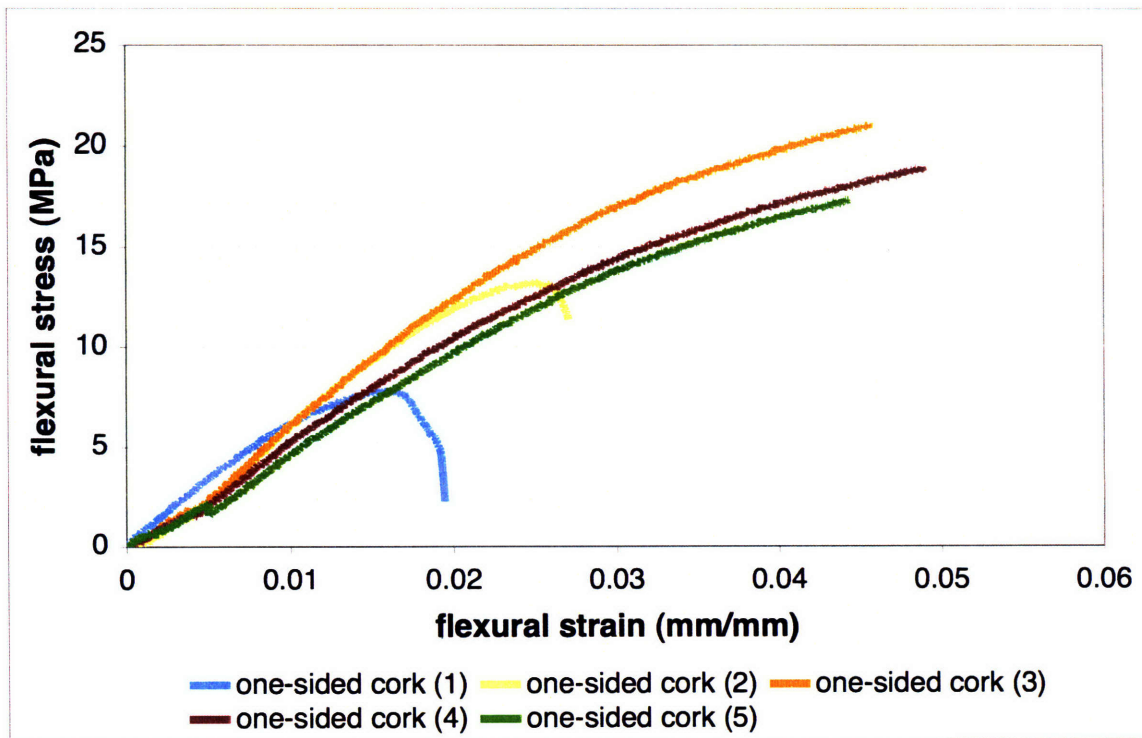
**Figure 16: Calculated stress-strain curves for representative data.**

It can be seen that the one-sided fiberglass sample is actually stronger than the two-sided one. This could be attributed to the variable nature of the making of the fiberglass samples, since the amount of epoxy added was qualitatively determined by the visual saturation of the fiberglass mat. Graphs displaying data for individual runs can be seen in Appendix (A).

It was also seen that the one-sided samples were stronger when tested with the layer of fiberglass cloth on the bottom, shown in Figures (17) and (18).

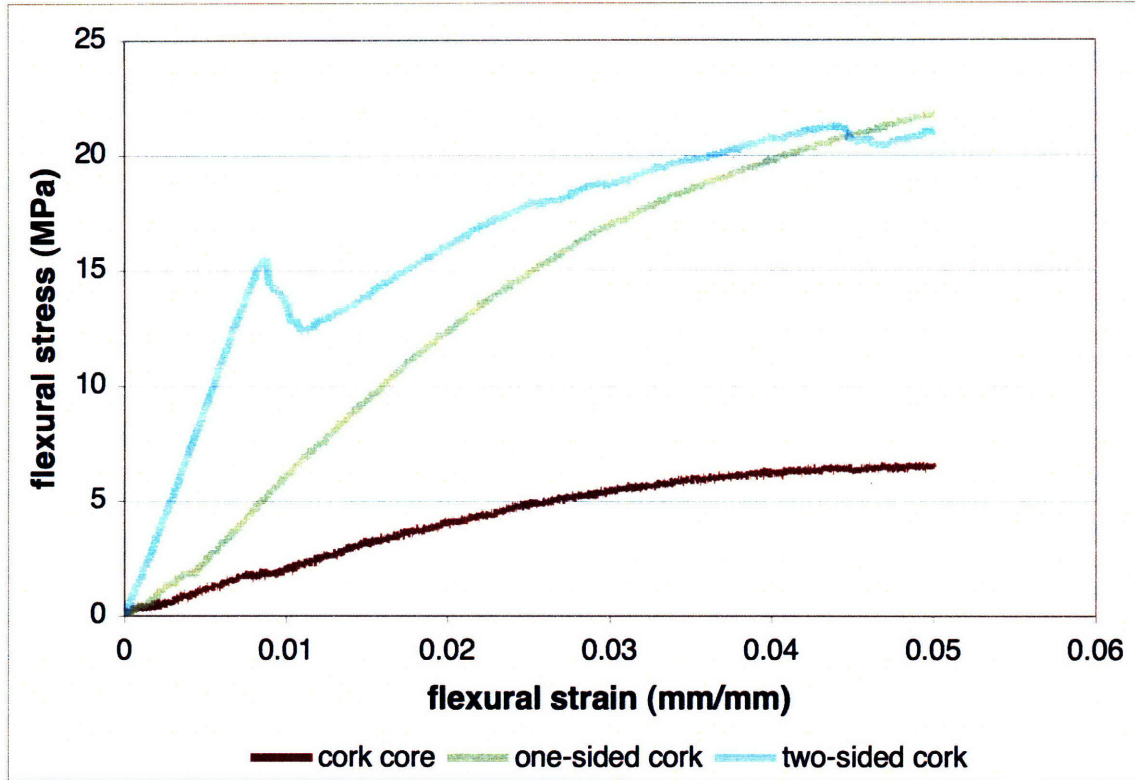


**Figure 17: Samples 1-3 were tested with the cloth on the top, while samples 4-6 were tested with the cloth on the bottom.**



