The Manufacture and Characterisation of Bagasse Composites

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Australia is around the eighth largest producer of sugarcane in the world. Bagasse is the by-product fibre of the sugar production process; making it very inexpensive and readily available. If bagasse can be consolidated into a solid by incorporating it in a relatively cheap matrix in order to produce a composite material, it may have many potential uses. The main objective of this project is to investigate ways to manufacture bagasse composites with a high fibre volume fraction and to determine the mechanical properties of the resultant composite material, in particular its impact resistance properties. In addition, this report investigates the potential use of bagasse fibres within composite material, and explores possible low-cost matrix systems. The applications for such a cost effective composite will also be explored, including examples such as impact barriers, acoustic and vibration damping and sound insulation.

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Nomenclature

\[ \rho = \text{Density [kg/m}^3\text{]} \]
\[ m = \text{Mass [kg]} \]
\[ V = \text{Volume [m}^3\text{]} \]
\[ F_B = \text{Buoyancy Force [N]} \]
\[ \rho_l = \text{Density of Fluid [kg/m}^3\text{]} \]
\[ g = \text{Gravity [m/s}^2\text{]} \]

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Traditionally, composites are materials that are comprised of a strong load carrying material known as reinforcement, which is imbedded into a weaker material known as the matrix. The use of composite materials dates back centuries and started with the use of natural fibres, for example clay was reinforced by straw to construct a composite used to build walls. However, the use of natural fibres has now been replaced with many more durable construction materials and artificial fibres, the most well-known being glass, aramid and carbon. Increased use of these composite materials and heightened environmental awareness has sparked a renewed interest in natural fibres as a replacement for some of these artificial fibres such as glass. Natural fibres have many advantages when compared to glass fibres, including weight saving potential, low raw material price and being derived from a renewable resource.

Being a renewable resource, natural fibres are biodegradable, in most cases are CO₂ neutral and generally apply low energy production processes, which increases the marketing appeal of the by-product.

A. Bagasse Fibres

As part of the sugar production process, sugarcane is harvested and crushed with the sugar then being collected, resulting in a by-product fibre called bagasse (also known as megass). Australia is the eighth largest producer of sugar in the world producing approximately 5.39 million tonnes of sugar per year. This results in roughly 11 million tonnes of bagasse fibre waste being produced as a by-product. Currently bagasse fibre waste is burned by the sugar mills as an additional source of energy or sold as mulch. Already natural fibres such as flax and hemp have replaced glass fibres within a number of applications, so it is possible that bagasse may also prove useful.

By comparing the material properties of natural fibres, it was found that both flax and hemp have a higher cellulose content in percentage of weight than bagasse, also bagasse has a higher moisture content than other bast fibres. The lower cellulose content is a result of the density of the fibres; bagasse has a density ranging between 550 – 700 kg/m³ whereas flax and hemp have a density of around 1400 – 1500 kg/m³. The difference in moisture content could be due to the process used to extract sugar from the sugarcane resulting in wet bagasse fibres. Bagasse fibres can be heated and dried before use, which would lower the moisture content, however there is no significant evidence to conclude whether or not the lower cellulose content of the bagasse fibre will affect the mechanical properties of a resulting composite material.[1-4]

B. Matrix Systems

There are four main categories of composite material these are: metal matrix composites, ceramic matrix composites, carbon-carbon composites and polymer matrix composites. The polymer matrix composite category has two sub-categories, which are thermoset and thermoplastic composites. These two sub-categories incorporate the most suitable resin systems, which proved to be the most viable when combined with bagasse fibre.

Thermoset resins are liquids or low melting point solids in their initial form. By the use of a catalyst (hardener) and/or heat the resin is cured (set). Once a thermoset resin has cured, the resin cannot be converted back to its original liquid form. The major advantage of thermoset resins is their ability to cure at room temperatures. The most commonly used thermoset resins are epoxy and vinyl ester. Research into the reinforcement of polyesters with cellulosic fibres such as jute, sisal, straw, coir and kapok has already been conducted with promising results.

