Mechanical and Thermal Characterizations of Biobased Thermoset Resins from Soybean Oil Reinforced with Natural Fiber Using Vacuum Injection Moulding Technique.

(MSc Thesis in Resource Recovery - Sustainable Engineering)

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Client: University of Boras, Sweden.

Date: September 2010
Preface

This final 30 credit points degree project, is the conclusive part of the Master programme in Resource Recovery- Sustainable Engineering (120 credits) at the University of Borås.

The project was carried out at the Polymer Technology laboratory, University of Borås.

This research work has been quite challenging because it gave us the opportunity to think independently and to be critically minded.

Our sincere appreciation goes to our supervisor, Kayode Adekunle for his availability and willingness to put us through at all times and Professor Mikael Skrifvars for his support. I also want to thank Adib, Jonas Hanson, Dan Åkesson, Haike Hilke, for their immense contribution towards the completion of this research.

Borås 2010-09-16

_______________________
Professor Mikael Skrifvars

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Kayode Adekunle

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Rima Ghoreishi

_____________________
Mehdi Ehsani Fatmehsari
Abstract

The aim of this research was to analyze the mechanical and thermal properties of composites and hybrid composites prepared with four types of jute fibers and two different resins; biobased thermoset resins acrylated epoxidized soybean oil (AESO) and mathacrylated anhydride modified soybean oil (MMSO). The processing technique used was vacuum injection molding (VIM). Tensile and, flexural testings and dynamic mechanical and thermal analysis (DMTA) were used to characterize the composites’ properties. The results showed that the AESO composites have better tensile and flexural properties. This may be due to the fact that the curing conditions were quite the same for both AESO and MMSO composites but MMSO composites showed different behavior during curing step. They were completely cured in a shorter time compared to AESO composites. Having equal curing time for both resins’ composites can damage the structure of MMSO composites and hybrids. Tan delta peak for the MMSO reinforced composites occurs at higher temperatures, compared to AESO reinforced composites, which means better thermal properties for MMSO reinforced composites.

Key words: Soybean oil resin, jute fiber, AESO, MMSO, hybrid composite, flexural test

Tensile test, DMTA, vacuum injection molding.
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1. Introduction

In recent time the use of renewable materials is increasing e.g. biobased polymers and natural fibers are being utilized instead of their synthetic counterparts. The aim of using renewable materials is to improve sustainability. The emission of carbon dioxide, methane and other greenhouse gases is affecting the environment by increasing the global warming, which is now being regulated according to the Kyoto and the G8 protocols [1]. In one hand the production and disposal of oil based polymers and composites produce hazardous emissions to the environment therefore the use of biobased polymers and composites could decrease these emissions and increase sustainability [2]. On the other hand the costs of synthetic fibers are higher than those of natural fibers [3, 4].

One industrial application of the biobased polymers is in the production of composites where the biobased polymer acts as a matrix and the fiber acts as the reinforcement [2].

There are different types of biobased polymers and natural fibers; also there are different ways to impregnate the natural fibers with biobased polymers [3, 5, 6]. Jute fibers have some advantages and disadvantages, they are cheap and have renewable sources, low density and non-abrasive production process [6] but they absorb high amounts of moisture which decreases the mechanical properties of the composites [7, 8, 9]. The reinforcement of resin with fiber improves the mechanical and thermal properties of the polymer [6, 10-12].

Soybean oil is the most abundant plant oil and it has been used extensively in industries [13-16]. In order to make resin from soybean oil, the oil must be functionalized [17]. Epoxidized soybean oil (ESO) is utilized as plasticizers and stabilizers [18]. In this experiment acrylated epoxidized soybean oil (AESO) and mathacrylated anhydride modified soybean oil (MMSO) were used as matrix in the composites preparations.

Vacuum injection molding (VIM) technique was used [19] to impregnate jute fibers with AESO and MMSO. Composites made by this technique have vast applications in industry e.g. automotive industry [19, 20, 22]. The VIM process was performed in bench scale. Under vacuum conditions, the resin was injected into the fiber. The fiber reinforced the resin and produced a rigid composite [19, 21]. The composite is called hybrid when different types of fibers are used [19, 20, 22].
Jute fibers do not have desirable mechanical and thermal properties on their own, but when impregnated and then cured jute fibers’ range of applications increases [6, 12, 23-25].