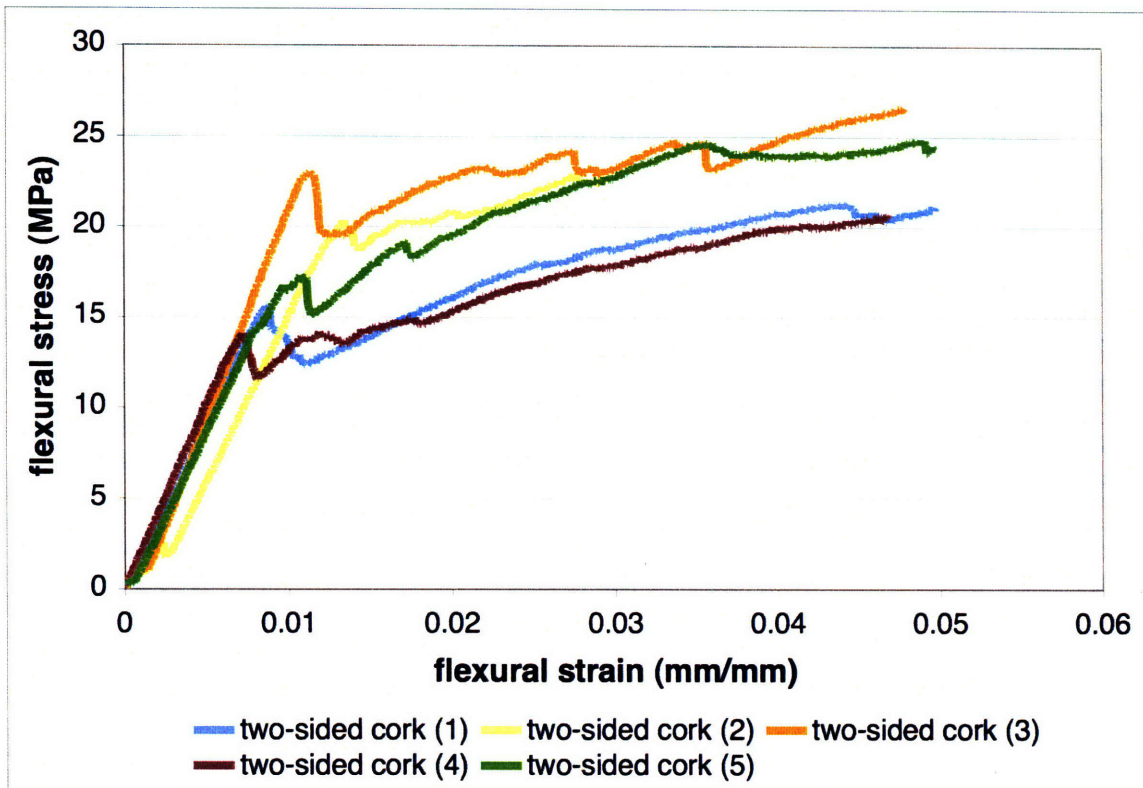
**Figure 18: Samples (1-2) were tested with the fiberglass cloth up, while samples (3-5) were tested with the cork core facing up.**

A closer look at the cork composite results is shown in Figure (19), where the presence of fiberglass cloth in the cork samples made a significant difference in the flexural strength.

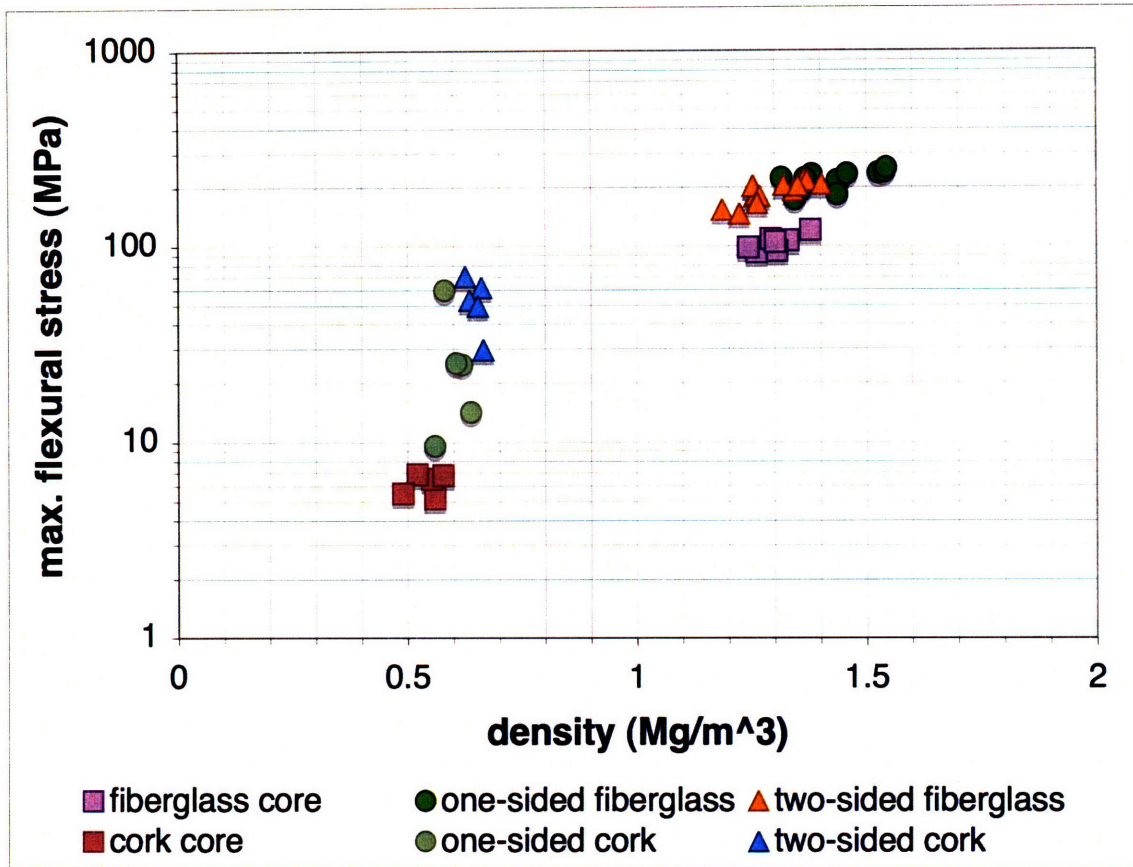


**Figure 19: Calculated stress and strain for representative cork data.**

In the results for the cork samples, there was always a sudden drop or plateau in the flexural stress. This hinge is most drastically shown in the two-sided cork samples, and is consistently present through the different samples, shown in Figure (19). This may be due to the core breaking before the outer fibers. More graphs can be seen in the Appendix (A).



**Figure 20: Two-sided cork results showing an exaggerated hinge in stress.**



**Figure 21: Semi-log plot of maximum flexural stress versus density of the sample**

As seen in Figure (21), while the cork samples were weaker than the fiberglass samples, the cork samples were two to three times less dense, even including the fiberglass cloth.

Plotting the maximum flexural stresses versus density on an Ashby chart<sup>9</sup> in Figure (22), the results for the fiberglass samples fall within the right regime of strength. The cork composite samples have a broad range due to the inclusion of the cork core data and the variability in the one-sided samples depending on fiberglass orientation during testing.