---

\[
W = \text{Weight [N]}
\]
\[
\rho_f = \text{Density of Fibre [g/cm}^3\text{]}
\]
\[
M_{f1} - M_{f2} = \text{Mass of Fibre in air [g]}
\]
\[
M_{f2} - M_{f3} = \text{Mass of Fibre in fluid [g]}
\]
\[
E_c = \text{Modulus for Compression [N/mm}^2\text{ or MPa]}
\]
\[
P = \text{Load [N]}
\]
\[
d = \text{Displacement [mm]}
\]
\[
L = \text{Deformation Gauge Length [mm]}
\]
\[
A = \text{Cross-Sectional Area [mm}^2\text{]}
\]
\[
k = \text{Stiffness [kg/s}^2\text{]}
\]
\[
\sigma = \text{Stress [N/mm}^2\text{ or MPa]}
\]
\[
\epsilon = \text{Strain}
\]
\[
\delta = \text{Deformation [mm]}
\]
\[
KE = \text{Kinetic Energy [m]}
\]
\[
v_i = \text{Initial Velocity found from High-Speed Camera [m/s]}
\]
Thermoplastic resins on the other hand require heat to make them usable and can be moulded while in this heated semi-fluid state, once cooled they become hard again. The process of reheating the thermoplastic resin often occurs without significant changes to the mechanical properties of the resin. Common thermoplastic resins are low-density and high-density polyethylene (LDPE and HDPE), polystyrene (PS) and polyvinyl chloride (PVC). The major problem with the use of thermoplastics is the required high processing temperature. When using such thermoplastics, the high processing temperature can degrade the natural fibres being used.\(^\text{[2]}\)

II. Significance

Artificial fibres whilst being very strong consume a great deal of energy to produce. With an increasing focus on the importance of the environment, renewable resources such as natural fibres should be studied. By reusing bagasse fibres, which are generally considered a waste material, as a replacement for artificial materials, you not only create another source of revenue for the sugar industry, but also reduce the carbon footprint of many other processes that could utilise natural fibres as a replacement for artificial fibres.

III. Objective

The purpose of this project report is to gain a better understanding on how to develop a bagasse fibre composite that has a high fibre volume faction in order to test the subsequent composites under compressive loads and impact resistance properties to determine the materials suitability to be used for impact barrier applications. The theory is that the denser the composite material the more energy it should be able to absorb, this was tested by varying the ratio of fibre to resin. Any viable applications of the resultant bagasse composite should be shown within the results of both the compression and impact tests.

IV. Methodology

A. Fibre Setup

The first step to be conducted before any manufacturing or testing of the bagasse composites can be started was to wash and dry the fibres to ensure the most accurate results. Sieving of the fibres was not conducted as in previous projects as the objective is to use what is originally waste material to make a product. By sieving fibres this not only adds another step in the production process but also creates waste, as a majority of the fibres are then not used.

To effectively calculate the required fibre volume fractions, the density of the bagasse fibre must be calculated. It was found during the literature review that bagasse has a density of around 550 – 700 kg/m\(^3\), and a previous thesis found the density to be 300 kg/m\(^3\). Due to this discrepancy, the density of the bagasse was recalculated as to ensure the most accurate results. The density of an object can be calculated by using the following equation Eq. 1.

\[
\rho = \frac{m}{V} \tag{1}
\]

The method used to calculate the density of the fibres and perhaps the most viable and simplest is the use of Archimedes principle outlined by the Australian Standard (ASTM-D3800-99, 2005). Archimedes principle states that the buoyant force acting on a body immersed in a fluid is equal to the weight of the fluid displaced by the body, and it acts upward through the centroid of the displaced volume. The equation for the buoyancy force is defined in Eq. 2.\(^\text{[5]}\)

\[
F_B = \rho_l g V = W \tag{2}
\]

For an object that has a density less than that of water, the weight of the entire body must be equal to the buoyant force, which is the weight of the fluid whose volume is equal to the volume of the submerged portion of the floating body. Going off past density values, it was safe to assume that bagasse fibre is less dense than water. In addition, the buoyancy force acting on the solid body is equal to the buoyancy force of the body of fluid as the pressure distribution around the boundary of both bodies must be equal (Figure 1). As the object being submerged is the fibres, the volume of the fibres is equal to the volume of liquid displaced by the fibres. With some rearranging and substitution the equation (Eq. 3)
described by the Australian Standard test method of calculating the density of high modulus fibres was arrived at. [6]

\[ \rho_f = \frac{(M_3-M_1)\rho_l}{(M_3-M_4)-(M_4-M_2)} \]  

(3)

The average density found was 340 kg/m$^3$. This was confirmed by another method which measured the volume displacement created by submerging the fibres in a fluid and using Eq. 1 as the mass of the fibres can be found using scales.