Many researches have been made on biobased composites prepared with various types of natural fibers e.g. sisal, jute, coir and flax fibers; the production techniques and their properties as well as different impregnation methods have been reported [1, 26, 27].

The objective of this research is to characterize the mechanical and thermal properties of AESO and MMSO resins reinforced with jute fibers using a vacuum injection moulding technique.

2. Experimental

2.1 Materials

The following materials were used in this experiment:

- **Reinforcements:**

  Three types of jute fabrics and a non-woven jute fiber were used as reinforcements (see table 1 and figure 1).

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Dimension</th>
<th>Surface weight (gr/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>17cm×17cm</td>
<td>810.7</td>
</tr>
<tr>
<td>W1</td>
<td>17cm×17cm</td>
<td>233.56</td>
</tr>
<tr>
<td>W2</td>
<td>17cm×17cm</td>
<td>322.50</td>
</tr>
<tr>
<td>W3</td>
<td>17cm×17cm</td>
<td>122.50</td>
</tr>
</tbody>
</table>

Figure 1. Pictures of the jute fibers used as reinforcement.
• Matrices and other reagents:
Matrix: Acrylated epoxidised soybean oil (AESO) and methacrylic anhydride modified soybean oil (MMSO) were used for different fiber categories, the exact amount will be mentioned in the experimental part, styrene (25 wt%) was used as a reactive diluent (supplied by Sigma-Aldrich, USA), dibenzol peroxide (2 wt%) as a free radical initiator, dimethylaniline (0.3 wt%) as an accelerator (supplied by Reichhold Adic Group Co.), sodium hydroxide pellets for fiber treatment ESO (epoxidized soybean oil, supplies by Cognis Gmbh Germany), hydroquinone as a free radical initiator, methacrylic acid (99%) as a co-monomer, methacrylic anhydride(94%) and N-methylimidazol (99%) as a catalyst (supplied by Sigma-Aldrich Chemical Company, USA), dichloromethane(99.5%)( supplied by Alfa Aesar Gmbht&Co. , KG).

2.2 Composite preparations

The sequence showed in tables 2 and table 3 was used for the production of both the composites and the hybrid composites.

Table 2. Composite laminate compositions.

<table>
<thead>
<tr>
<th>Composite Name</th>
<th>Number of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>2</td>
</tr>
<tr>
<td>W1</td>
<td>3</td>
</tr>
<tr>
<td>W2</td>
<td>3</td>
</tr>
<tr>
<td>W3</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3. Hybrid composite laminate compositions.

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of layers</th>
<th>NW</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW/W1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>NW/W2</td>
<td>3</td>
<td>1</td>
<td>-----</td>
<td>2</td>
<td>-----</td>
</tr>
<tr>
<td>NW/W3</td>
<td>3</td>
<td>1</td>
<td>-----</td>
<td>-----</td>
<td>2</td>
</tr>
</tbody>
</table>
2.2.1 Fiber treatment

A solution of Sodium hydroxide (4 wt %) was used for fiber treatment. The treatment process consists of the following steps:

- Soaking fibers in NaOH solution for one hour
- Draining the NaOH solution
- Fiber Washing with plenty of water
- Using Litmus paper to check neutrality
- Drying over night at room temperature
- Post drying the fibers at 105 °C for about 2 hours in an oven
- Ironing fibers to get proper alignments.
- Fiber cutting (17cm × 17cm)

2.2.2 Resin blending

Resin viscosity is an important parameter in vacuum injection molding process, therefore the viscosity of AESO should be decreased in order to improve the diffusion of resin through the fiber for a better impregnation. To decrease the viscosity, the resin was heated up in an oven at 60 °C for 8-10 minutes. The warm resin was mixed with Styrene (25wt %) as solvent, Dibenzol Peroxide (2wt %) as an initiator and Dimethylaniline (0.3 wt %) as an accelerator. Different percentages of Styrene, Dibenzol Peroxide and Dimethylaniline were blended to determine the optimum resin/initiator ratio and acceptable cured condition. It was well mixed to give a homogenous solution. The resin blending for MMSO was the same as the one for AESO.