<sup>9</sup> “Materials and Process Selection Chart”. Granta – Material Intelligence.

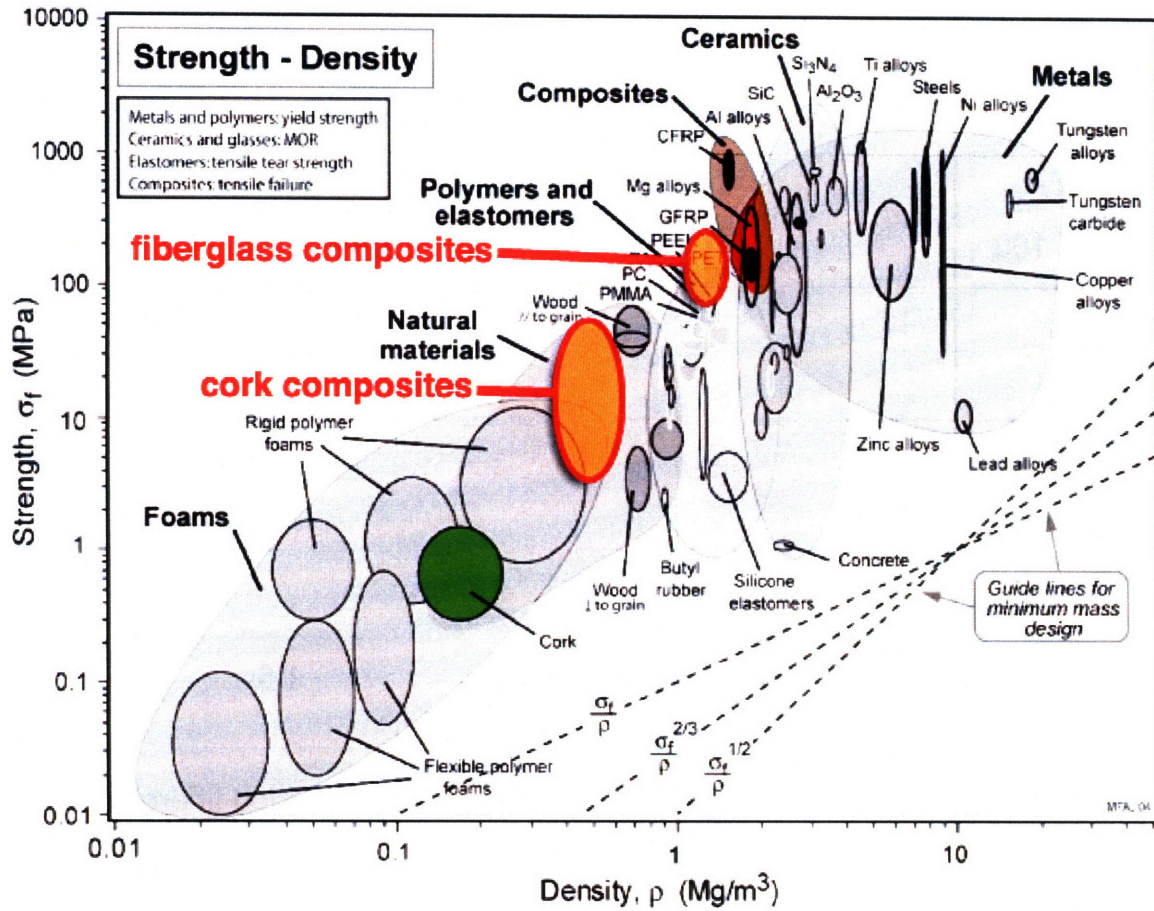
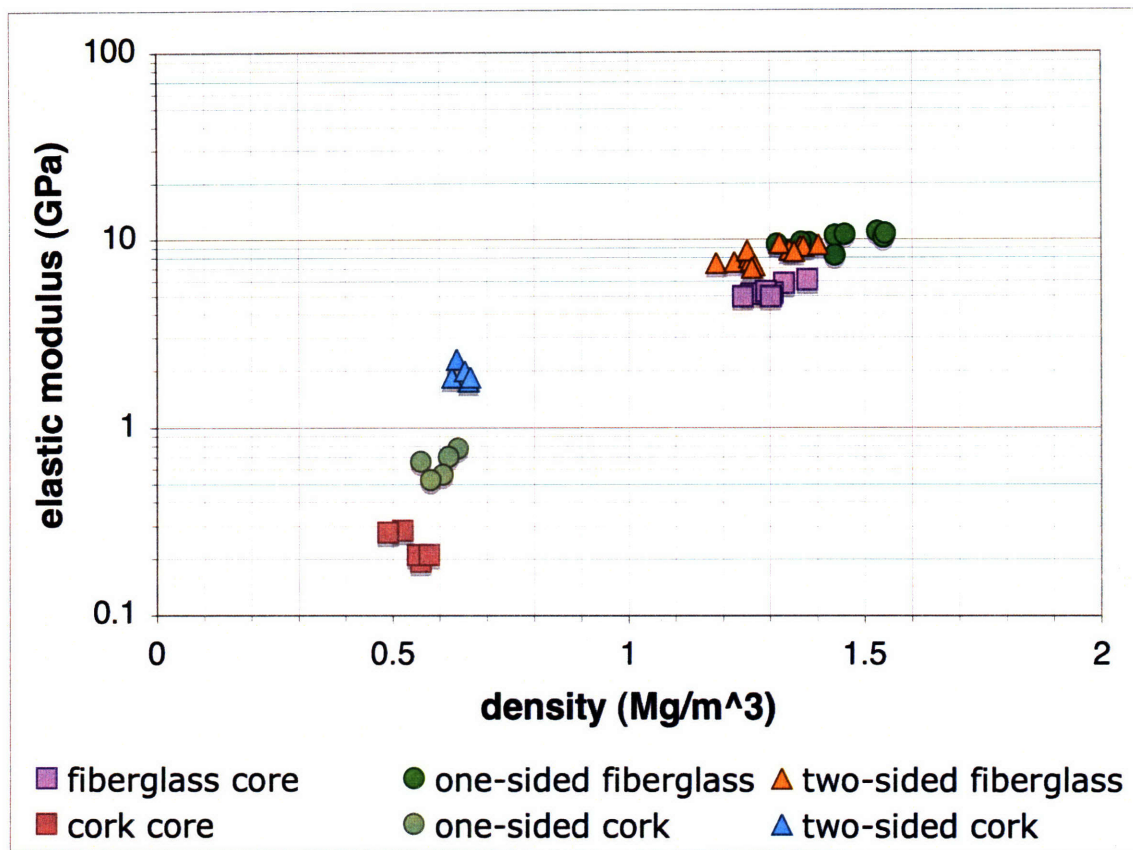


Figure 22: Comparing maximum flexural strengths from bending tests on an Ashby chart<sup>10</sup>.