The calculated density was then used to calculate the fibre volume fractions. It is important to note that the volume fibre fraction is being calculated, not the weight fibre fraction. The volume fibre fraction is a measure of the volume of fibre relative to the total volume of the composite and is a number between zero and one depending on the required volume fraction. [7-8]

B. Composite Manufacture

The manufacture of the bagasse composites was completed in the old composites lab within the UNSW@ADFA engineering building. Two different types of resins were used and compared as per the research conducted within the literature review; these were melamine-urea formaldehyde (Selleys 308) and polyurethane (Selleys Durabond).

1. Compression

Unfortunately for the compression testing, no relevant international or Australian standards could be found that would suit the required testing material. A specimen for a compression test is most commonly a simple cylinder with ranging length to diameter ratios depending on the material; in this case, samples were made by using moulds of PVC pressure pipe. The most suitable length over diameter ratio for compression testing was initially thought to be 1.5, as the sample was believed to behave like a brittle material. It was important to note however that for materials that are capable of withstanding a large amount of deformation in compression and having a too small length to diameter ratio, may result in a situation where the behaviour of the sample is dominated by edge effects, meaning that the test is not measuring the fundamental compressive behaviour. [9-10]

Occasionally the samples would stick to the moulds creating the problem of getting them out without damaging the mould or the sample. The solution to this problem was to develop a mould release device, which allowed the sample to be removed with minimal damage.

2. Impact

The impact samples were manufactured in the same way as the compression samples. As the compression testing was quasi-static, by conducting dynamic impact testing of the same samples by the same sized device would allow a comparison analysis to be conducted between the differences in the absorption of energy between the two test methods. As a result, the same sized samples for the compression tests were also used for the impact tests.

C. Testing

1. Compression

The JJ Lloyd accumulated the load and displacement data into an excel spread sheet. The raw data produced positive load values in kilo-newtons (kN) and a displacement in millimetres (mm). The compression force was changed from kilo-newtons to newtons to ensure the correct units were used when calculating the stress. From this data, load vs. displacement diagrams were created. The slope of the elastic section (linear portion) of the graph was found by adding a trendline to the selected data, ensuring that the coefficient of determination ($R^2$) is as close to one as possible whilst maintaining a sufficient amount of data within the linear section. The closer the coefficient of determination is to one, the closer the trendline matches the original data. From the trendline the slope is used to calculate the compressive modulus (Eq. 4). The modulus of compression was calculated in order to compare the capacity of the samples to withstand the loads of compression. [11]

\[ E_c = \frac{P}{\frac{d}{A}} \times \frac{1}{A} \]  

(4)

The stiffness of the material was also calculated using the slope of the elastic section of the load vs. displacement graphs as stiffness is defined as Eq. 5.

\[ k = \frac{P}{d} \]  

(5)

The stiffness also known as rigidity, is the ability of a material to resist elastic deformation created by a force and is an important property of the material as it can be used to compare the different materials and
volume fractions. From the data, stress vs. strain graphs, were created by using the equations (Eq. 6 and 7) below.\(^{[10]}\)

\[
\sigma = \frac{p}{A} \quad (6)
\]

\[
\epsilon = \frac{\delta}{L} \quad (7)
\]

It is important to note that the stress and strain values calculated are engineering stress and engineering strain, not true stress and true strain. Engineering stress and strain use the original cross-sectional area and original length respectively; true stress and strain differ in that finite changes in area and length are specifically considered. It would have been possible to find the true stress, however the changes in the cross-sectional area would need to be monitored and recorded to find the true stress, which would have been difficult as the change in the cross-sectional area was not uniform. Generally as a cylindrical material deforms under a compressive load a barrelling effect occurs. The cross-sectional area of the material uniformly expands keeping its original circular shape. With the bagasse samples however, the barrelling effect had more of an elliptical shape, this resulted in the cohesive failure of the samples by shearing at an angle of 45° to the horizontal plane as the material is not homogeneous, consequently making it very difficult to accurately measure the true stress.\(^{[10-12]}\)