3. Manufacturing techniques

3.1 Vacuum injection molding

Resins such as AESO and MMSO do not have appropriate mechanical and thermal properties. In order to increase their performances, these resins could be reinforced with different kinds of reinforcements. In this experiment, jute fibers (woven and non-woven) were used. A simple laboratory made vacuum bag was constructed see Figure 2.
The vacuum bag inlet was connected to a resin container and the outlet was connected to a vacuum pump. The vacuum pump pressure is in the range of 200-300mmHg. During the injection process, the resin flowed slowly into the fiber. At the end of the process, the fiber was totally impregnated with resin. This equipment was just for one time use, therefore new equipment (vacuum bag) was constructed for each sample.

**3.2 Vacuum injection molding of AESO**

Different combinations of reinforcements were impregnated and cured thermally. The impregnated fibers (prepreg) were taken into the oven at 60°C for 1 hour. To post cure the (prepreg), they were put between two hot plates (170°C) for 5 minutes. No pressure was used during the composite post curing process, but for the hybrids, a pressure of 5 bar was used. The closer the sample to the heat transfer surfaces, the better the polymer cross linking density.
3.3 Vacuum injection molding of MMSO

The whole vacuum injection molding process was the same for AESO and MMSO.

3.3.1 Synthesis of methacrylic and hydride modified soybean oil (MMSO)

MMSO synthesis has two stages. The first stage takes approximately 12 hours and the second one takes about 4 hours. The product of the first stage is MSO (Methachrylated Soybean Oil). MSO was further modified to MMSO during the second step.

- First step: 370g ESO was poured into a round bottom three neck flask and heated up using an oil bath to 120°C. A 0.32g Hydroquinone was added to the hot ESO and after mixing; 120g methachrylic acid was added. Methachrylic acid acts as a monomer in the polymerization process. A mechanical stirrer was used during the whole process. Because of the fact that the stirrer by itself can not prevent gel formation, hydroquinone, which is a free radical inhibitor, was used. After about 8 hours, 0.14g hydroquinone was added to the reaction mixture followed by 48 g methachrylic acid. The reaction mixture’s color was brown and denser than before. After 4 hours, the first stage was ready and the product named MSO.

- Second step: A 417g MSO was diluted with dichloromethane. Approximately 250g dichloromethane was added. The solution was stirred and heated up to 60°C, then 0.46g hydroquinone was added followed by a solution of 204g methachrylic anhydride and 2.06g N-methylimidazol. N-methylimidazol acts as a catalyst to increase the reaction rate. At this point, the temperature was fixed at 80°C. After 4 hours, MMSO was ready.

3.3.2 Curing of the MMSO reinforced composites

MMSO was completely cured in the oven at 60°C; therefore there was no need for MMSO composites to be post cured between the hot surfaces at 170°C. We wanted to compare MMSO and AESO composites with each other, for this reason the same experimental conditions was needed. Therefore we also put the MMSO composites between the hot surfaces at 170°C for 5 minutes.
4. Characterization

The composite laminate were cut and tested according to ISO standard for tensile, flexural and dynamic mechanical thermal analysis (DMTA).

4.1 Tensile testing

The tensile testing was performed based on ISO 527-1 and ISO 527-4 using a Tinius Olsen UTM (Universal Testing Machine) called H10KT (maximum capacity 10KN). The gauge length was 25mm and the test speed was 10mm/min. At least 10 specimens (Fig. 3) were tested for every material.

![Figure 3. Sketch of specimen for tensile testing.](image)

4.2 Flexural testing

The three point flexural testing was performed based on ISO 14125 using a Tinius Olsen UTM (Universal Testing Machine) called H10KT (maximum capacity 10KN). The span length was 64mm and the test speed was 1 mm/min. At least 7 specimens (Fig. 4) were tested for every material.

![Figure 4. Sketch of specimen for flexural testing.](image)
4.3 Dynamic mechanical thermal analysis (DMTA)

The DMTA testing was performed using a DMA Q800 TA Instrument. One specimen was tested for every material.

![Figure 5. Sketch of specimen for DMTA.](image)

5. Results

Using AESO and MMSO as biodegradable (renewable) and reinforced with natural fibers using a vacuum injection molding process provides a good chance of making biodegradable composites. The tensile, flexural and thermal properties of these composites were analyzed.

5.1. Tensile test

Tables 4 and table 5 Show the results of the tensile test for MMSO and AESO reinforced composites.