<sup>10</sup> "Materials and Process Selection Chart". Granta – Material Intelligence.



**Figure 23: Semi-log plot of the calculated elastic moduli versus density.**

The elastic moduli have more defined grouping. The fiberglass samples show little difference between the different forms, but fiberglass increases the modulus of elasticity for the cork samples. The expected flexibility of cork may not be present due to its form as filler for the epoxy. Tests could be run with just the epoxy to see the effect of various fillers.

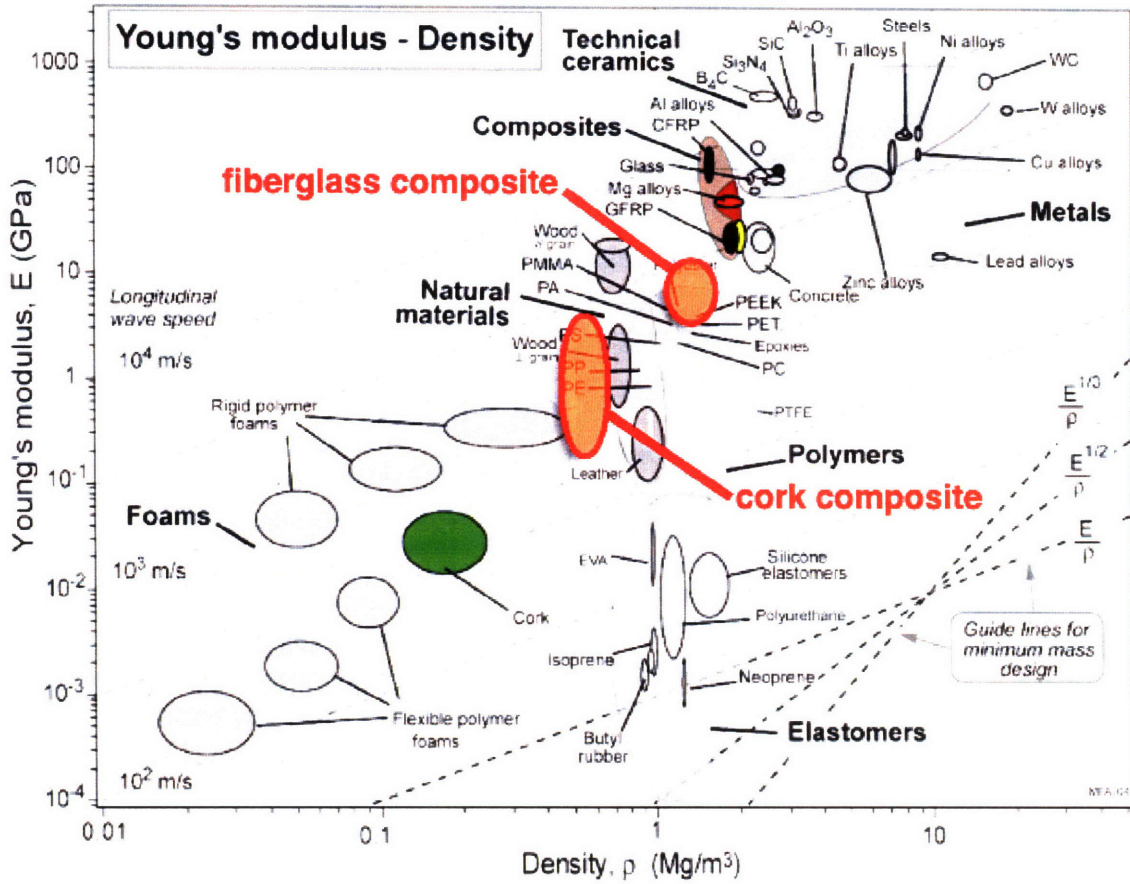


Figure 24: Comparing moduli of elasticity from bending tests on an Ashby chart<sup>11</sup>.

### Charpy V-Notch Test Results

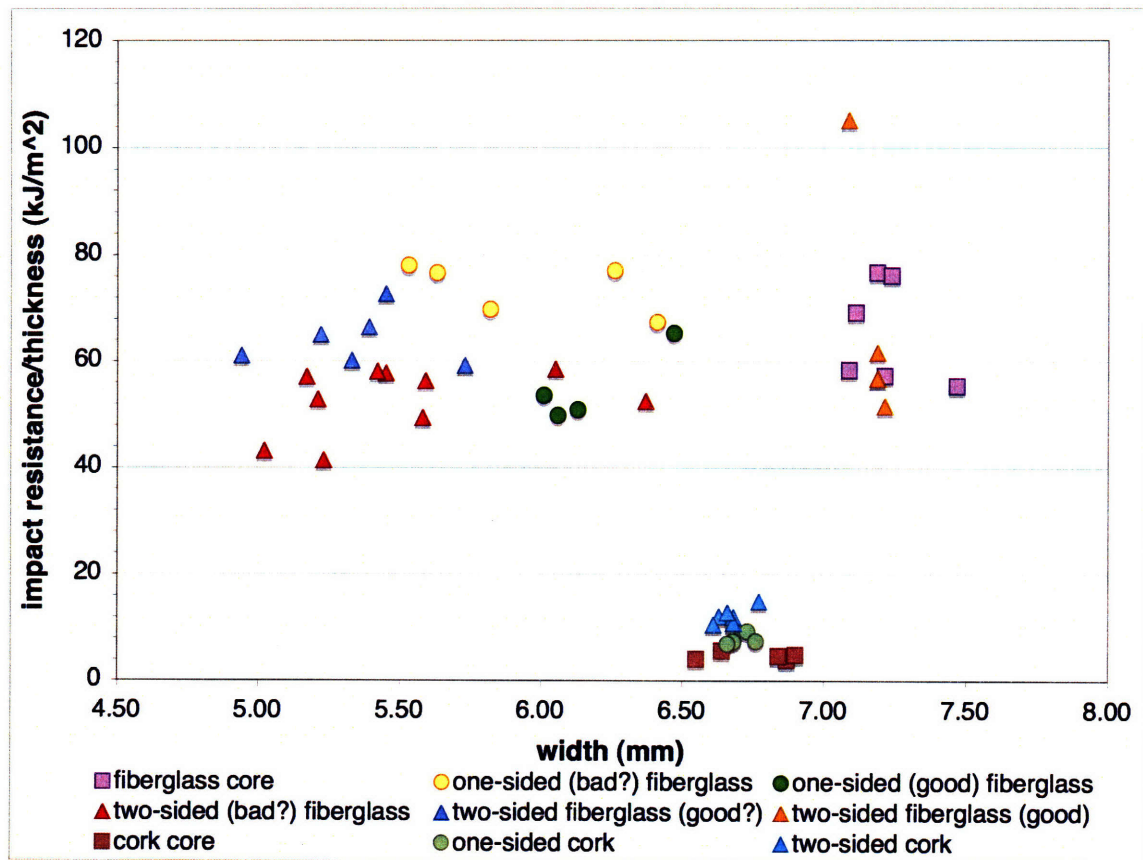


Figure 25: Close-up of cork specimen after undergoing Charpy test

<sup>11</sup> "Materials and Process Selection Chart". Granta – Material Intelligence.