From the stress vs. strain graphs, the yield stress and densification strain can be found for the appropriate materials. The yield stress is the point where the material begins to deform into the plastic region of the curve as shown (Figure 2). It was used to compare which samples have a greater compressive strength as it represents the highest load that can be applied to the material without permanently deforming. The densification strain represents the strain at which the material has completely failed.

\[\text{Figure 2: Stress vs. Strain Plot Displaying Regions}\]

A polynomial trend curve was fitted to the stress vs. strain curves to gain the equation of the graph, making sure that the coefficient of determination was as close to one as possible. Trend lines were also fitted to the elastic, plastic and densification sections of the stress vs. strain curve as per the diagram above (Figure 2), once again ensuring that the coefficient of determination was as close to one as possible. The intersection of the elastic and plastic trendline gives the yield stress and the intersection of the plastic and densification trendline gives the densification strain. The area under the polynomial trendline is the energy per unit volume (J/m\(^3\)) absorbed by the sample in joules per meter cubed which was then converted into joules (J) by multiplying the value by the volume of the sample.

2. Impact

The drop tower required two velocity sensors and an accelerometer in order to gain the relevant information needed to find the energy absorbed by the bagasse sample. A high-speed camera was also situated behind a plexiglass screen to capture images of the impact. The camera started recording when the last velocity sensor was triggered by the impact device.

Before any testing could be completed the accelerometer needed to be calibrated. This was done by using a Bruel and Kjaer Calibration Exciter and an oscilloscope. The accelerometer was placed on top of the Exciter and connected to the oscilloscope. The Exciter vibrates at a constant acceleration of 10 m/s\(^2\). The oscilloscope gets the voltage output from the accelerometer and graphs it as a sinusoidal plot. The maximum and minimum data points represent the voltage RMS which can be read off the display. The voltage output from the accelerometer was saved as an excel file by the data acquisition program within the impact lab. A Matlab code calls upon the file and uses the raw voltage data to get acceleration by converting the data to millivolts and multiplying by the
voltage RMS over the gain as set on the charge amplifier. In addition, it was important to make sure that the settings on the charge amplifier were changed to match those on the data sheet for the particular accelerometer used.

The testing of the impact samples was conducted from four differing heights, which correspond to different potential energies of impact, with each combination of resin and fibre volume fraction being tested with the same amount of potential energy (same height).

The accelerometer data acquired from the test was used to graph acceleration vs. time, the integral of which is velocity vs. time and the double integral finds the displacement vs. time. To complete the integration to find velocity, a constant is needed. Originally the initial velocity was found by using the velocity sensors, however it was more accurate to find the initial velocity by using the camera through a program called Kinovea. Kinovea enables pixels to be tracked through a video produced by image coloration. The velocity sensors record the initial velocity when the impact device was around two to three centimetres above the sample, the velocity found from the camera images does not have this error. In addition it was essential that the velocity sensors are exactly parallel to the vertical axis of impact as the values for distance and time are so small (using millimetres and milliseconds), any variation in the angle of the sensors can have a significant effect on the calculated velocity. Due to levelling the camera setup on the tripod, the orientation errors were insignificant compared to those associated with the velocity sensors. Hence the velocity found by the camera was used within the integration and to calculate the kinetic energy (Eq. 8) of impact.

\[ KE = \frac{1}{2}mv^2 \]  

(8)

Once values for displacement were gained from the integration within a Matlab code, they were plotted in a force vs. displacement graph. The area under the curve was used to calculate the energy absorbed which represents the total amount of energy that is transferred from the impact device to the sample through the impact process. The code outputted the data into an excel file which was filtered to smooth the force vs. displacement curves. The maximum force of the impact and maximum displacement of the samples was found from the plots. The maximum force corresponds to the maximum displacement, where the velocity of the impact device is zero as the device has reached its point of maximum acceleration. The stiffness of the material (Eq. 5) was also calculated as described within the compression section of this report. \(^{[10]}\)

V. Results

A. Compression

By using a combination of excel and Matlab, stress vs. strain graphs were used to find the modulus of compression (E), stiffness (k), yield stress (σy), the densification strain (εd) and the energy absorbed by the bagasse samples. This was done for both the Durabond and the Melamine samples so the matrix systems could be compared with varying fibre volume fractions as shown below (Table 1 and Table 2).