Table 4. Tensile properties of AESO reinforced composites.

<table>
<thead>
<tr>
<th>Name</th>
<th>Tensile Modulus (GPa)</th>
<th>Standard Deviation</th>
<th>Tensile Strength (MPa)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite NW (2-PLY)</td>
<td>1.3</td>
<td>0.32</td>
<td>9.4</td>
<td>1.78</td>
</tr>
<tr>
<td>Composite W1 (3-PLY)</td>
<td>0.52</td>
<td>0.14</td>
<td>9.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Composite W2 (3-PLY)</td>
<td>0.62</td>
<td>0.12</td>
<td>9.1</td>
<td>0.73</td>
</tr>
<tr>
<td>Composite W3 (6-PLY)</td>
<td>1.1</td>
<td>0.31</td>
<td>9.2</td>
<td>1.66</td>
</tr>
<tr>
<td>HYBRID NW/W1</td>
<td>1.7</td>
<td>0.2</td>
<td>17</td>
<td>1.55</td>
</tr>
<tr>
<td>HYBRID NW/W2</td>
<td>2.0</td>
<td>0.58</td>
<td>17</td>
<td>3.84</td>
</tr>
<tr>
<td>HYBRID NW/W3</td>
<td>2.4</td>
<td>0.8</td>
<td>18</td>
<td>3.81</td>
</tr>
</tbody>
</table>
Table 5. Tensile properties of MMSO reinforced composites.

<table>
<thead>
<tr>
<th>Name</th>
<th>Tensile Modulus (GPa)</th>
<th>Standard Deviation</th>
<th>Tensile Strength (MPa)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite NW (2-PLY)</td>
<td>0.41</td>
<td>0.60</td>
<td>4.12</td>
<td>0.86</td>
</tr>
<tr>
<td>Composite W1 (3-PLY)</td>
<td>0.88</td>
<td>0.41</td>
<td>8.32</td>
<td>2.76</td>
</tr>
<tr>
<td>Composite W2 (3-PLY)</td>
<td>1.03</td>
<td>0.76</td>
<td>9.84</td>
<td>2.98</td>
</tr>
<tr>
<td>Composite W3 (6-PLY)</td>
<td>2.44</td>
<td>0.92</td>
<td>18</td>
<td>3.33</td>
</tr>
<tr>
<td>HYBRID NW/W1</td>
<td>2.19</td>
<td>1.30</td>
<td>9.8</td>
<td>2.02</td>
</tr>
<tr>
<td>HYBRID NW/W2</td>
<td>1.90</td>
<td>0.89</td>
<td>17.5</td>
<td>1.18</td>
</tr>
<tr>
<td>HYBRID NW/W3</td>
<td>0.87</td>
<td>0.80</td>
<td>6.68</td>
<td>4.02</td>
</tr>
</tbody>
</table>

The tensile strength of the AESO reinforced composites varies between 9.1 and 9.4 MPa. The tensile modulus of the AESO reinforced composites varies between 0.52 and 1.3 GPa. The tensile strength of the AESO hybrid composites varies between 17 and 18 MPa. Whereas the tensile modulus of the AESO hybrid composites varies between 1.7 and 2.4 GPa. The tensile strength of the MMSO reinforced composites varies between 4 and 18 MPa. The tensile modulus of the MMSO reinforced composites varies between 0.4 and 2.4 GPa. The tensile modulus of the MMSO hybrid composites varies between 0.87 and 2.4 GPa. The tensile strength of the MMSO hybrid composites varies between 6.7 and 17.5 MPa. As one can see, the tensile strength of the MMSO composites has a wider range compared to AESO composites. MMSO composite W3 has the highest tensile strength among others (18 MPa). Comparison of tensile modulus and tensile strength for AESO and MMSO reinforced composites and hybrid composites are shown in the following sections.
5.1.1 Tensile Modulus

![Graph showing tensile modulus comparison for AESO and MMSO reinforced composites.]

Figure 6. Comparison of tensile modulus for AESO and MMSO reinforced composites.

![Graph showing tensile modulus comparison for AESO and MMSO hybrid composites.]

Figure 7. Comparison of tensile modulus for AESO and MMSO hybrid composites.
5.1.2 Tensile Strength

Figure 8. Comparison of tensile strength for AESO and MMSO reinforced composites.