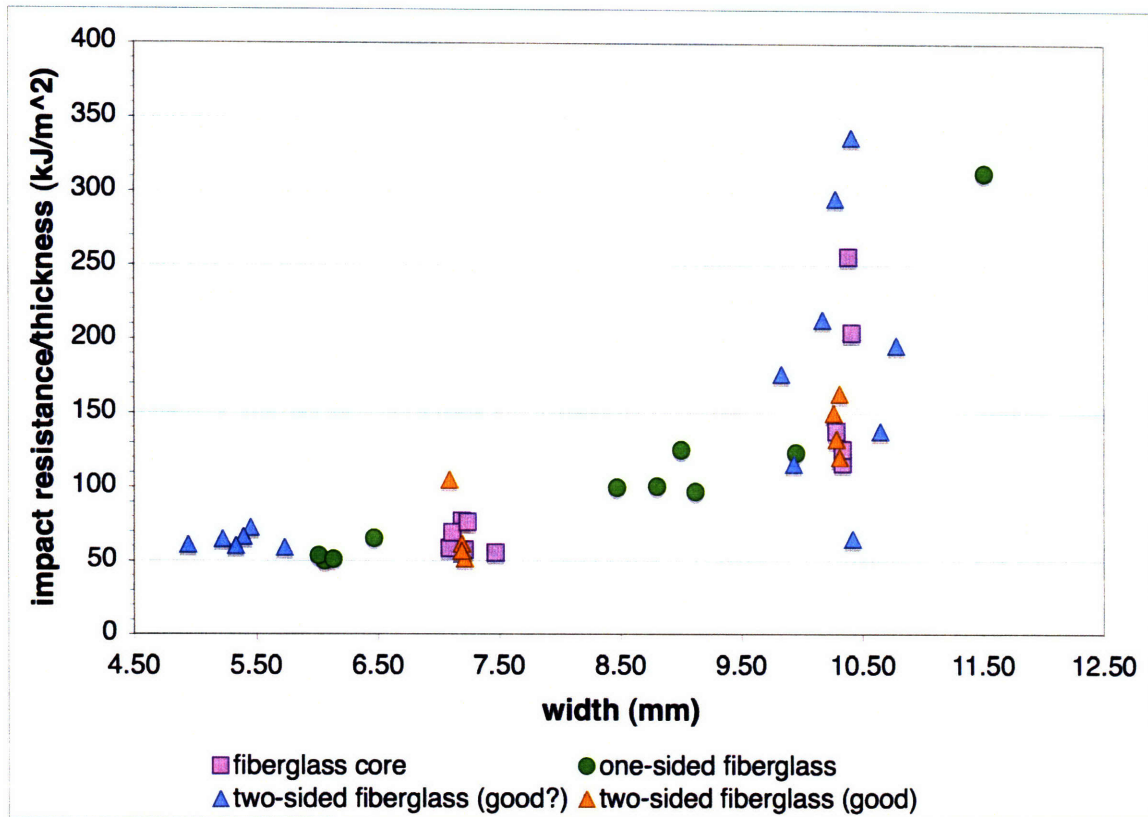
The fiberglass composite samples proved to have higher impact resistance than the cork samples as well. The presence of cloth showed little difference across the different fiberglass samples, even in the defected samples<sup>12</sup> marked as (bad?) and (good) in Figure (26). As described in the Experimental Theory, the impact resistances were taken over the cross-sectional area of the sample to account for the varying thicknesses, thus represented as impact resistance/thickness in the graphs.



**Figure 26: Charpy test results.**

The sample widths shown in Figure (26) are the ones that all give the same range of impact resistance. It was found with wider samples that there was a jump in the impact resistance, shown in Figure (27). There is also increased variability in the results, so the increased resistance may be attributed to energy devoted to plane strain or possibly buckling.

<sup>12</sup> Samples were suspected to be defected if the vacuum time was cut short, if the vacuum pump was losing shape, or if they were separated from the mold by force.



**Figure 27: Displaying an increase in impact resistance/thickness as the width of the samples increased.**

There is still significant headway for the cork samples to make in order to compete with fiberglass samples. As seen in Table (1), the fiberglass samples were significantly stronger in all the determined properties.

**Table 1: Summary of material properties, average values displayed.**

	$\sigma_{FS}$ (MPa)	$E_{eff}$ (GPa)	$R_{impact}$ (kJ/m <sup>2</sup> )
<b>Fiberglass (FG): core</b>	104 ± 10	5.3 ± 0.4	65.5 ± 9.7
<b>FG: one-sided, cloth on top</b>	203 ± 24	9.6 ± 1.2	54.9 ± 7.1
<b>FG: one-sided, mat on top</b>	234 ± 11	10 ± 0.6	54.9 ± 7.1
<b>FG: two-sided</b>	191 ± 23	8.4 ± 0.8	64.5 ± 13.9
<b>Cork: core</b>	6 ± 1	0.2 ± 0.0	4.6 ± 0.7
<b>Cork: one-sided, cloth on top</b>	12 ± 3	0.7 ± 0.1	7.7 ± 0.9
<b>Cork: one-sided, cork on top</b>	37 ± 20	0.6 ± 0.1	7.7 ± 0.9
<b>Cork: two-sided</b>	53 ± 15	2.0 ± 0.2	12.1 ± 1.5

## **Conclusions**

Composite samples were made via vacuum bagging and underwent a three-point bend test<sup>[1]</sup> and a Charpy impact test<sup>[3]</sup> to investigate maximum flexural stress, effective elastic modulus, and impact resistance. The fiberglass samples were on average four times stronger than the cork-epoxy samples in flexural strength. The elastic modulus was also four times greater than that of the cork, and the impact resistance per thickness was up to five times greater. The cork composite samples, however, were up to three times lighter than the fiberglass.

## ***Future Testing***

While the cork samples are significantly weaker than the fiberglass, a sudden drop or plateau in the stress was observed in most of the bend tests. Doing further testing by loading and unloading them in the anticipated elastic region could determine if the cause was delamination, hardening, or a defect. It may also be worthwhile to test the core's shear modulus of elasticity, since core materials in composites are often compared by this property. Another possibility is to incorporate loose chopped fiberglass strands into the cork samples, and to find a relationship between strength and density.