Table 1: Durabond Quasi-Static Results

<table>
<thead>
<tr>
<th>Resin Volume Fraction</th>
<th>E (MPa)</th>
<th>k (N/mm)</th>
<th>σy (KPa)</th>
<th>εd</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>383.37</td>
<td>13521.24</td>
<td>7253.50</td>
<td>0.34</td>
<td>206.29</td>
</tr>
<tr>
<td>70%</td>
<td>289.05</td>
<td>10214.64</td>
<td>5291.60</td>
<td>0.38</td>
<td>205.66</td>
</tr>
<tr>
<td>80%</td>
<td>324.26</td>
<td>12705.82</td>
<td>3593.30</td>
<td>0.31</td>
<td>131.11</td>
</tr>
</tbody>
</table>

Table 2: Melamine Quasi-Static Results

<table>
<thead>
<tr>
<th>Resin Volume Fraction</th>
<th>E (MPa)</th>
<th>k (N/mm)</th>
<th>σy (KPa)</th>
<th>εd</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>45.70</td>
<td>1106.20</td>
<td>1111.60</td>
<td>0.48</td>
<td>73.42</td>
</tr>
<tr>
<td>70%</td>
<td>41.57</td>
<td>1006.10</td>
<td>696.00</td>
<td>0.44</td>
<td>57.97</td>
</tr>
<tr>
<td>80%</td>
<td>68.58</td>
<td>2202.70</td>
<td>739.30</td>
<td>0.31</td>
<td>24.43</td>
</tr>
</tbody>
</table>

Results were compared against one another to analyse the different compositions of each composite material. The Durabond and Melamine results were accumulated into stress vs. strain graphs. Five samples of each differing volume fraction were tested in compression with the stress and strain results for each sample being displayed within graphs for analysis. The average values for all the Durabond and Melamine samples tested were found and gathered to create the plot below (Figure 3). This compares the stress vs. strain values for both of the different matrix systems and different volume fractions.
With the main aspect being on the energy absorption capabilities, the energy and specific energy absorbed by each variation in sample were analysed through a bar chart (Figure 4).

**B. Impact**

The output results from the Matlab code and excel spread sheet were used to find the maximum force ($F_{max}$) conveyed by the impact device, the maximum displacement/deformation ($\delta$), the stiffness ($k$), the energy absorbed ($E_{abs}$) and the kinetic energy of the impact (KE) and are displayed below (Tables 3-6).

![Average Stress vs. Strain](image)

**Figure 3: Average Stress vs. Strain**

![Energy & Specific Energy Absorbed](image)

**Figure 4: Quasi-Static – Energy & Specific Energy Absorbed**

**Table 3: Impact Results – 60J**

<table>
<thead>
<tr>
<th></th>
<th>$F_{max}$ (N)</th>
<th>$\delta$ (mm)</th>
<th>$k$ (N/mm)</th>
<th>$E_{abs}$ (J)</th>
<th>KE (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melamine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>4082.9</td>
<td>13.8</td>
<td>871.6</td>
<td>40.9</td>
<td>42.0</td>
</tr>
<tr>
<td>70%</td>
<td>4208.8</td>
<td>14.4</td>
<td>438.7</td>
<td>38.6</td>
<td>40.5</td>
</tr>
<tr>
<td>80%</td>
<td>3195.2</td>
<td>16.1</td>
<td>762.6</td>
<td>38.7</td>
<td>39.6</td>
</tr>
<tr>
<td><strong>Durabond</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>12890.1</td>
<td>6.3</td>
<td>4142.1</td>
<td>29.6</td>
<td>41.6</td>
</tr>
<tr>
<td>70%</td>
<td>10680.7</td>
<td>6.2</td>
<td>3159.4</td>
<td>32.3</td>
<td>41.5</td>
</tr>
<tr>
<td>80%</td>
<td>6219.8</td>
<td>11.5</td>
<td>698.7</td>
<td>38.6</td>
<td>42.0</td>
</tr>
</tbody>
</table>