Figure 9. Comparison of tensile strength for AESO and MMSO hybrid composites.
5.2 Flexural Test

Table 6. Flexural Properties of AESO reinforced composites.

<table>
<thead>
<tr>
<th>Name</th>
<th>Flexural Strength (MPa)</th>
<th>Stan. dev.</th>
<th>Flexural Modulus (GPa)</th>
<th>Stan. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite NW (2-PLY)</td>
<td>13.7</td>
<td>1.6</td>
<td>0.83</td>
<td>0.13</td>
</tr>
<tr>
<td>Composite W1 (3-PLY)</td>
<td>25.4</td>
<td>12.2</td>
<td>1.37</td>
<td>0.69</td>
</tr>
<tr>
<td>Composite W2 (3-PLY)</td>
<td>18.4</td>
<td>3.17</td>
<td>0.54</td>
<td>0.07</td>
</tr>
<tr>
<td>Composite W3 (6-PLY)</td>
<td>7.7</td>
<td>4.7</td>
<td>0.48</td>
<td>0.33</td>
</tr>
<tr>
<td>HYBRID NWW1</td>
<td>26.5</td>
<td>3.14</td>
<td>1.5</td>
<td>0.18</td>
</tr>
<tr>
<td>HYBRID NWW2</td>
<td>21.2</td>
<td>1.14</td>
<td>0.88</td>
<td>0.05</td>
</tr>
<tr>
<td>HYBRID NWW3</td>
<td>35.5</td>
<td>6</td>
<td>2.24</td>
<td>0.36</td>
</tr>
</tbody>
</table>

The flexural strength of the AESO reinforced composites varies between 7.7 and 25.5 MPa. The flexural modulus of the AESO reinforced composites varies between 0.4 and 0.9 GPa. The flexural strength of the AESO hybrid composites vary between 21 and 36 MPa. The flexural modulus of the AESO hybrid composites vary between 0.8 and 2.3GPa.

Table 7. Flexural Properties of MMSO reinforced composites.

<table>
<thead>
<tr>
<th>Name</th>
<th>Flexural Strength (MPa)</th>
<th>Stan. dev.</th>
<th>Flexural Modulus (GPa)</th>
<th>Stan. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite NW (2-PLY)</td>
<td>12.9</td>
<td>1.92</td>
<td>0.82</td>
<td>0.15</td>
</tr>
<tr>
<td>Composite W1 (3-PLY)</td>
<td>40</td>
<td>7</td>
<td>2.17</td>
<td>0.46</td>
</tr>
<tr>
<td>Composite W2 (3-PLY)</td>
<td>18.7</td>
<td>1.4</td>
<td>0.68</td>
<td>0.09</td>
</tr>
<tr>
<td>Composite W3 (6-PLY)</td>
<td>9.5</td>
<td>2</td>
<td>0.46</td>
<td>0.17</td>
</tr>
<tr>
<td>HYBRID NWW1</td>
<td>13</td>
<td>1</td>
<td>0.43</td>
<td>0.03</td>
</tr>
<tr>
<td>HYBRID NWW2</td>
<td>20.5</td>
<td>3.37</td>
<td>0.63</td>
<td>0.15</td>
</tr>
<tr>
<td>HYBRID NWW3</td>
<td>18.5</td>
<td>4.8</td>
<td>0.82</td>
<td>0.25</td>
</tr>
</tbody>
</table>
The flexural strength of the MMSO reinforced composites varies between 9 and 40 MPa. The flexural modulus of the MMSO reinforced composites varies between 0.4 and 2.2GPa. The flexural strength of the MMSO hybrid composites vary between 12 and 18.5 MPa. The flexural modulus of the MMSO hybrid composites vary between 0.4 and 0.82GPa.

A figurative comparison of flexural modulus and flexural strength for AESO and MMSO reinforced composites and hybrids are shown in the following sections.

5.2.1 Flexural Strength

![Figure 10. Comparison of flexural strength for AESO and MMSO reinforced composites.](image-url)
5.2.2 Flexural Modulus

Figure 11. Comparison of flexural strength for AESO and MMSO hybrid composites.