To advance the investigation of cork application in boating materials, it may be useful to compare moisture absorption properties. Expanding the types of materials used for control samples to include honeycomb (paper, plastic, and aluminum) and foam core would be another step in seeing where cork could compete. The same reasoning applies to running the tests again using polyester resin or vinylester resin instead of epoxy.

## ***Suggested Improvements***

While the procedure for testing polymer matrix composite materials (ASTM D7264)<sup>[4]</sup> references that for reinforced plastics<sup>[1]</sup> the shear strength of the materials were not determined before deciding the specimen size. The standard ratio of support span to thickness is noted as 32:1, while the ratio used

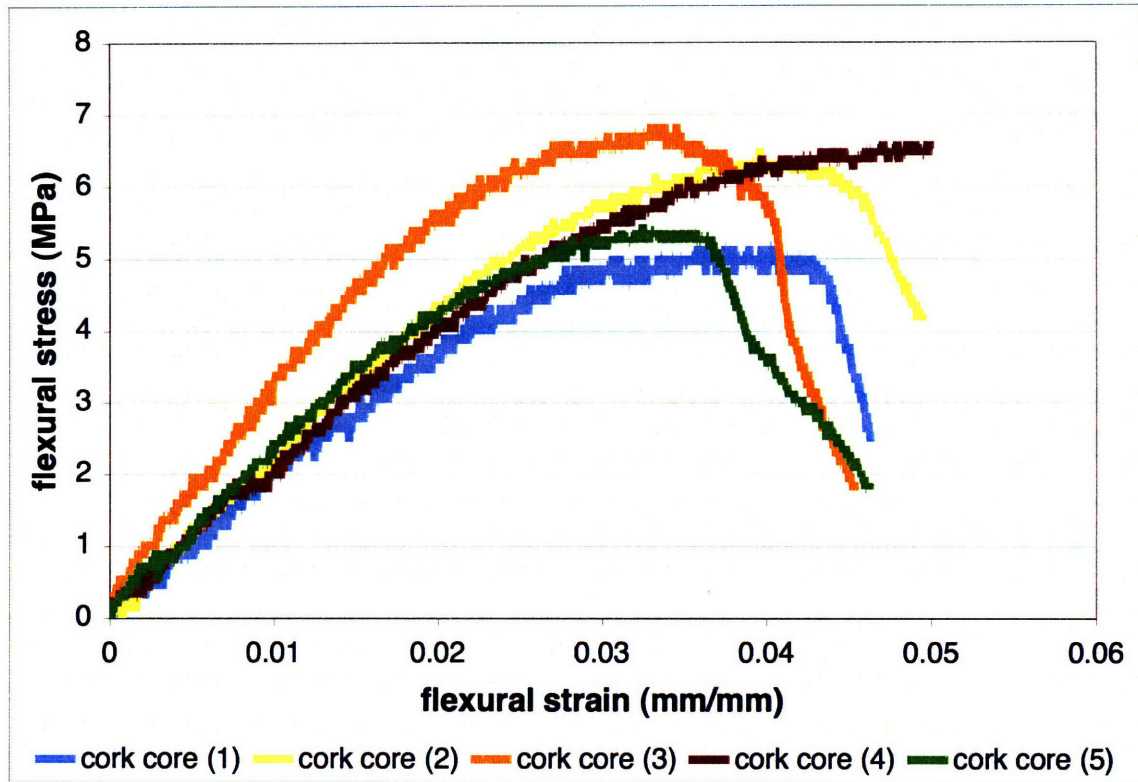
in practice is closer to 18:1. Optional ratios were listed in ASTM D7264 as low as 16:1, but the failure needs to first occur at the outer fibers.

To obtain a more accurate calculation of flexural stress, the different moments of inertia can be incorporated as discussed in the Experimental Theory section.

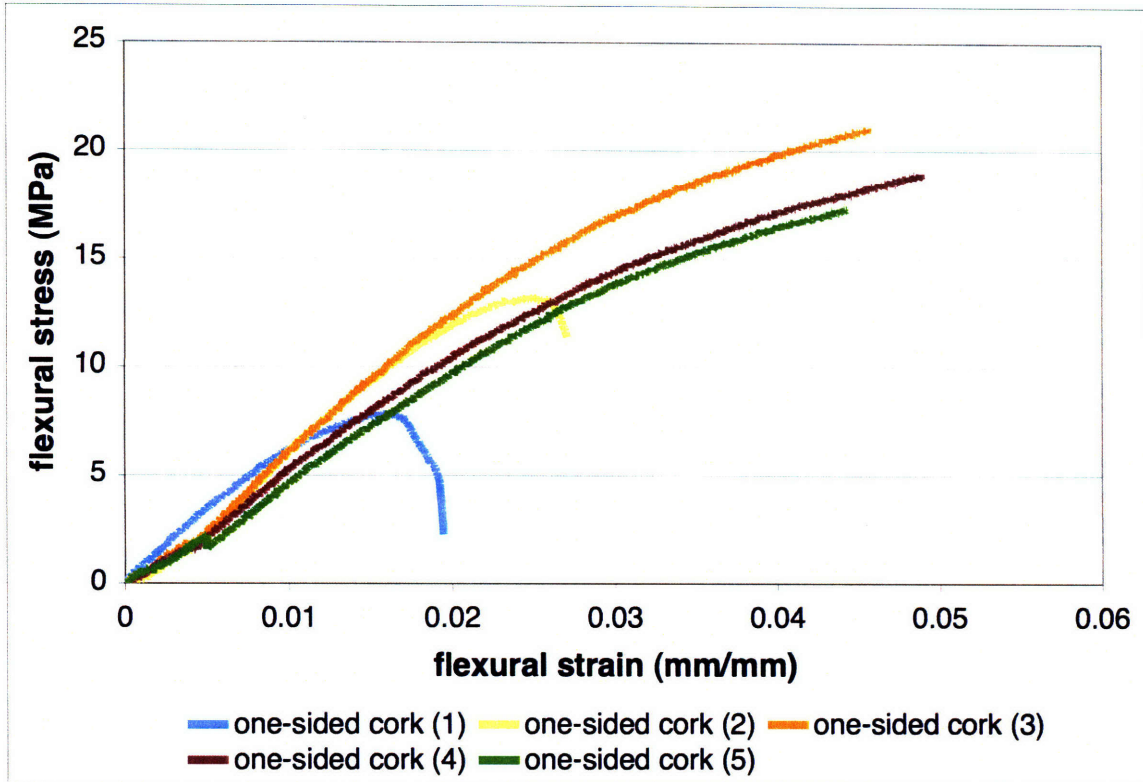
While the lay-up process was the same, the resulting samples sometimes varied in thickness. Experimenting with different pressures during the vacuum bagging process and perhaps clamping could produce more consistent thicknesses and possibly more consistent results.