**Table 4: Impact Results – 85J**

<table>
<thead>
<tr>
<th></th>
<th>$F_{max}$ (N)</th>
<th>$\delta$ (mm)</th>
<th>$k$ (N/mm)</th>
<th>$E_{abs}$ (J)</th>
<th>KE (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melamine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>4420.8</td>
<td>22.5</td>
<td>529.3</td>
<td>68.7</td>
<td>70.1</td>
</tr>
<tr>
<td>70%</td>
<td>4904.9</td>
<td>21.7</td>
<td>204.7</td>
<td>68.8</td>
<td>70.5</td>
</tr>
<tr>
<td>80%</td>
<td>4419.2</td>
<td>23.6</td>
<td>698.1</td>
<td>68.9</td>
<td>69.7</td>
</tr>
<tr>
<td><strong>Durabond</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>12937.8</td>
<td>7.2</td>
<td>4586.0</td>
<td>49.4</td>
<td>69.6</td>
</tr>
<tr>
<td>70%</td>
<td>12889.3</td>
<td>7.9</td>
<td>3338.8</td>
<td>61.6</td>
<td>72.9</td>
</tr>
<tr>
<td>80%</td>
<td>6851.0</td>
<td>16.0</td>
<td>796.4</td>
<td>70.55</td>
<td>73.1</td>
</tr>
</tbody>
</table>
For the low velocity impact results, the absorbed energy of the impact by the sample was displayed within bar charts for ease of comparison. The next two charts (Figure 5 and Figure 6) show the ratio of energy absorbed by the sample over the kinetic energy of the impact and the specific energy absorbed from impact by the samples respectively.

![Energy Ratio Chart](image)

![Specific Energy Absorbed Chart](image)

**VI. Discussion**

Firstly as mentioned within the methodology, the most suitable length over diameter ratio for a brittle sample to be used in compression testing was 1.5, for a ductile material it was recommended that a value of 3 be used. This value was chosen as the samples were initially believed to be more brittle than ductile due to the addition of the matrix system. However at the conclusion of the results it can be seen that the samples tested under a compressive load displayed ductile attributes, so a value of 3 for the length to diameter ratio may have proven to be more appropriate. Nonetheless the difference between the lengths to diameter ratio would not have affected the results in a significant manner.

The setting process of the Durabond material was unexpected and so is the next point of discussion. As the binder set it drew in air and expanded into the gaps between the fibres, thus creating a smooth finish to the final product. A comparison between the finish of the two different materials can be seen in the cross-sectional image below (Figure 6) with the Durabond sample on the left, the Melamine sample on the right.

![Cross-sectional Image](image)

The unique setting process of the Durabond binder caused a number of problems in getting the samples out of the moulds without damaging them, as the release agent used didn’t provide an effective barrier between the mould and the binder, which was caused by the expansion of the binder during the setting process.
Within the quasi-static results there seems to be no trend between the variations in volume fraction of the same material with the modulus of compression.

However it is clear that the samples made with the Durabond binder have a much larger modulus of compression than the equivalent samples made from Melamine as seen within Tables 1 & 2, thus meaning that the Durabond samples have a greater capacity then the Melamine samples at withstanding loads. For example the modulus of compression for 80% Melamine is 68.58 MPa compared to the equivalent volume fraction Durabond sample of 324.26 MPa. As expected the material with the highest modulus of compression (383.37 MPa) was the 60% volume fraction Durabond sample. It was expected that with an increasing volume fraction the capacity for the samples to withstand the compressive loads would decrease. Yet for both Durabond and Melamine it can be seen that the samples with a volume fraction of 80% are greater than the equivalent material of a 70% volume fraction. Upon further analyse of the load vs. displacement curves for samples of 80% volume fractions for both materials there are one or two samples that have a significantly larger slope within the plot then the other samples which would be the cause of the increase in the modulus of compression for the 80% samples, as the modulus is calculated by averaging the values found for each of the five samples tested.

This discrepancy in slope for the load vs. displacement plots could be attributed to a variation in the fibre size and position within the sample. The variation in stiffness models the same trends as the modulus of compression as the stiffness relates to the materials capacity to tolerate loads.