Figure 12. Comparison of flexural modulus for AESO and MMSO reinforced composites.
5.3 Comparison of the mechanical properties of AESO and MMSO composites

An overall comparison of tensile and flexural properties of AESO and MMSO reinforced composites is shown in Table 8 below.

Table 8. Comparison of the mechanical properties of AESO and MMSO composites.

<table>
<thead>
<tr>
<th>Property</th>
<th>Tensile Modulus (GPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Flexural Modulus (GPa)</th>
<th>Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Name</td>
<td>AESO</td>
<td>MMSO</td>
<td>AESO</td>
<td>MMSO</td>
</tr>
<tr>
<td>Composite NW(2-PLY)</td>
<td>1.3</td>
<td>0.41</td>
<td>9.4</td>
<td>4.12</td>
</tr>
<tr>
<td>Composite W1(3-PLY)</td>
<td>0.52</td>
<td>0.88</td>
<td>9.2</td>
<td>8.32</td>
</tr>
<tr>
<td>Composite W2(3-PLY)</td>
<td>0.62</td>
<td>1.03</td>
<td>9.1</td>
<td>9.84</td>
</tr>
<tr>
<td>Composite W3(6-PLY)</td>
<td>1.1</td>
<td>2.44</td>
<td>9.2</td>
<td>18</td>
</tr>
<tr>
<td>Hybrid NW/W1</td>
<td>1.7</td>
<td>2.19</td>
<td>17</td>
<td>9.8</td>
</tr>
<tr>
<td>Hybrid NW/W2</td>
<td>2</td>
<td>1.9</td>
<td>17</td>
<td>17.5</td>
</tr>
<tr>
<td>Hybrid NW/W3</td>
<td>2.4</td>
<td>0.87</td>
<td>18</td>
<td>6.68</td>
</tr>
</tbody>
</table>
5.4 Dynamic mechanical thermal analysis results

5.4.1 DMTA Results for AESO

Figure 14. Tan Delta comparison of the AESO reinforced composites.

Figure 15. Storage Modulus vs. Temperature for AESO reinforced composites.
5.4.2 DMTA Results for MMSO

Figure 16. Loss Modulus vs. Temperature for AESO reinforced composites.

Figure 17. Tan Delta comparison of the MMSO reinforced composites
Figure 18. Storage Modulus vs. Temperature for MMSO reinforced composites

Figure 19. Loss Modulus vs. Temperature for MMSO reinforced composites.
6. Discussion

Table 9 shows Overall comparison for mechanical and thermal properties of AESO and MMSO reinforced composites and hybrid composites.

Table 9. Overall comparison for mechanical and thermal properties of AESO and MMSO reinforced composites and hybrid composites.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Matrix</th>
<th>Tensile</th>
<th>Flexural</th>
<th>DMTA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Modulus</td>
<td>Strength</td>
<td>Modulus</td>
</tr>
<tr>
<td>NW (2-PLY)</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>W1 (3-PLY)</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>W2 (3-PLY)</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>W3 (6-PLY)</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NW/W1</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
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<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
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</tr>
<tr>
<td>NW/W3</td>
<td>AESO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>MMSO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓: Higher values for tensile, flexural and DMTA test results.

The curing conditions for AESO and MMSO samples were exactly the same, but MMSO samples were completely cured during the first step (in the oven at 60 degrees centigrade for one hour), therefore the post curing step did not affect the MMSO composites and hybrids. The cured AESO samples had a better appearance compared to MMSO samples; they had smooth surfaces and were bonded together more tightly. This can affect the mechanical and thermal properties of the MMSO samples.

Blending AESO and MMSO with styrene increases the resin stiffness and mechanical properties. Blending is done by hand; therefore it affects the resin properties. More blending time leads to a more homogenous resin. It is recommended that blending is done by a mechanical agitator with a certain speed in a certain time in order to have the same resin for each sample.
Water affects the properties of the fibers. Natural fibers that were used in this experiment absorb water very quickly; therefore they have to be dried in an oven directly before use. Although all the fibers were dried, they may differ in water content. It is better to move the oven close to the working area to make sure that no moisture is absorbed after drying.