## Appendix

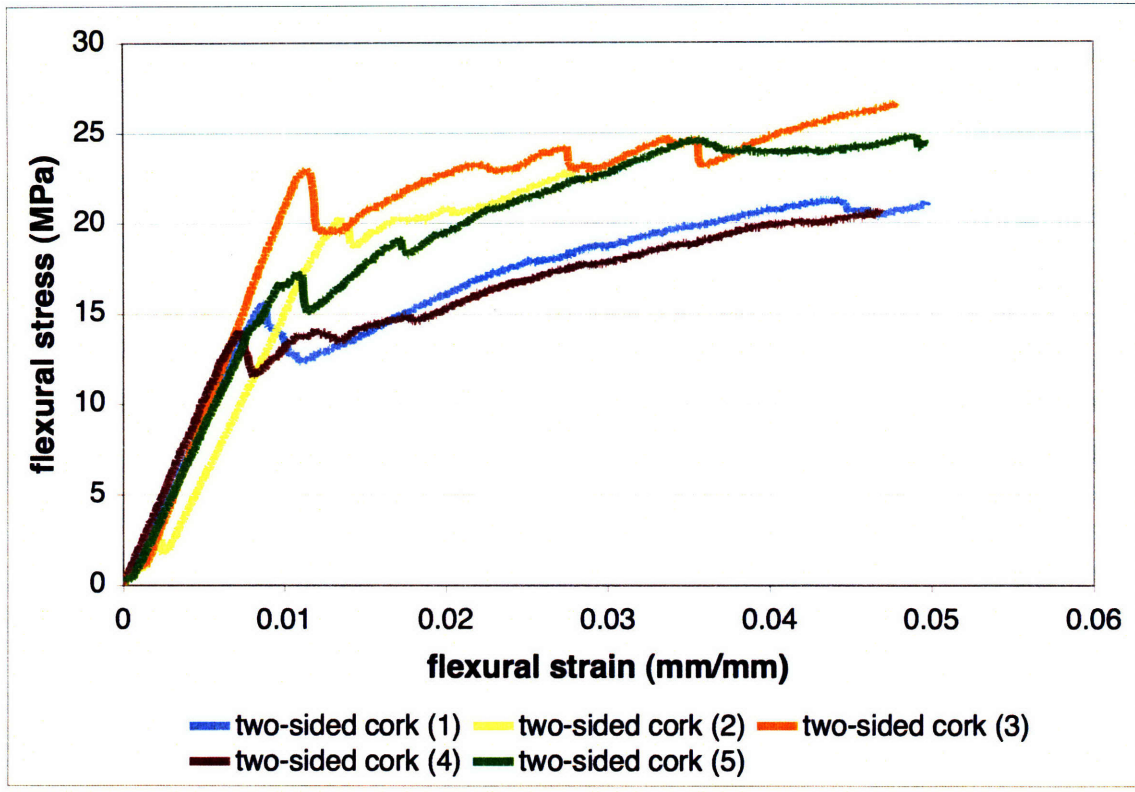
### *A: Stress-strain curves for cork and fiberglass samples*



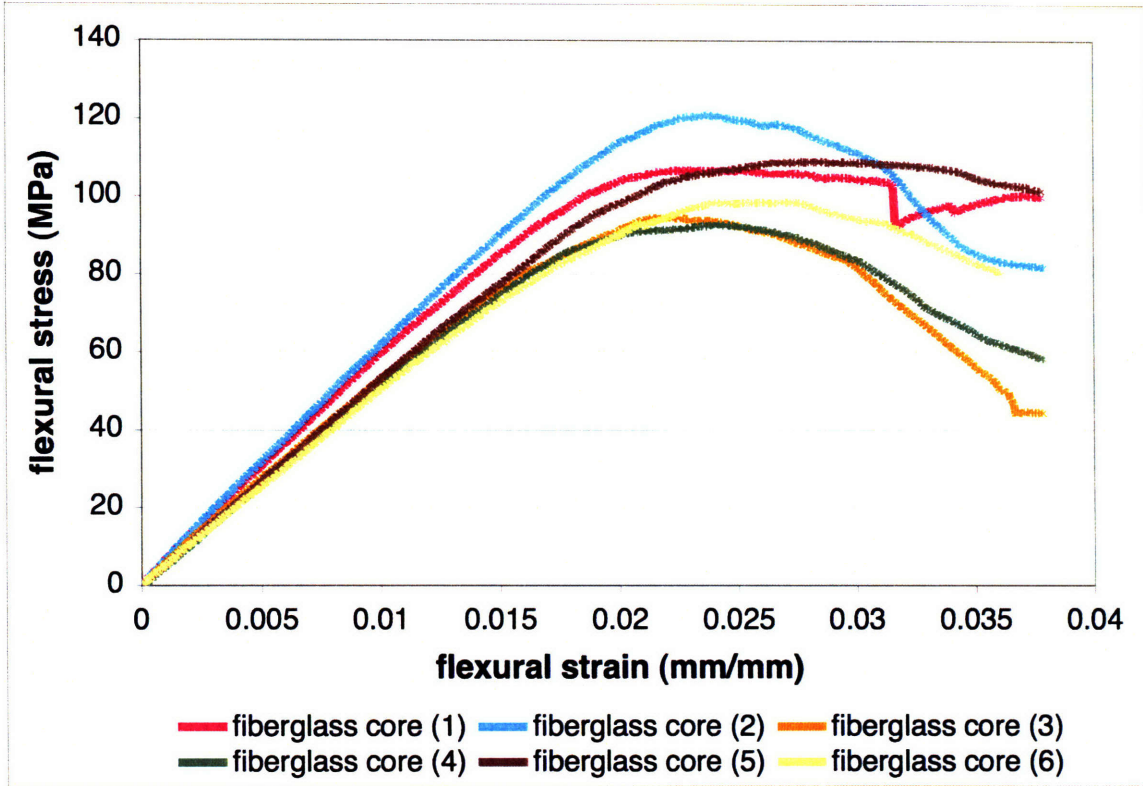
**Figure A - 1: Stress-strain curves for the cork core.**



**Figure A - 2: Stress-strain curves for cork with fiberglass cloth on one side, repeated from text. Samples (1-2) were tested with the cloth up, while the others were with the cloth down.**