The calculation of the yield stress and densification strain was achieved by finding the intersections of the trend lines of the stress vs. strain plot (Figure 2). Similar to the results displayed for the modulus of compression, again there is no trend between the results of the Melamine samples for the yield stress; however it can be seen that as the volume fraction increases for samples made with Durabond the yield stress decreases, as the yield stress was calculated from the gradient of the elastic section of the stress vs. strain curves where the material begins to deform into the plastic region. For the Durabond samples, the volume fraction with the highest yield stress is the 60% sample (7253.5 KPa) and the lowest is the 80% sample (3593.3 KPa). In contrast the Melamine sample with the highest yield stress (1111.6 KPa) is the 60% sample; the lowest (696.0 KPa) is the 70% volume fraction sample. It can be concluded that as the volume fraction of the samples increase, the highest load that the samples can endure without permanent deformation occurring decreases.

The densification strain results display no clear trend within the Durabond samples; the Melamine samples however have a decreasing densification strain as volume fraction increases from 60% (0.48) to 80% (0.31). The Melamine densification strain for the 60% and 70% samples is greater than the equivalent volume fractions for the Durabond samples with both the resin and binder having the same densification strain for a volume fraction of 80%. This difference can be seen with the average stress vs. strain plot (Figure 3), by comparing where the densification region is located as shown by Figure 2. From the densification results it can be concluded that generally the samples made with the Melamine resin are more ductile than those made with Durabond as the densification strain represents the strain at which the material has failed.

The tables from the impact testing (Tables 3-6) display the maximum force of the impact device on the sample. A slight trend can be seen between the volume fractions of the samples made with Durabond, with the samples of 60% volume fraction having the greatest maximum force to that of the 80% samples having the lower maximum force. As expected there is a relation between the displacement of the initial sample height and the impact energy, more so with the Melamine samples than the Durabond samples. Although there is a trend within the Durabond samples, as volume fraction increase so does the displacement created on the samples by the impact, which can once again be seen more closely by comparing the values within the tables (Tables 3-6) and was supported by the image array analysis.

The stiffness results of both resin/binder samples, compares the extent in which the samples deform under the impact load. The relationship between the stiffness of the material and deformation can be seen by comparing the change in displacement values to the change in the stiffness values as it shows that the stiffer material generally being the Durabond samples deforms less than the Melamine samples. The tables (Tables 3-6) also show that a variation in impact energy does not govern the stiffness, the stiffness of the samples is related to the material composition and thus materials of the same volume fraction have around the same stiffness, with however the occasional outlier which can be linked to the variation in fibre size within the sample.

The compression test was conducted at a rate slow enough to be quasi-static and the impact head was the same diameter as the compression device diameter thus justifying the comparison between the energy results of the two tests. Firstly, before any comparison can be made, an understanding of what each chart is portraying must be grasped. The amount of energy absorbed was graphed against the specific energy in Figure 4 from the quasi-static testing, it can be seen that both the Melamine and Durabond samples show that the energy absorbed decreases with an increasing volume fraction, yet there is not much of a difference between the 60% and 70% Durabond samples with the results being around 206.3 J and 205.7 J. It was interesting to note that the specific energy of the 70% Durabond sample is actually higher than the 60%. This indicates that between the 60% and 70% fraction there is possibly a peak in the material’s ability to absorb energy. The impact energy absorbed was
plotted as a ratio over the kinetic energy of the impact (Figure 5). The results from the low velocity tests show the opposite trend as it can be seen that the Melamine samples have absorbed a greater fraction of the kinetic energy from impact than the equivalent Durabond samples. It can be seen that as the volume fraction increases within the Durabond samples, the energy absorbed also increases. Furthermore, the maximum energy absorbed is greatest for the 80% fibre volume fraction samples when comparing samples of the same resin/binder and impact kinetic energy. Thus proving the theory that the higher the volume fraction the more energy absorbent the sample is. However as seen within Figure 4 the theory is only valid for dynamic impacts not quasi-static.

The energy absorbed by the samples from the quasi-static tests is related more to the strength of the material and the samples ability to prolong plastic deformation and densification. Additionally, the densification and the maximum displacement results are closely related to their respective test energy absorbed results which show the relation between the deformations caused on the samples during the tests and the energy absorbed. The final bar chart of the low velocity test (Figure 6) displays the trend between an increasing volume fraction and increasing specific energy. The specific energy removes the variations in the mass of the samples so as to actually compare the two matrix systems, however the trends shown within the energy ratio chart (Figure 5) still hold as there is not a great deal of difference in the mass of the samples to significantly affect this trend.