Residence time in vacuum injection molding is an important issue; it may have positive or negative effects on composite/hybrid properties. In this experiment different residence times were observed during the injection molding process. The vacuum pump pressure was the same for all samples but the number of layers, type of reinforcements and matrix and the platform conditions were slightly different; therefore the injection time was different for each sample. There should be a certain injection time for the composites depending on many factors such as vacuum pressure, viscosity of the resin, etc. So it is recommended that the vacuum injection molding process takes place in an equipment where the vacuum pressure could be regulated.

The tensile modulus values for MMSO reinforced composites W1, W2 and W3 are higher than the ones for the same AESO composites, which means that MMSO resin shows better binding properties in reinforced woven composites. The tensile modulus value for the non-woven MMSO reinforced composite is lower than the one for the non-woven AESO reinforced composite.

The non-woven AESO composite has the highest tensile modulus among other AESO reinforced composites which may indicate that bi-axial woven fabrics decrease the tensile modulus values in AESO reinforced composites. The tensile modulus value for non-woven MMSO reinforced composite is the lowest among other MMSO composites which may be as a result of inappropriate curing conditions.

In both AESO and MMSO reinforced woven composites, W2 and W1 show quite similar tensile modulus. The composite W3 shows better tensile modulus when compared to composites W2 and W1. This may be because of the fact that the distance between the adjacent roving wefts and warps in W3 fabric is much longer than the distance in W2 and W1.

The NW/W3 AESO reinforced hybrid composite shows the highest tensile modulus among all AESO hybrid composites whereas the NW/W1 MMSO hybrid composite has the highest tensile modulus among the MMSO hybrid composites. This may be due to the good binding properties of MMSO resin.
The tensile strength for all AESO reinforced composites are quite the same but it follows an increasing pattern for MMSO reinforced composites. One can conclude that the MMSO reinforced composites behave positively to different reinforcement while different fibre reinforcement did not have considerable effects on the AESO composites. The same happens for AESO hybrid composites but the NW/W3 MMSO hybrid composite has lower tensile strength than NW/W1 and NW/W2. The reason may due to the fact that W2 jute fabric has a more compact weaving structure than the W1 jute fabric and the W1 jute fabric has a more compact weaving structure than the W3 jute fabric.

The flexural strength results for AESO and MMSO composites follow quite the same pattern. The NW composite has low flexural modulus in both AESO and MMSO composites. The W3 composite has the lowest flexural modulus. The distance between the warp and weft in this type of fabric is more than the one in other fabrics which can cause voids in the final composite and therefore affecting the flexural modulus properties negatively. The flexural modulus for W1 composite is higher than the one for W2 which indicates that a better bonding was achieved between layers of W1 jute fabrics. The more distance between warp and weft, the better flexural strength for AESO hybrid composites.

The results for MMSO hybrids are not reliable in this part because of the inappropriate curing conditions. MMSO hybrids have lower flexural strength compared to AESO reinforced composites. This may be as a result of improper curing conditions or that AESO shows a better bonding with reinforcements compared to MMSO.

The distance between the warp and weft in this type of fabric is more than the one in other woven fabrics causing voids in the final composite and therefore affecting the flexural modulus properties. The flexural modulus for W1 hybrid composite is higher than the one for W2 which may be as a result of a better bonding between layers of W1 fabrics. One can say that the flexural strength for MMSO reinforced composites is roughly higher than the ones for AESO composites, showing better flexural properties in MMSO.

The NW/W1 AESO reinforced hybrid composite has a higher flexural modulus than the NW/W2 AESO composite. The W2 jute fabric is more packed than the W1. Packed warp and weft may inhibit bonding. The NW/W3 for the AESO composite has the highest flexural modulus. The distance between warp and weft in the W3 fabric is longer than the one in other woven fabrics, causing better flexural modulus properties. The pattern which MMSO hybrid composites follow on the flexural modulus chart
is totally different from the pattern AESO hybrids follow, which may be a result of unsuitable curing conditions.

For MMSO composites and hybrid composites tan delta peak occurs at higher temperatures (over 110°C) compared to AESO composites and hybrid composites (less than 100°C). The peak in tan delta diagram shows the glass transition temperature, up to this temperature, the polymer has elastic behavior but at this temperature, the polymer starts to show viscoelastic behavior. This means better thermal properties for MMSO composites and hybrid composites. The storage modulus for the AESO reinforced composites was maximum in composite NW/W3 which show that these hybrid composites have superior mechanical properties.
7. References