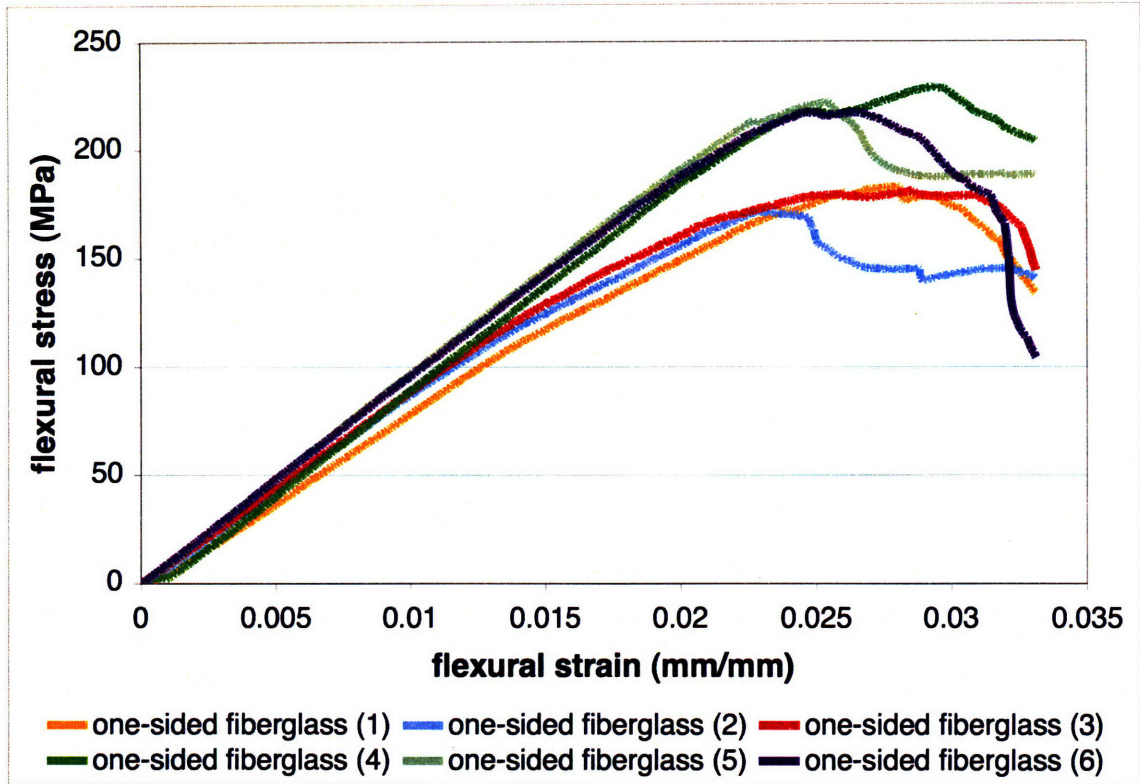


**Figure A - 3: Stress-strain curves for cork samples with fiberglass cloth on both sides, repeated from text.**

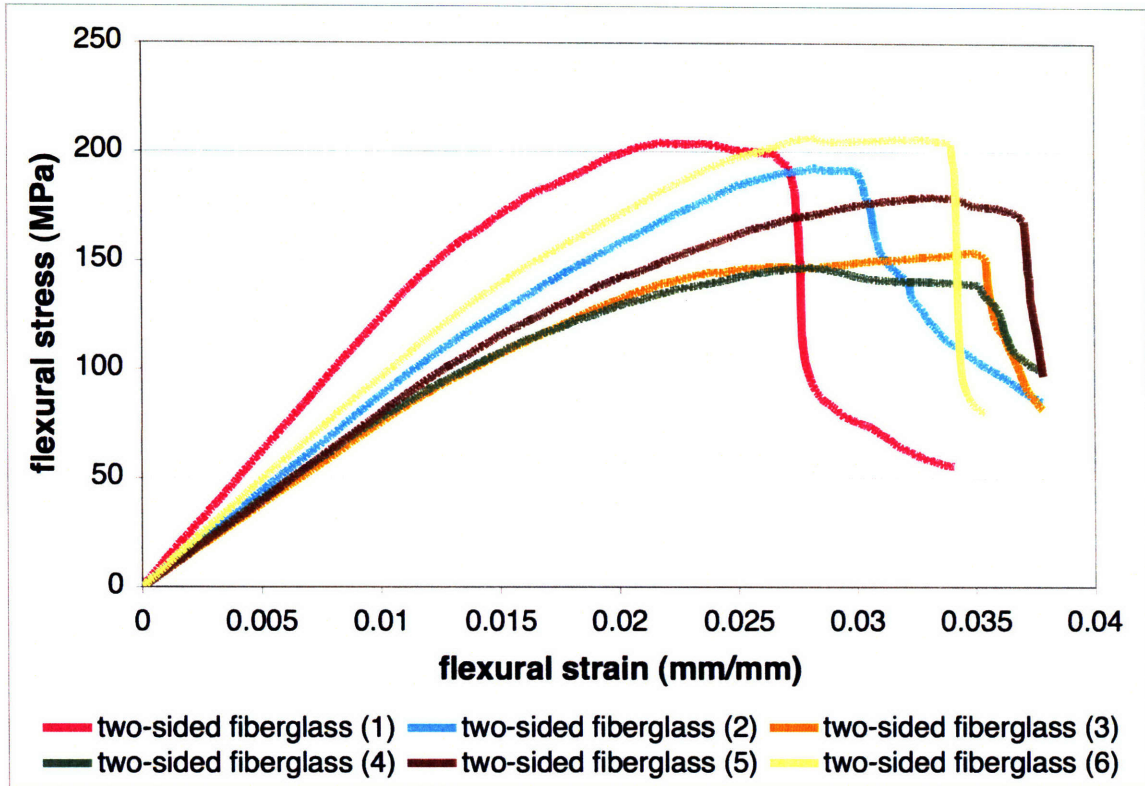


**Figure A - 4: Stress-strain curves for the all-core fiberglass samples.**





**Figure A - 5: Stress-strain curves for one-sided fiberglass samples, repeated from text. Samples (1-3) were tested with the cloth on top, while samples (4-6) were tested with the cloth on the bottom.**



**Figure A - 6: Stress-strain curves for the two-sided fiberglass samples.**

## References

- [1] ASTM D 790-07: Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. American Society for Testing and Materials Annual Book of ASTM Standards.
- [2] ASTM D 5687: Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation. American Society for Testing and Materials Annual Book of ASTM Standards.
- [3] ASTM D 6110-06: Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics. American Society for Testing and Materials Annual Book of ASTM Standards.
- [4] ASTM D 7264: Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials. American Society for Testing and Materials Annual Book of ASTM Standards.
- [5] B. Soares, L. Reis, and A. Silva, "Testing of Sandwich Structures with Cork Agglomerate Cores". 2008.
- [6] "Core Materials in Polymeric Composites." The A to Z of Materials. Feb. 2008 <<http://www.azom.com/details.asp?ArticleID=1092>>
- [7] "Materials and Process Selection Charts." Granta – Material Intelligence. Apr. 2008. <<http://www.grantadesign.com/userarea/teachingresource/ashbycharts.htm>>