VII. Conclusion

The objective of the project was in investigate whether high fibre volume fraction bagasse composites could be manufactured, and to evaluate the suitability and possible applications of the resultant materials with the emphasis on impact barriers.

The objective was achieved by the manufacture of bagasse composites using two different matrix systems, with three fibre volume fractions of 60%, 70% and 80%. The bagasse composite samples produced were tested in quasi-static compression and low velocity impacts in order to determine and analyse the important properties of the material with a focus on the amount of energy absorbed by the samples. The Durabond samples suffered minimal deformation with the energy levels tested on the drop tower compared to the equivalent Melamine samples. This indicates that if both the Durabond and Melamine samples were to undergo the same displacement, the Durabond samples would be conducted at higher impact energies and would be able to absorb more of that energy. This is shown within the results for the quasi-static tests where the Durabond samples were proven to be able to absorb more energy than the equivalent Melamine samples. Therefore when the samples have the same final displacement, the Durabond samples have absorbed more of the energy then the Melamine samples. This can also be contributed by the higher yield stress obtained by the Durabond. To gauge a better understanding of the structural limitations of the Durabond samples, testing of higher energy level impacts such as using a medium velocity gas gun should be conducted, whereas the Melamine samples appear to have reached their limit in regards to the absorption of energy from impact. As the ductility of the Melamine samples is higher than the equivalent of the Durabond samples it would be necessary to decrease the fibre volume fraction to around 40% to 50% if any testing of the Melamine samples is to be conducted with higher energy impacts.

The focus application for a bagasse composite is its suitability for impact barriers; an effective impact barrier is able to absorb most of the energy from the impact object. As discussed, the Melamine samples were effective at absorbing the energy from the impact device on the drop tower however, the Durabond samples proved to be more effective at higher velocities due to its ability to withstand higher loads as demonstrated with the quasi-static tests. Consequently, for the use of a bagasse sample in the application of an impact barrier, the lower volume fraction Durabond sample would be more applicable.

In conclusion, current impact barrier materials are rubber tyres, water containers and hay bales which all endure environmental effects, so for a bagasse composite material to be seriously considered a wide range of environmental tests in addition to further impact tests of higher velocities need to be completed to further discover the true potential of a bagasse composite.

VIII. Recommendations

A number of recommendations can be made to further develop the work conducted within this project. One of the main problem areas was during the manufacturing phase. The problem was associated with the release agent used within the moulds when the Durabond binder was being used. As Durabond sets, it draws in air and expands. It is believed that this process disrupts the layer of release agent applied to the PVC pressure pipe making it quite difficult to remove the sample from the mould. To overcome this problem it is recommended that a mould made out of aluminium be tried or a different release agent such as a wax be used.

To improve the impact results gained from the drop tower additional samples of the same type should be tested to improve the accuracy of the results. In addition, a wider range of energies could be used to test the samples. As can be seen from the impact results some of the Durabond samples have hardly been damaged. If
lower fibre volume fractions are to be tested it is believed that the use of the vertical gas gun would be a more viable option than the drop tower as it allows a higher range of impact energies to be tested.

IX. Future Work

The use of natural fibres such as bagasse is still a relatively new concept; there is little information on the mechanical properties of these fibres in the use of composite materials. As possible applications for natural fibres are investigated many resulting tests will follow. This project has researched and explored many possible resins and binders, which could be used as a matrix, yet only two were used within the manufacturing and testing phase. A wider range of binders and resins should be experimented with in order to determine which is the best suitable matrix material for a bagasse fibre composite in terms of cost, ability to be used with high fibre volume fractions and curing properties.

As investigated within the literature review of this project, possible applications such as a sound and thermal absorption material could possibly be tested in future projects. This could be done in a similar way as the compression and impact samples within this project were manufactured with a focus on sample with high volume fractions. A similar theory to that of the impact testing in that a sample with a greater density, hence a high fibre volume fraction may be quite applicable for use as either a sound/vibration or thermal insulator.

Another aspect for future works would be to look into the moisture absorption properties in addition the effect of heat on bagasse composite samples. Bagasse samples, which have been left in water for varying time periods, could be compared to other samples of the same composition with the same testing procedure. Also sample could be cooled and heated to gauge what sort of effect a variation in temperature may have on bagasse fibre composite materials. This type of testing would simulate the effects a bagasse composite material may face in an open environment.

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